



Wind effects on snow cover in Pascua-Lama, Dry Andes of Chile

Simon Gascoin, Stefaan Lhermitte, Christophe Kinnard, Kirsten Borstel, Glen E. Liston

► **To cite this version:**

Simon Gascoin, Stefaan Lhermitte, Christophe Kinnard, Kirsten Borstel, Glen E. Liston. Wind effects on snow cover in Pascua-Lama, Dry Andes of Chile. *Advances in Water Resources*, Elsevier, 2013, 55, pp.25-39. <10.1016/j.advwatres.2012.11.013>. <hal-00756902>

HAL Id: hal-00756902

<https://hal.archives-ouvertes.fr/hal-00756902>

Submitted on 23 Nov 2012

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Wind effects on snow cover in Pascua-Lama, Dry Andes of Chile

Simon Gascoin^{a,b}, Stefaan Lhermitte^{c,b}, Christophe Kinnard^b, Kirsten Borstel^b, Glen E. Liston^d

^a*Centre d'Études Spatiales de la Biosphère (CESBIO), Toulouse, France*

^b*Centro de Estudios Avanzados en Zonas Áridas (CEAZA), La Serena, Chile*

^c*Royal Netherlands Meteorological Institute (KNMI), De Bilt, The Netherlands*

^d*Cooperative Institute for Research in the Atmosphere (CIARA), Colorado State University, Fort Collins, USA*

Abstract

We present the first application of a distributed snow model (SnowModel) in the instrumented site of Pascua-Lama in the Dry Andes (2600-5630 m above sea level, 29° S). A model experiment was performed to assess the effect of wind on the snow cover patterns. A particular objective was to evaluate the role of blowing snow on the glacier formation. The model was run using the data from 11 weather stations over a complete snow season. First, a cross-validation of the meteorological variables interpolation model (MicroMet submodel) was performed to evaluate the performance of the simulated meteorological forcing. Secondly, two SnowModel simulations were set up: one without and the other with the wind transport submodel (SnowTran-3D). Results from both simulations were compared with in situ snow depth measurements and remotely sensed snow cover data. The inclusion of SnowTran-3D does not change the fact that the model is unable to capture the small-scale snow depth spatial variability (as captured by in situ snow depth sensors). However, remote sensing data (MODIS daily

snow product) indicate that at broader scales the wind module produced an improved representation of the snow distribution near the glaciers (2-D correlation coefficient increased from $R=0.04$ to $R=0.27$). The model outputs show that a key process is the sublimation of blowing snow, which amounts to 18% of the total ablation over the whole study area, with a high spatial variability. The effect of snow drift is more visible on the glaciers, where wind-transported snow accumulates preferentially. Net deposition occurred for 43% of the glacier grid points, whereas it is only 23% of non-glacier grid points located above the minimum glacier altitude (4475 m).

Keywords: snow, glacier, wind, sublimation, Andes, MODIS, SnowModel, snowdrift, blowing snow sublimation, semiarid mountain

1. Introduction

2 The Dry Andes region spans from 20° S to 35° S and covers the aridest
3 part of the Andes Cordillera [1]. Due to the low precipitation and high solar
4 radiation, glacier cover is small in the Dry Andes in comparison with the
5 tropical Andes in the north or the Andes of central Chile in the south [2].
6 In the semi-arid lowlands of Chile, the annual precipitation is not sufficient
7 for sustaining the agriculture sector, which provides most of the regional
8 employment. The cultivators rely on snowmelt, and glacier runoff to a lesser
9 extent, from the high-altitude area for irrigating the fields during the growing
10 season [3]. The mining industry is the other main economic activity in this
11 mineral-rich region. The scarcity of the water resource is the cause of a
12 persistent conflict between both sectors [4]. In 2005 a controversy about
13 the Pascua-Lama mine project, which initially implied the displacement of

14 glacial ice, revealed that the local population was particularly concerned by
15 the fate of the glaciers in the Dry Andes both in Chile and Argentina [5].

16 In the Dry Andes, two particular processes are known to be critical for
17 the study of the cryosphere. First, sublimation is a major component of
18 the snow and ice mass balance. Low air humidity, high solar radiation and
19 strong winds result in large sublimation rates. For example, sublimation was
20 estimated to represent 89% (327 mm w.e.) of the mean annual ablation near
21 the summit of the Tapado glacier between 1962 and 1999 (5536 m a.s.l.) [6].
22 At the same location Ginot et al. [7] observed daily sublimation rate of 1.9
23 mm w.e from lysimeter measurements. In Pascua-Lama further lysimeter
24 measurements revealed that sublimation rates could exceed 3 mm/d [8]. An-
25 other key aspect of the Dry Andes cryosphere is the effect of the wind on the
26 snow distribution. This aspect was much less documented but pointed out
27 by Ginot et al. [6] to explain the presence of a glacier on the Cerro Tapado,
28 while higher surrounding mountains are glacier-free. Rabatel et al. [9] also
29 emphasized the effect of wind on the spatial distribution of glaciers in the
30 Pascua-Lama area, in addition to the shading effect. Based on the hydro-
31 logical balance equation, Gascoin et al. [8] found that the contribution of
32 the glacierized fraction of the catchment area to the mean annual stream-
33 flow was greater than the contribution from the non-glacierized fraction and
34 suggested that this was mainly due to enhanced meltwater production from
35 negative net glacier mass-balance, while deposition of wind-transported snow
36 from the non-glacier area to the glacier surface increased the winter balance
37 of the glaciers. However, no study has brought conclusive evidence that wind
38 contributes to glacier formation in the Dry Andes. Yet, there is growing

39 evidence that wind-related processes have a strong impact on glacier accu-
40 mulation in other mountain ranges. Based on a similar hydrological balance
41 analysis in the Paznaun basin (Austrian Alps), Kuhn [10] introduced an em-
42 pirical “redistribution factor” in order to account for the fact that “glaciers
43 receive twice as much precipitation as the basin average”. This observation
44 was attributed to the combined effects of wind transport of snow from the
45 ice-free areas, precipitation variability and avalanches. The specific effect of
46 wind on glacier accumulation was further characterized at the glacier scale
47 by Machguth et al. [11], Mott et al. [12], Bernhardt et al. [13], Dadic et al.
48 [14], Carturan et al. [15] in the European Alps, and Purdie et al. [16] in the
49 Southern Alps of New-Zealand. The physical processes governing the wind
50 influence on snow accumulation were recently summarized into two main pro-
51 cesses by Dadic et al. [14], based on previous work by Lehning et al. [17]:
52 (i) the transport of already-deposited snow (often referred to as snow drift),
53 which includes suspension and saltation processes; (ii) the preferential de-
54 position of precipitation due to topographic-induced wind field perturbation
55 during a snow storm.

56 Yet the wind does not only play an important role in shaping the snow
57 accumulation on glaciers. Apart from the process of snow erosion due to
58 wind shear stress on the surface, the local wind field is also a critical factor
59 of the snow ablation since it determines the turbulent exchanges of heat and
60 moisture between the snow surface and the atmosphere, especially over small
61 ice bodies and snow patches [18, 19]. Hence the wind is an important driver of
62 the static-surface sublimation and melting [20]. Furthermore, wind transport
63 of suspended snow increases sublimation and thus ablation [21, 22, 23]. To

64 our knowledge, a full assessment of all these processes for glaciers over a
65 season or longer has not yet been achieved yet.

66 There are relatively fewer studies dealing with the effects of wind on snow
67 cover in semi-arid mountains than in temperate climate mountains. Marks
68 and Winstral [24] emphasized the importance of accounting for spatially-
69 variable energy inputs and snow deposition patterns to model snowmelt in a
70 semi-arid mountain catchment of southern Idaho. In the same area, Winstral
71 and Marks [25] used terrain-based parameters to model the distributed wind
72 speeds and accumulation rates. The snow model forced with these fields suc-
73 cessfully simulated the observed snow distribution and melt, while the same
74 model forced with spatially constant wind and accumulation overestimated
75 peak snowmelt.

76 In this paper, we have considered only the wind effects on snow cover due
77 to snow drift (suspension and saltation) and blowing snow sublimation in
78 order to understand the effects of wind on snow cover and glacier formation
79 in the Dry Andes. The wind effect on static-surface snow sublimation was
80 not directly investigated as it is not related to snow transport. For that pur-
81 pose we applied a distributed snow model that accounts for snow transport
82 by the wind (SnowModel, [26]) in the Pascua-Lama area. SnowModel is a
83 distributed mass and energy balance model, which allows the interpolation
84 of the meteorological forcing based on in situ data (weather stations). The
85 wind speeds and directions are modified according to the topography using
86 terrain-based parameters [27]. A similar application of SnowModel was pre-
87 sented by Bernhardt et al. [13] in the Bavarian Alps. The authors found
88 that the wind fields generated by the MM5 atmospheric model were more

89 reliable than the standard interpolated wind fields generated by SnowModel.
90 However, the MM5-generated wind speeds and directions were still corrected
91 with the same terrain-based parameterizations as in SnowModel, and yielded
92 a good representation of the snow patterns. The model was used to estimate
93 the amount of transported snow from the surrounding areas to the glacier
94 [13].

95 Based on these insights, and because it is the first application of a dis-
96 tributed snow model in the semi-arid Andes that we are aware of, this study
97 focused on the model assessment based on multiple data sources. First, the
98 model spatial interpolation scheme was tested for all the input meteorological
99 variables. Secondly, the model was run with and without the wind transport
100 module to analyze the effects of wind on the snow mass balance. Finally,
101 both simulations were compared to in situ observations and remote sensing
102 data.

103 **2. Study area**

104 The Pascua-Lama area is located in the high Andes of the Chilean At-
105 acama Region near the border of Argentina (29.3° S; 70.1° W) (Fig. 1).
106 The elevation ranges between 2600 m and 5630 m a.s.l. Vegetation cover is
107 extremely sparse and virtually absent above 3800-m. The landscape is domi-
108 nated by large and steep granitic outcrops. The study area comprises various
109 glaciers (including glaciarets, i.e. small ice bodies with little or no sign of
110 flow) occurring on the southern slopes of the highest peaks between 4780
111 and 5485 m a.s.l [2, 9]. As north-westerly winds dominate, southern slopes
112 correspond to the leeward slopes. The snow cover and glaciers in the study

113 area are characterized by the formation of penitents, a typical feature of the
114 Dry Andes which derive from the sublimation process [1]. These columnar
115 shapes of snow or ice can frequently exceed 2 m in height, especially in wind-
116 sheltered spots. They grow as a result of a differential ablation rate between
117 the crest and the base of the penitents [28]. The ablation rate is higher at
118 the base of a penitent, because the humidity and radiation conditions are
119 more favorable to melting, while the crest lose mass predominantly by sub-
120 limation. However, the initiating processes remain unclear [29], which helps
121 explain why they are not represented in any snow evolution model. In this
122 study we did not account for the formation of the penitents. The study area
123 usually gets completely snow covered in winter. Nonetheless, the snowfall
124 interannual variability is pronounced as the region is under the influence of
125 the El Nino Southern Oscillation (ENSO). The last ENSO episode affecting
126 the study area was in winter 2002 and caused heavy snowfalls [8]. The en-
127 vironmental impact assessment process for the Pascua-Lama mining project
128 decided by the Chilean Government [30] involves the monitoring of various
129 environmental variables related to snow, glaciers and atmosphere. This con-
130 text explains the wealth of meteorological data that were available for this
131 study (11 weather stations). As of today it is one of the best documented
132 sites for the study of the cryosphere in the Dry Andes [9, 8].

133 **3. Method**

134 *3.1. Model description*

135 SnowModel is a spatially-distributed snow model adapted for the study
136 of snow redistribution by wind [26, 31]. It has already been applied in a va-

137 riety of alpine (Rocky Mountains, [32]; European Alps, [13]) and arctic land-
138 scapes [33], but never in the Andes. SnowModel comprises four submodels:
139 MicroMet, EnBal, SnowPack and SnowTran-3D. MicroMet performs spatial
140 and temporal interpolation to produce the spatially distributed meteorolog-
141 ical fields required to run the other submodels [34]. EnBal is a standard
142 energy balance snow model [35, 36] which simulates energy and water fluxes
143 from MicroMet outputs. SnowPack is a snow depth and snow density evo-
144 lution model [35]. SnowTran-3D simulates the evolution of snow depth due
145 to wind blowing snow [21, 26, 31]. Snow transport by avalanches is not rep-
146 resented. The model works by coupling the four submodels at the forcing
147 data time step (typically 1 hour), effectively resolving the mass balance of
148 the snowpack at each time step. A complete description of the model struc-
149 ture and a summary of the previous applications can be found in Liston and
150 Elder [26]. Here we focus on blowing snow sublimation and snow transport
151 by wind, which are expected to be key processes of the snow mass balance.
152 The MicroMet submodel interpolates the weather stations measurements to
153 a two-dimensional grid based on the Barnes objective function [37]. The
154 Barnes interpolator does not account directly for elevation. Prior to the in-
155 terpolation, the data are converted to sea-level surface data using a linear
156 lapse rate. The interpolated grid is taken back to the actual elevation using
157 the same lapse rates. The wind speed and direction are interpolated using
158 this method, then the gridded values are modified according to topographic
159 slope and curvature relationships [31]. A static-surface sublimation term is
160 simulated by EnBal as a result of the energy balance equation (turbulent flux
161 of latent heat from the surface). Additionally, SnowTran-3D simulates the

162 sublimation of windborne snow during the saltation and turbulent suspension
163 processes [31].

164 The latest available version of SnowModel was used for this study (last
165 update on 08-Sep-2011). The original Walcek [38] parameterizations for cloud
166 cover fraction in MicroMet [34] was modified, because preliminary analyses
167 indicated underestimation of the simulated fraction, resulting in an overes-
168 timation of incoming shortwave and underestimation of incoming longwave
169 (not shown here). This was corrected by rescaling the obtained cloud cover
170 fraction using Walcek’s parametrization to the 0-1 cloud cover interval, based
171 on the cloud cover data derived from the analysis of shortwave radiation mea-
172 surements in the study area [39].

173 *3.2. Model setup*

174 The modeling domain is shown in Fig. 1. The computational grid has the
175 same resolution as the digital elevation model, which was extracted from the
176 Shuttle Radar Topography Mission 90 m spatial resolution data version 2.1
177 [40]. While a main objective of the study is the analysis of the snow mass
178 balance over the glaciers, we chose to simulate the snow cover over a larger
179 area, for two reasons (i) it enables a better model assessment since most of
180 the snow depth measurements sites are off-glacier and a large domain allows
181 the comparison with satellite observations; (ii) it enables to compare the
182 snow mass balance over glacier with glacier-free areas. Most of the model
183 parameters were set to their default value (Tab. 1). The threshold surface
184 shear velocity was assumed to be constant during the simulation (0.25 m/s).
185 The snow subgrid redistribution was not activated [41]. The curvature length
186 scale was estimated based on the DEM to be 500 m, i.e. approximately

187 one-half the wavelength of the topographic features within the domain [31].
188 SnowModel was run for the period 1-May-2008 to 31-November-2008, which
189 corresponds to a complete snow season. At the beginning of the simulation
190 the snowpack was set to zero. Meteorological data from 11 AWS were used to
191 force MicroMet (Tab. 2, Fig. 2). A summary of the available meteorological
192 forcing data is given in Tab. 2. The longwave radiation sensors were operated
193 only from 09-Oct-2008 at Toro 1 and Guanaco AWS (75% missing values).
194 As a result, there are few longwave data for the simulation period to be
195 assimilated by MicroMet. Snow depth was recorded every hour at six weather
196 stations using Campbell Scientific SR50 and SR50A acoustic sensors (Tab. 2).
197 Among these six stations, three are located on a glacier (Guanaco, Toro 1,
198 and Ortigas), while the three others are located on bare ground (La Olla, El
199 Toro, Tres Quebradas).

200 Since vegetation is essentially absent in the model area, the land cover
201 type was set to bare ground everywhere except for the glaciated areas where
202 we used the “permanent snow/glacier” class defined in SnowModel.

203 There are precipitation gauges in the study area but the data were found
204 to be unusable due to inappropriate operation and maintenance. There-
205 fore precipitation was estimated from snow depth measurements. First, we
206 used as a reference the manual snow depth measurements which are made
207 at the mine base camp (“Campamento”, Fig. 1). At this site, during each
208 precipitation event, a meteorologist typically surveyed the depth of accumu-
209 lated snow on the ground every two hours. These data were interpolated
210 to a 1 hour time step. In addition, we used the continuous hourly snow
211 depth measurements from six meteorological stations equipped with acoustic

212 snow gauges. These data were filtered to extract only positive snow depth
 213 increases during the days that precipitation was observed at Campamento.
 214 We assumed that snow settling during the snowfall can be neglected at this
 215 hourly timestep. The filter was applied to the days of Campamento precip-
 216 itation (rather than the hours) to allow for some delay in the precipitation
 217 occurrence between Campamento and the other sites. The resulting hourly
 218 snowfall records (seven series including Campamento) were then converted
 219 from snow depth to water equivalent using the empirical formula of Anderson
 220 [42] for new snow density (ρ):

$$\rho = 50 + 1.7(T_w - 258.16)^{1.5} \quad (1)$$

221 where T_w is the wet-bulb temperature. T_w was calculated following Liston
 222 and Hall [35], i.e. using the formula given by Rogers [43]:

$$T_w = T_a + (e_a - e_s(T_w)) \frac{0.622L_v}{P_a C_p} \quad (2)$$

223 where T_a is the surface-air temperature, e_a is the atmospheric vapor pressure,
 224 $e_s(T_w)$ is the vapor pressure of the surface at wet-bulb temperature, L_v is the
 225 latent heat of sublimation, P_a is the atmospheric pressure at the surface and
 226 C_p is the specific heat of air. The atmospheric vapor pressure was computed
 227 with the coefficients for saturation vapor pressure over ice [44]:

$$e_a = Ah \exp \frac{B(T_a - T_f)}{C + (T_a - T_f)} \quad (3)$$

228 with $A = 611.21$ Pa; $B = 22.452$; $C = 272.55^\circ$ C, and where h is the relative
 229 humidity and T_f is the freezing temperature. The vapor pressure of the
 230 surface at wet-bulb temperature is given by [45]:

$$\log_{10}(e_s(T_w)) = 11.40 - 2353/T_w \quad (4)$$

231 The wet bulb temperature was obtained by iteration until a $0.01K$ conver-
232 gence criteria was reached.

233 These precipitation data were used as input to MicroMet. The resulting
234 precipitation rates averaged per event over the study area are given in Tab. 3.

235 To account for the variations of air temperature and relative humidity
236 with elevation, SnowModel uses standard values of air temperature and dew-
237 point temperature monthly lapse rates. However, SnowModel also allows
238 the user to specify these lapse rates to better capture the local meteorologi-
239 cal conditions. For this study we computed the lapse rates using data from
240 the 11 meteorological stations (Tab. 2). For every month between May and
241 November 2008 the regression slope between the monthly air temperature
242 and the station elevation was determined using the Matlab robustfit default
243 algorithm [46] (iteratively reweighted least squares with a bisquare weighting
244 function). This algorithm was chosen because it decreases the influence of
245 outliers on the regression. The same procedure was applied to the dewpoint
246 temperature (only 10 stations). The lapse rates were computed for the dew-
247 point temperature because the relative humidity is a non linear function of
248 elevation. The lapse rates obtained for the study area are shown in Tab. 4.

249 *3.3. Model experiments*

250 First, the MicroMet submodel performance was assessed using a leave-
251 one-out cross-validation approach. For a given meteorological variable, each
252 AWS (the target) was successively removed from the calibration data set.
253 This reduced data set was used to predict the left-out variable at the target
254 location using MicroMet. This procedure was repeated for each AWS using
255 all the available data over the simulation period (Tab. 2). The accuracies of

256 the predicted variables were analyzed using the coefficient of determination
257 (R^2) and the bias (B) calculated from hourly data. For the wind direction,
258 only the bias was calculated, which corresponds to the mean of the angu-
259 lar difference between the simulated and observed wind direction at each
260 timestep.

261 Secondly, we carried out two simulations with SnowModel: for the first
262 simulation SnowTran-3D was disabled (labeled without SnowTran), while it
263 was activated for the second one (labeled with SnowTran). Otherwise, both
264 simulations had the same input data and parameters. We used the study-
265 area lapse rates. The results were compared to snow depth measurements
266 from AWS and to snow cover area from MODIS data.

267 *3.4. Simulated snow cover area*

268 Snow cover area (SCA, i.e. the area of the modeling domain which is
269 covered by snow) is not a standard output of SnowModel. Various meth-
270 ods exist to convert the simulated snow depth or snow water equivalent to
271 a snow covered fraction of a model element [47]. However, these methods,
272 such as the depletion curve parameterization [48] are largely dependent upon
273 the model cell size, topography and land cover and must be adapted empir-
274 ically to the modeling domain provided that sufficient field observations are
275 available. An accurate SCA-SWE transformation is required for assimilating
276 SCA data into a hydrological model. Here we only aimed at discriminating
277 two simulations using the MODIS snow cover product, which allowed more
278 flexibility. We opted for a SWE-SCA conversion that matches the reported
279 detection accuracy of MODIS snow product. Klein and Barnett [49] reported
280 that the majority of misdetections occurred at snow depths of less than 40

281 mm. Hence, a grid cell was flagged as snow-covered if the simulated SWE
282 was larger than 10 mm w.e. on the same day (i.e. approximately 20 to
283 100 mm of snow depth). The sensitivity of the computed snow cover area to
284 this threshold was assessed using two additional SWE thresholds (4 mm w.e.
285 and 20 mm w.e.). These values correspond to the conversion of 40 mm snow
286 depth to SWE under the typical range of observed snow densities (100 kg/m³
287 and 500 kg/m³). To perform a pixel-to-pixel comparison between MODIS
288 and SnowModel, the SCA maps were resized to the MODIS spatial resolution
289 using a bilinear smoothing method (in this case the SWE threshold was set
290 to 10 mm w.e.).

291 *3.5. Validation data*

292 *3.5.1. Snow depth*

293 The acoustic snow gauge records were partly used to generate the pre-
294 cipitation forcing (Sect. 3.2.1.). However, only the positive snow depth
295 deviations recorded by the snow gauges during the precipitation events mea-
296 sured at Campamento were used to calculate the precipitation, i.e. a few
297 values among the whole records, so that the snow depth series from these
298 gauges can still be used to validate the temporal evolution of the snowpack at
299 these sites. The data from the stations on ground were filtered to remove the
300 noise around the reference height (i.e. snow depth was set to zero when the
301 measured distance oscillates around the sensor-ground distance). This pro-
302 cessing was not performed for the glacier station data as the reference height
303 may fluctuate naturally due to the compaction or melting of the underlying
304 glacier layers.

305 *3.5.2. Snow cover area*

306 We used the MODIS/Terra daily snow cover product MOD10A version 5
307 [50], which provides binary snow cover data (snow or no snow) on a 500 m
308 resolution grid and a cloud mask on a daily basis since 2000. The MOD10A
309 v5 product and previous versions were validated using ground snow measure-
310 ments in various mountainous regions [51], including the semi-arid Southern
311 Rocky Mountains [49], which present some analogous climatic and topo-
312 graphic conditions as in the north-central Andes. One of the main issues
313 related to the MODIS data exploitation for model assessment is the cloud
314 obstruction. Nebulosity is low in the Norte Chico so that cloud cover is ex-
315 pected not to be prohibitive for model validation even in winter and spring.
316 In the study area, only 27% of the data are marked as cloud over the model
317 simulation period (214 days). Nonetheless cloud obstruction must be ac-
318 counted for to estimate the snow coverage over the region of interest. For
319 this study we generated a cloud-free snow mask for every date by interpo-
320 lating the MOD10A1 product based on the nearest-neighbors method along
321 the time dimension (temporal filter, [52]). In the original data, the mean
322 maximal duration of successive cloudy days is 9.5 days (standard deviation
323 3.2 days). This means that in average for each time series the interpolation
324 algorithm can fill up to 5 days of cloud-flagged data with the previous or the
325 next non-obscured available data. We found that the cloud obstruction prob-
326 ability is much higher over the ore body (up to 38 successive days flagged as
327 cloud obscured), suggesting that the cloud detection algorithm failed in this
328 area. This might be related to the bright aspect of this weathered portion of
329 the igneous bedrock, forming a highly reflective surface in the visible spec-

330 tra. Otherwise the cloud mask appeared qualitatively reliable. The cloud-free
331 snow maps were then used to compute the snow cover fraction over the whole
332 domain (1043 km², Fig. 1). Because of the possible persistence of cloud ob-
333 struction over several day, the interpolated data must be considered with
334 caution. Hence we represented the cloud coverage in addition to the snow
335 coverage derived from MOD10A1 to avoid misinterpretation of the results.
336 The MODIS snow product was used in two ways (i) as a temporal validation
337 (without the spatial component) and (ii) as a seasonal and spatial validation
338 (without the temporal component).

339 4. Results

340 4.1. *MicroMet validation*

341 The results of the cross-validation (Tab. 5) indicate that most variables
342 are well simulated by MicroMet. The coefficients of determination (R^2) com-
343 puted for each station range between 0.83 and 0.98 for air temperature and
344 between 0.58 and 0.93 for the relative humidity. The biases are relatively
345 low for these variables (temperature: mean bias: -0.15° C, standard devia-
346 tion: 0.66° C; humidity: mean bias -0.37%, standard deviation: 4.7%). High
347 values of the coefficient of determination mostly result from the good corre-
348 lation of the diurnal cycles. Low biases, however, are due to the inclusion of
349 the observed lapse rates in MicroMet, which allowed the reduction of large
350 discrepancies in temperature and humidity if the standard lapse rates were
351 used (not shown here).

352 As expected, the accuracy of MicroMet is much lower for the wind vari-
353 ables. In particular, the wind speeds are generally underestimated by Mi-

354 croMet by about 1 m.s^{-1} up to 4 m.s^{-1} at Guanaco (Tab. 5). The biases in
355 wind direction approximately range within -40° and 40° , except for Tres Que-
356 bradas where a large angular discrepancy is observed (Fig. 2). The largest
357 discrepancies are observed in the valley stations (Tres Quebradas and La
358 Olla), which are protected from the general wind flow, and where the fine-
359 scale topography and the diurnal cycle (slope-wind circulation, at La Olla)
360 are essential in determining the wind speed. On the other hand, the wind
361 field is relatively consistent with the data at the high-elevation stations as it
362 reproduces the dominant north-western flow (Fig. 2). Based on these results,
363 we conclude here that the MicroMet output are realistic enough to test with
364 SnowTran-3D the effects of wind on snow cover in the high altitude areas,
365 which are more prone to the dominant wind field.

366 Comparison of the observed and modeled incoming shortwave radiation
367 on a flat surface shows high correlation coefficients and relatively low biases.
368 Moreover, these biases are mainly the result of systematic offsets at the
369 beginning and end of the diurnal cycle (not shown here), which can be caused
370 by small timing differences (e.g. clock timing offset) or small leveling errors of
371 shortwave sensors. However, as these biases are relatively low in comparison
372 with the incoming shortwave radiation, the high correlation coefficients reflect
373 the robustness of Micromet used in combination with shortwave assimilation
374 to represent the observed incoming shortwave radiation. Conclusions on the
375 accuracy of modeled incoming longwave radiation are more difficult to draw
376 as we only have incoming longwave radiation observations for two stations
377 since October (Tab. 2). Nevertheless, longwave data comparisons yields high
378 R^2 values and low biases. Moreover, given the low nebulosity of the area

379 and consistent longwave time series before and after assimilation in October,
380 we believe Micromet accurately represents the incoming longwave radiation
381 before October.

382 *4.2. SnowTran-3D effect*

383 *4.2.1. Model mass budget*

384 Fig. 3 shows that the activation of SnowTran-3D has an important impact
385 on the temporal distribution of the monthly water budget for the whole do-
386 main. Sublimation of windborne snow increased by 17 mm w.e. the mass loss
387 in winter (between June and August). As a result, less snow is available for
388 melting in the spring. However, the static-surface sublimation computed in
389 the EnBal submodel remains the main ablation component of the total snow
390 ablation in both simulations, which is consistent with the findings of [23]
391 in the Swiss Alps. The total contribution of the sublimation (static-surface
392 and blowing snow sublimation) to the total ablation was only marginally
393 modified by the activation of SnowTran-3D (73% without SnowTran-3D vs.
394 71% with SnowTran-3D). The wind transported snow term corresponds to
395 the mean snow loss by saltation and suspension drifted outside of the model
396 domain and accounts for only 6% of the total mass loss (12 mm w.e.). How-
397 ever, the amount of transported snow is highly variable within the model
398 domain. Some grid cells located on the south-eastern slopes of the highest
399 crest (leeward side) have gained up to 200 mm w.e. at the end of the simu-
400 lation period (Fig. 4). In average 30% of the grid cells have gained snow due
401 to wind transport. The resulting distribution of the mean SWE is skewed to
402 the higher SWE depths (Fig. 6), showing that SnowTran-3D tends to “con-
403 centrate” the snow distribution by depleting the snowpack from the majority

404 of the grid cells to accumulate large amounts of snow on a few grid cells. As
405 shown in Fig. 7, both simulations yield different spatial distribution of the
406 mean SWE depth, in particular in the eastern half of the domain, where the
407 highest peaks and all the glaciers are found (see Sect. 4.2.4).

408 *4.2.2. Comparison with snow depth observations*

409 The pointwise comparison with the snow depth measurements yields
410 rather poor results (Fig. 8). While the simulated snow depths at Tres Que-
411 bradas site is satisfactory, large discrepancies are observed between the sim-
412 ulation and the measurements at the other sites. The model underestimated
413 the snow ablation at Guanaco and La Olla sites, but overestimated it on
414 glaciers Ortigas and Toro 1. Given the high spatial heterogeneity of the
415 glacier surface in this area (e.g. formation of snow penitents), such a dis-
416 crepancy can be expected for the glaciers stations. The model results for the
417 ground stations El Toro and Tres Quebradas are in better agreement with
418 observations. At El Toro site, a closer analysis reveals that the precipitation
419 input in May and June caused an overestimation of the initial accumulated
420 snow depth, but the snowpack ablation rate is actually well represented, as
421 in Tres Quebradas. However, the model failed to represent the extremely
422 fugitive snowpack observed at La Olla. La Olla weather station is located on
423 an artificial platform with a steep edge facing the prevailing wind, making
424 it vulnerable to wind erosion. As a consequence it may not be representa-
425 tive of the actual snow behavior in the surrounding area, i.e. at the model
426 spatial scale (90 m). This is confirmed by field observations, which indicate
427 that the snow on the weather station platform is rapidly depleted, whereas
428 snow persists in the immediate vicinity (Fig. 9). At all sites the snow depth

429 decreased more rapidly with SnowTran-3D, including the sites located on the
430 glaciers. At this stage, the results are too uncertain to indicate whether the
431 activation of SnowTran-3D improved the simulation.

432 *4.2.3. Comparison with remotely sensed snow cover*

433 The comparison of the snow cover area deduced from SnowModel simu-
434 lations and the snow cover area computed from MOD10A1 is presented in
435 Fig. 10. The result is encouraging given the large errors observed previously
436 at the station scale.

- 437 • All the expected precipitation events are evident in the MOD10A1
438 dataset. However, a strong increase of MOD10A1 snow cover in Septem-
439 ber was not registered by in situ sensors, which suggests that this is
440 an error of the MOD10A1 dataset. This error is probably a cloud mis-
441 detection, as this abnormal snow cover area occurred in the middle a
442 long period of cloudy conditions.
- 443 • The effect of the SWE threshold used for snow cover mapping is smaller
444 than the effect of SnowTran-3D on the snow cover area simulation,
445 which indicates that the simple SWE-SCA conversion used here is suf-
446 ficient for the purpose of this study.
- 447 • The activation of SnowTran-3D reduced the difference between the
448 model and the observed SCA. In particular, the snow cover recession
449 over the melting season (September to December) is better represented.
- 450 • Independently of SnowTran-3D, the model generally overestimated the
451 snow cover area after a snowfall event. The simulated snow covered

452 fraction of the domain reached one for four events, while MODIS data
453 indicated that the area was never completely snow covered.

454 The spatially distributed snow cover probability over the modeling do-
455 main is shown in Fig. 11. The simulation results are presented at the model
456 grid resolution (90 m) and compared with the MOD10A1 data (500 m).
457 This comparison demonstrates that the snow cover pattern simulated with
458 SnowTran-3D appears more consistent with the MODIS data than the one
459 simulated without SnowTran-3D. These maps show that the temporal de-
460 crease of the snow cover area observed in Fig. 10 has essentially occurred in
461 the area where most of the glaciers exist (but not as much on the glaciers
462 themselves), suggesting that the wind effect is higher in this area. To provide
463 further statistical ground to the previous results, we computed for each pixel
464 the phi coefficient between the MOD10A1 and the simulated snow cover area
465 daily time series (identical to the Pearsons correlation coefficient for two bi-
466 nary variables, in this case the absence/presence of snow at a given pixel).
467 We focused on the glacierized region, extended to the northern and south-
468 ern boundaries of the model domain, where most of SnowTran-3D effect is
469 visible. Fig. 12 shows that more pixels have a correlation $R > 0.3$ which is
470 statistically significant at the 5% level (P-value < 0.05) if SnowTran-3D is
471 activated (155 pixels, i.e. an improvement of 8%) . In this area, the 2-D
472 correlation coefficient between the simulated and the observed snow cover
473 probability maps is higher with SnowTran-3D. (0.036 without SnowTran,
474 0.27 with SnowTran).

475 *4.2.4. Wind effects on glacier vs. non-glacier areas*

476 The simulated transported snow pattern (Fig. 5) show that the north-
477 ern halves of Guanaco and Estrecho glaciers and the western half of Ortigas
478 glacier (i.e the three largest ice bodies in the area) have accumulated trans-
479 ported snow over the simulation period. The smallest ice bodies located west
480 of Guanaco glacier and south of Ortigas glacier have high accumulation rates,
481 as expected due to their position on the leeward side of the highest ridges.

482 To better characterize the effects of wind in the glacier areas, we selected
483 the grid points located above the minimum glacier altitude (4475 m a.s.l.)
484 and computed the net transport at the end of the simulation period for the
485 glacier (union of all the glacier polygons) and non-glacier areas. The glacier
486 fraction of this subdomain is 2.7%. The results show that positive transport
487 rates (net deposition) are more frequent over the glaciers (Fig. 15). Net
488 deposition at the end of the simulation period occurs for 43% of the glacier
489 grid points, whereas it is only 23% of non-glacier grid points.

490 The different components of snow mass balance were averaged over the
491 glacier area and over the non-glacier pixels located above the minimum glacier
492 altitude (4475 m a.s.l., Fig. 13). In both cases, the snow sublimation (static-
493 surface and blowing snow) is the dominant ablation term (at least 75% of the
494 total ablation). The sublimation of blowing snow prevails over the glaciers,
495 while static-surface is dominant over the non-glacierized area. Blowing snow
496 sublimation also accelerates the net mass loss over the glaciers in compari-
497 son with a run without SnowTran-3D (not shown here). Snow melt remains
498 almost negligible over the glaciers during the whole the simulation period,
499 while it is an important ablation term in glacier-free areas during the spring

500 months. But the main result is that wind transport of snow is positive on
501 the glacier areas during the first half of the simulation period, i.e. in win-
502 ter, whereas it is almost always negative in the non-glacier areas over the
503 same period (Fig. 13). At the end of the period, the net transport values
504 are -6 mm w.e for glacier surface and -26 mm w.e. for non-glaciers (Fig. 13),
505 which shows that glaciers do not gain or lose much mass by wind trans-
506 port, while outside glaciers, wind erosion is significant. Fig. 14 shows
507 the wind speed and incoming shortwave radiation simulated by MicroMet
508 over the glacier and non-glacier areas. The abrupt drop in the cumulated
509 snow transport on September-02 over the glacier areas (Fig. 13) is related
510 to the highest wind speed values modeled both over glacier and non-glacier
511 areas (reaching 10 m/s), which have led to a strong but isolated erosion
512 event. In addition, Fig. 14 shows that the glacier areas receive much less so-
513 lar energy than the non-glacier areas, especially during spring and summer,
514 which explains the lower melting rates. Hence the more positive snow mass
515 balance modeled for glacier areas relative to glacier-free areas is predomi-
516 nantly explained by (i) shading, i.e, glaciers are mostly found on southerly
517 slopes [2] and are thus more shaded from the sun; (ii) preferential deposition
518 of wind-transported snow from glacier-free areas onto glacier surfaces during
519 the winter period. The latter occurred mostly during winter (May-August),
520 causing the more positive mass-balance over glacier, while sun shading is
521 most pronounced in spring (September-November), which retards ablation
522 of snow on glaciers compared to glacier-free areas. Hence the thicker snow-
523 pack on glaciers (115 mm w.e.) at the end of winter relative to glacier free
524 terrain (77 mm w.e.) persists longer during the spring mostly due to delayed

525 snowmelt and runoff.

526 **5. Discussion**

527 *5.1. Meteorological forcing*

528 The main assumption of this study is that the MicroMet standard inter-
529 polation scheme is sufficient to generate the wind fields over the study area.
530 This assumption was examined based on the comparison with in situ data.
531 In particular, the wind field appears relatively well simulated in the high-
532 est part of the domain, which is the most important for the purpose of this
533 study. In these high-elevation areas, the local winds are mainly driven by the
534 synoptic wind. In this context the Barnes objective function for the spatial
535 interpolation of in situ data is well-suited. However, it is not appropriate to
536 simulate the wind fields in the valleys, which are strongly influenced by the
537 diurnal cycle (catabatic and anabatic flow) and the local topography. Thus,
538 a large part of the model uncertainties probably originates from the dis-
539 tributed wind fields. The underestimation of the wind velocity by MicroMet
540 may explain the lack of ablation at La Olla or Toro 1 stations. Preliminary
541 tests indicated that the calibration of the MicroMet parameters based on
542 the wind speed AWS data did not succeed in improving the simulated wind
543 (curvature length scale, slope and curvature weights, Tab. 1). Thus, the wind
544 simulation should be the focus for further applications of SnowModel or any
545 distributed snow model in this area, e.g. by using a high-resolution weather
546 forecast mesoscale model [12, 13, 14, 53, 54].

547 However, another part of the model uncertainties is related to the precip-
548 itation data. The comparison with snow depth measurements showed that

549 the magnitude of the precipitation was not well reproduced by the model, in
550 spite of our efforts to incorporate the measurements of snow depth during
551 the precipitation events. The problem is that the snow depth measurements
552 recorded by the ultrasonic gauges during a snow storm are difficult to in-
553 terpret as they combine the accumulation of precipitating snow with the
554 deposition or removal of snow from the snowpack caused by the wind. Fur-
555 ther work will be necessary to separate the relative contribution of these
556 processes from ultrasonic gauge measurements, especially if the model were
557 to be used for hydrological applications. Another option is to assimilate the
558 snow depth measurements in the model. SnowModel includes an option to
559 force the model towards SWE observations by precipitation and/or melt cor-
560 rection [41]. However, as noted before, based on field observations, it is likely
561 that finer grid resolution might be necessary if snow depth data are to be
562 assimilated in the Pascua-Lama area.

563 *5.2. Wind effects on snow cover*

564 We attempted to assess the effect of the SnowTran-3D submodel by com-
565 paring simulations with and without SnowTran-3D against in situ snow depth
566 measurements. However, the discrepancy between the data and the model
567 is too large to conclude on the effect of SnowTran-3D at the local scale. On
568 the other hand, the comparison with MODIS snow data suggests that the
569 simulated snow patterns are closer to reality when SnowTran-3D is activated.
570 The same conclusion was drawn by Prasad et al. [55] using SnowTran-3D.
571 This conclusions should be taken with caution as the comparison between
572 the model output and the MODIS data raises various methodological is-
573 sues (e.g. SWE to SCA conversion). For this study, however, the SWE

574 to SCA conversion had little impact on the conclusions (Fig. 10). Satellite
575 imagery with higher spatial resolution (e.g. Landsat) could help to further
576 assess the model but the temporal resolution would not allow the validation
577 of the rapid snow cover variations. A more rapid decrease of the SCA oc-
578 curs with SnowTran-3D (Fig. 10) because the combined effects of snow drift
579 and blowing snow sublimation result in more heterogeneous snow cover pat-
580 terns. (Fig. 7). Model output analyses suggest that the dominant effect of
581 the wind transport on snow cover is the sublimation of the blowing snow,
582 which represents 26% of the total sublimation and 18% of the total ablation.
583 Note that the wind effect on the static-surface energy balance was simu-
584 lated with EnBal but not analysed here as we focused on the wind effects
585 on snow cover through the saltation and suspension processes (SnowTran-3D
586 submodel). The static-surface sublimation, which is the main contributor to
587 the total ablation, is expected to be largely controlled by the wind speed and
588 near-surface atmospheric vapor pressure fields through the energy balance
589 equation (EnBal submodel)..

590 The activation of the blowing snow sublimation does not change the total
591 sublimation rate averaged over the whole domain and the whole simulation
592 period. Indeed, in both configurations, the model simulates very high subli-
593 mation rates, (71% to 73% of the total ablation), which is in agreement with
594 previous estimates [8]. Such sublimation rates are much higher than what
595 has been generally reported from model applications in other mountainous
596 regions [56, 57, 58, 23]. However, the contribution of blowing snow sublima-
597 tion to the snow mass balance is similar to [57] (also 18% of snow ablation).
598 The effects of blowing snow sublimation are strongly variable in space as

599 illustrated by [58]. Hence, blowing snow sublimation is responsible for the
600 modification of the main snow patterns across the domain, leading to a better
601 representation of the snow cover area as observed by MODIS. The blowing
602 snow sublimation is highest in the high-altitude region, because the wind
603 speeds are also highest (Fig. 5). The blowing snow sublimation is also higher
604 on glacierized areas than non-glacierized areas (Fig. 13), but this difference
605 is only the result of a strong drifting event on September-02 (Fig. 14). On
606 this day, the wind transport is much larger on the glaciers, which explains
607 why the blowing snow sublimation is also very high. The blowing snow sub-
608 limination also modifies the temporal distribution of the snow mass balance,
609 leading to a lower runoff in September and October because the snowpack is
610 more depleted when the main snowmelt season starts (Fig. 3). Similar results
611 were reported in a semi-arid mountain catchment [25] (see Introduction).

612 Wind transport has a lower effect on the overall snow mass balance. This
613 is partly due to the model resolution, which does not enable to model the
614 redistribution of snow at scales lower than 90 m. For smaller grid increment,
615 the wind transport is expected to be greater [31]. Another possible reason
616 for the low rates of snow transport is the absence of the preferential snow
617 deposition process in the model [17]. It has been shown that preferential
618 deposition of snow during precipitation events contributes to a large fraction
619 of the redistributed snow at the ridges scale in the Swiss Alps [53]. Yet, the
620 simulated snow transport pattern (Fig. 5) matches well the string of small
621 cornice glaciers, which are known to form because of drift accumulation be-
622 hind ridges, but do not give a conclusive answer over the largest glaciers.
623 However, Fig 13 indicates that a slight gain of snow mass due to wind trans-

624 port occurred from May to September on the glaciers, while the non-glacier
625 areas experienced significant losses. This gain was lost in September due
626 to a strong wind event which eroded away most of the accumulated snow.
627 Later, the wind transport becomes negative over the glaciers because most
628 remaining snow patches from the surrounding slopes are too far from the
629 glaciers to provide them snow, hence, only erosion remains on the glaciers
630 (erosion also occurred before in some parts of the glaciers, but was hidden
631 due to the larger deposition from outside). This snow drift event might be
632 overestimated by the model in its current configuration, since we used a
633 constant wind friction threshold for snow transport, while (i) the snowpack
634 consolidates with time and (ii) rising temperatures during spring should in-
635 creases the minimum wind shear stress required to initiate snow transport.
636 Therefore, the evolution of the wind friction threshold should be considered
637 for future studies.

638 A simple test was performed to assess the sensitivity of the model to the
639 uncertainty on the relative humidity. We have run two additional simulations
640 with + and - the prediction error on the relative humidity from the cross-
641 validation exercise i.e. the root mean square error (within the limits 100% -
642 1%). The RMSE computed from all the available data is 9.8%. The relative
643 difference between both simulations is 14% on the total sublimation, 11% on
644 the static-surface sublimation, 20% on the blowing snow sublimation. The
645 effect is not strong enough to modify the shape of the monthly water budget
646 described in Sect. 4.2.1. However, this test indicates that the uncertainty on
647 the air humidity forcing may contribute to a significant part of the model
648 error.

649 **6. Conclusion**

650 We have investigated the effects of wind on the snow cover in the high-
651 altitude semi-arid Andes using a distributed snow model. The model suggests
652 that the blowing snow sublimation strongly affects the snow mass balance in
653 the highest areas, where glacier are found. The results also tend to confirm
654 the hypothesis that snow is transported onto the glacier from the surrounding
655 ridges. This process reduces the snow mass loss over the snow season in
656 combination with the shading effect by topography. In these conditions,
657 snow transport may be a key “recharge” mechanism for glaciers, as it means
658 that when snowfall is low in the area, glaciers would still receive preferential
659 accumulation of drifting snow (similar insights can be found in [59]). This
660 additional snow may also be critical to reduce the glaciers melt during the
661 dry years by decreasing the glacier albedo. However, the model in its current
662 setup suffers from several limitations, which are related to (i) the input data
663 (lack of reliable precipitation measurements, low resolution digital elevation
664 model), (ii) the characteristics of the study area (complex terrain leading to
665 complex wind fields), (iii) the model parameters (terrain-based parameters
666 and wind friction threshold) and (iv) the complexity of the physical processes
667 involved in the wind-snow interactions (preferential deposition of falling snow
668 is not represented). We believe that these specific issues should be addressed
669 to further understand the hydrological balance of the semi-arid Andes, where
670 the snow and the glacier represent critical water resources.

Table 1: Snowmodel parameters

Parameter	Value	unit
Curvature length scale	500	m
Slope weight	0.58	-
Curvature weight	0.42	-
Threshold surface shear velocity	0.25	m/s
SnowTran-3D snow density	250	kg/m ³
Melting snowcover albedo	0.6	-
Dry snow albedo	0.8	-
Glacier surface albedo	0.4	-

Table 2: List of automatic weather stations and available hourly data, which were used to run SnowModel. TA: air temperature, RH: air humidity, SD: snow depth, WS: wind speed, WD, wind direction, SI: incoming shortwave radiation, LI: incoming longwave radiation. For the wind speed and direction, the measurement heights (m) are indicated in subscript. If there are data gaps, the percentage of missing values is given in parenthesis. The stations located on glaciers are in italics.

Station name	Altitude (m a.s.l.)	Variables
El Colorado	2618	TA, RH, WS _{2,10} , WD _{2,10} , SI
Potrerrillos	3282	TA, RH, SI
Tres Quebradas	3583	TA (15%), RH (15%), SD, WS _{2,10} (13%), WD _{2,10} (13%), SI
Campamento	3717	TA, RH
El Toro	3735	TA, RH, SD, WS _{2,10} (1%), SI
La Olla	3976	TA, RH, SD, WS _{2,10} , WD _{2,10}
Frontera	4933	TA, RH, WS _{2,10} (43%), WD _{2,10} (43%), SI
<i>Ortigas</i>	5209	TA, RH, SD
<i>Toro 1</i>	5226	TA, SD, WS _{4,6} (1%), WD _{4,6} , SI (75%), LI (75%)
La Cumbre	5292	TA, RH, WS _{3,6} (13%), WD _{3,6}
<i>Guanaco</i>	5317	TA, RH, SD, WS ₆ (75%), WD ₆ (75%), SI (75%), LI (75%)

Table 3: Precipitation generated by MicroMet (cumulated by precipitation event)

date	Precipitation (mm w.e.)
27-28/05/2008	48
18-19/06/2008	67
26/06/2008	7
21/07/2008	16
01/08/2008	9
15-16-17/08/2008	36

Table 4: Monthly lapse rates of air temperature (Γ_a) and dewpoint temperature (Γ_d). The lapse rates in the study area were determined for air temperature (T_a) and dewpoint temperature (T_d) by linear regression between the observations and the elevations of the meteorological stations. The square of the correlation coefficient is indicated for every variable and month.

Month	MicroMet default		Study area		R^2	
	Γ_a	Γ_d	Γ_a	Γ_d	T_a	T_d
5	-5.5	-4.9	-7.9	-3.5	0.996	0.784
6	-4.7	-4.9	-8.0	-3.2	0.984	0.549
7	-4.4	-5.0	-8.2	-3.6	0.976	0.775
8	-5.9	-5.1	-8.4	-3.9	0.982	0.680
9	-7.1	-4.9	-8.6	-3.9	0.990	0.629
10	-7.8	-4.7	-8.7	-3.9	0.996	0.739
11	-8.1	-4.6	-8.4	-4.8	0.995	0.917

Table 5: Results of MicroMet cross-validation (coefficient of determination and bias calculated on hourly data) for each station (air temperature and humidity lapse rates monthly values were set from local observations). For the wind direction, only the bias was computed.

Station	TA ($^{\circ}\text{C}$)		RH (%)		WS (m/s)		WD ($^{\circ}$)	SI (W/m^2)		LI (W/m^2)	
	R^2	B	R^2	B	R^2	B	B	R^2	B	R^2	B
Guanaco	0.98	-0.20	0.92	2.14	0.24	-4.39	-1.70	0.99	-49.68	0.95	6.50
Ortigas	0.95	-0.75	0.80	7.35	-	-	-	-	-	-	-
El Toro	0.95	-1.33	0.90	3.54	0.03	-1.01	-	0.97	21.97	-	-
Tres Que.	0.91	-0.17	0.87	2.06	0.25	-0.90	-79.25	0.95	23.21	-	-
Portrerillo	0.83	0.46	0.58	-6.44	-	-	-	0.99	-0.74	-	-
Frontera	0.96	-0.41	0.81	-2.93	0.31	-1.24	-41.33	0.92	-26.27	-	-
La Olla	0.95	0.97	0.86	-5.18	0.13	0.53	16.46	0.97	5.59	-	-
La Cumbre	0.98	0.06	0.93	2.41	0.36	-3.65	12.37	-	-	-	-
Toro 1	0.97	-0.03	-	-	0.25	-1.89	28.14	0.97	-37.37	0.96	-6.68

671 **References**

- 672 [1] L. Lliboutry, Glaciers of the Dry Andes, in: Satellite Image Atlas of
673 Glaciers of the World: South America, United State Geological Survey
674 Professional Paper 1386-I, 1998.
- 675 [2] L. Nicholson, J. Marin, D. Lopez, A. Rabatel, F. Bown, A. Rivera,
676 Glacier inventory of the upper Huasco valley, Norte Chico, Chile: glacier
677 characteristics, glacier change and comparison with central Chile, An-
678 nals of Glaciology 50 (2010) 111–118.
- 679 [3] V. Favier, M. Falvey, A. Rabatel, E. Praderio, D. López, Interpreting
680 discrepancies between discharge and precipitation in high-altitude area
681 of Chile’s Norte Chico region (26–32 S), Water Resources Research 45
682 (2009) W02424.
- 683 [4] J. Oyarzún, R. Oyarzún, Sustainable development threats, inter-sector
684 conflicts and environmental policy requirements in the arid, mining rich,
685 northern chile territory, Sustainable Development 19 (2011) 263–274.
- 686 [5] S. Fields, The Price of Gold in Chile, Environmental Health Perspectives
687 114 (2006) A536.
- 688 [6] P. Ginot, C. Kull, U. Schotterer, M. Schwikowski, H. W. Gäggeler,
689 Glacier mass balance reconstruction by sublimation induced enrichment
690 of chemical species on Cerro Tapado (Chilean Andes), Climate of the
691 Past 2 (2006) 21–30.
- 692 [7] P. Ginot, C. Kull, M. Schwikowski, U. Schotterer, H. Gäggeler, Effects of
693 postdepositional processes on snow composition of a subtropical glacier

- 694 (Cerro Tapado, Chilean Andes), *Journal of Geophysical Research* 106
695 (2001) 32375–32.
- 696 [8] S. Gascoin, C. Kinnard, R. Ponce, S. Lhermitte, S. MacDonell, A. Rabatel,
697 Glacier contribution to streamflow in two headwaters of the Huasco
698 River, Dry Andes of Chile, *The Cryosphere* 5 (2011) 1099–1113.
- 699 [9] A. Rabatel, H. Castebrunet, V. Favier, L. Nicholson, C. Kinnard, Glacier
700 changes in the pascua-lama region, Chilean Andes (29 S): recent mass
701 balance and 50 yr surface area variations, *The Cryosphere* 5 (2011)
702 1029–1041.
- 703 [10] M. Kuhn, Redistribution of snow and glacier mass balance from a hy-
704 drometeorological model, *Journal of Hydrology* 282 (2003) 95–103.
- 705 [11] H. Machguth, O. Eisen, F. Paul, M. Hoelzle, Strong spatial variability of
706 snow accumulation observed with helicopter-borne GPR on two adjacent
707 Alpine glaciers, *Geophysical Research Letters* 33 (2006) 13503.
- 708 [12] R. Mott, F. Faure, M. Lehning, H. Lowe, B. Hynek, G. Michlmayer,
709 A. Prokop, W. Schonert, Simulation of seasonal snow-cover distribution
710 for glacierized sites on Sonnblick, Austria, with the Alpine3D model,
711 *Annals of Glaciology* 49 (2008) 155–160.
- 712 [13] M. Bernhardt, G. Liston, U. Strasser, G. Zängl, K. Schulz, High reso-
713 lution modelling of snow transport in complex terrain using downscaled
714 MM5 wind fields, *The Cryosphere* 4 (2010) 99–113.
- 715 [14] R. Dadic, R. Mott, M. Lehning, P. Burlando, Wind influence on snow

- 716 depth distribution and accumulation over glaciers, *Journal of Geophys-*
717 *ical Research* 115 (2010) F01012.
- 718 [15] L. Carturan, F. Cazorzi, G. D. Fontana, Distributed mass-balance mod-
719 *elling on two neighbouring glaciers in Ortles-Cevedale, Italy, from 2004*
720 *to 2009, Journal of Glaciology* 58 (2012) 467–486.
- 721 [16] H. Purdie, B. Anderson, W. Lawson, A. Mackintosh, Controls on spatial
722 *variability in snow accumulation on glaciers in the Southern Alps, New*
723 *Zealand; as revealed by crevasse stratigraphy, Hydrological Processes*
724 *25 (2011) 54–63.*
- 725 [17] M. Lehning, H. Löwe, M. Ryser, N. Raderschall, Inhomogeneous precipi-
726 *tation distribution and snow transport in steep terrain, Water Resources*
727 *Research* 44 (2008) W07404.
- 728 [18] K. Fujita, K. Hiyama, H. Iida, Y. Ageta, Self-regulated fluctuations
729 *in the ablation of a snow patch over four decades, Water Resources*
730 *Research* 46 (2010) W11541.
- 731 [19] R. Mott, C. Gromke, T. Grünewald, M. Lehning, Relative importance
732 *of advective heat transport and boundary layer decoupling in the melt*
733 *dynamics of a patchy snow cover, Advances in Water Resources in press*
734 *(2012) –.*
- 735 [20] R. Dadic, R. Mott, M. Lehning, M. Carezzo, B. Anderson, A. Mackin-
736 *tosh, Sensitivity of turbulent fluxes to wind speed over snow surfaces in*
737 *different climatic settings, Advances in Water Resources (2012) –.*

- 738 [21] G. Liston, M. Sturm, A snow-transport model for complex terrain,
739 Journal of Glaciology 44 (1998) 498–516.
- 740 [22] J. Pomeroy, R. Essery, Turbulent fluxes during blowing snow: field
741 tests of model sublimation predictions, Hydrological Processes 13 (1999)
742 2963–2975.
- 743 [23] C. Groot Zwaaftink, H. Löwe, R. Mott, M. Bavay, M. Lehning, Drifting
744 snow sublimation: A high-resolution 3-D model with temperature and
745 moisture feedbacks, Journal of Geophysical Research 116 (2011) D16107.
- 746 [24] D. Marks, A. Winstral, Comparison of snow deposition, the snow cover
747 energy balance, and snowmelt at two sites in a semiarid mountain basin,
748 Journal of Hydrometeorology 2 (2001) 213–227.
- 749 [25] A. Winstral, D. Marks, Simulating wind fields and snow redistribution
750 using terrain-based parameters to model snow accumulation and melt
751 over a semi-arid mountain catchment, Hydrological Processes 16 (2002)
752 3585–3603.
- 753 [26] G. Liston, K. Elder, A distributed snow-evolution modeling system
754 (SnowModel), Journal of Hydrometeorology 7 (2006) 1259–1276.
- 755 [27] B. Ryan, A mathematical model for diagnosis and prediction of sur-
756 face winds in mountainous terrain., Journal of Applied Meteorology 16
757 (1977) 571–584.
- 758 [28] J. Corripio, R. Purves, A. Rivera, Modeling climate-change impacts on
759 mountain glaciers and water resources in the Central Dry Andes, in:

- 760 Darkening Peaks: Glacier Retreat, Science and Society, University of
761 California Press, USA, 2007, pp. 126–135.
- 762 [29] M. D. Betterton, Theory of structure formation in snowfields motivated
763 by penitentes, suncups, and dirt cones, *Phys. Rev. E* 63 (2001) 056129.
- 764 [30] Comisión Regional del Medio Ambiente, Región de Atacama, Gobierno
765 de Chile, Resolución rca 024, 2006.
- 766 [31] G. Liston, R. Haehnel, M. Sturm, C. Hiemstra, S. Berezovskaya,
767 R. Tabler, Simulating complex snow distributions in windy environ-
768 ments using SnowTran-3D, *Journal of Glaciology* 53 (2007) 241–256.
- 769 [32] E. Greene, G. Liston, R. Pielke Sr, Simulation of above treeline snow-
770 drift formation using a numerical snow-transport model, *Cold Regions*
771 *Science and Technology* 30 (1999) 135–144.
- 772 [33] G. Liston, M. Sturm, Winter precipitation patterns in arctic alaska
773 determined from a blowing-snow model and snow-depth observations,
774 *Journal of hydrometeorology* 3 (2002) 646–659.
- 775 [34] G. Liston, K. Elder, A meteorological distribution system for high-
776 resolution terrestrial modeling (micromet), *Journal of Hydrometeorol-*
777 *ogy* 7 (2006) 217–234.
- 778 [35] G. Liston, D. Hall, Sensitivity of lake freeze-up and break-up to climate
779 change: a physically based modeling study, *Annals of Glaciology* 21
780 (1995) 387–393.

- 781 [36] G. Liston, Local advection of momentum, heat, and moisture during the
782 melt of patchy snow covers, *Journal of Applied Meteorology* 34 (1995)
783 1705–1715.
- 784 [37] S. Barnes, A technique for maximizing details in numerical weather map
785 analysis, *J. Appl. Meteor* 3 (1964) 396–409.
- 786 [38] C. Walcek, Cloud cover and its relationship to relative humidity during
787 a springtime midlatitude cyclone, *Monthly Weather Review* 122 (1994)
788 1021–1035.
- 789 [39] S. MacDonell, L. Nicholson, C. Kinnard, Parameterisation of incoming
790 longwave radiation over glacier surfaces in the semiarid Andes of Chile,
791 *Theoretical and Applied Climatology* (2012) 1–16.
- 792 [40] T. Farr, P. Rosen, E. Caro, R. Crippen, R. Duren, S. Hensley, M. Ko-
793 brick, M. Paller, E. Rodriguez, L. Roth, et al., The Shuttle Radar
794 Topography Mission, *Reviews of Geophysics* 45 (2007).
- 795 [41] G. Liston, C. Hiemstra, A simple data assimilation system for complex
796 snow distributions (SnowAssim), *Journal of Hydrometeorology* 9 (2008)
797 989–1004.
- 798 [42] E. Anderson, A point of energy and mass balance model of a snow cover,
799 *Technical Report*, NOAA, 1976.
- 800 [43] R. Rogers, *A Short Course in Cloud Physics*, Pergamon Press, Elmsford
801 (NY, USA), 1979.

- 802 [44] A. Buck, New equations for computing vapor pressure and enhancement
803 factor, *Journal of Applied Meteorology* 20 (1981) 1527–1532.
- 804 [45] R. Fleagle, J. Businger, An introduction to atmospheric physics, vol-
805 ume 25, Academic Press, 1980.
- 806 [46] P. Holland, R. Welsch, Robust regression using iteratively reweighted
807 least-squares, *Communications in Statistics-Theory and Methods* 6
808 (1977) 813–827.
- 809 [47] G. Liston, Representing subgrid snow cover heterogeneities in regional
810 and global models, *Journal of Climate* 17 (2004) 1381–1397.
- 811 [48] K. Andreadis, D. Lettenmaier, Assimilating remotely sensed snow ob-
812 servations into a macroscale hydrology model, *Advances in Water Re-
813 sources* 29 (2006) 872–886.
- 814 [49] A. Klein, A. Barnett, Validation of daily MODIS snow cover maps of
815 the Upper Rio Grande River Basin for the 2000-2001 snow year, *Remote
816 Sensing of Environment* 86 (2003) 162–176.
- 817 [50] D. Hall, G. Riggs, V. Salomonson, N. DiGirolamo, K. Bayr, MODIS
818 snow-cover products, *Remote sensing of Environment* 83 (2002) 181–
819 194.
- 820 [51] D. Hall, G. Riggs, Accuracy assessment of the MODIS snow products,
821 *Hydrological Processes* 21 (2007) 1534–1547.
- 822 [52] J. Parajka, G. Blöschl, Spatio-temporal combination of MODIS images–
823 potential for snow cover mapping, *Water Resour. Res* 44 (2008) W03406.

- 824 [53] R. Mott, M. Lehning, Meteorological modeling of very high-resolution
825 wind fields and snow deposition for mountains, *Journal of Hydrometeo-*
826 *rology* 11 (2010) 934–949.
- 827 [54] R. Mott, M. Schirmer, M. Bavay, T. Grünewald, M. Lehning, Under-
828 standing snow-transport processes shaping the mountain snow-cover,
829 *The Cryosphere* 4 (2010) 545–559.
- 830 [55] R. Prasad, D. Tarboton, G. Liston, C. Luce, M. Seyfried, Testing a blow-
831 ing snow model against distributed snow measurements at Upper Sheep
832 Creek, Idaho, United States of America, *Water Resources Research* 37
833 (2001) 1341–1356.
- 834 [56] O. Schulz, C. de Jong, Snowmelt and sublimation: field experiments
835 and modelling in the High Atlas Mountains of Morocco, *Hydrology and*
836 *Earth System Sciences* 8 (2004) 1076–1089.
- 837 [57] M. K. MacDonald, J. W. Pomeroy, A. Pietroniro, On the importance
838 of sublimation to an alpine snow mass balance in the Canadian Rocky
839 Mountains, *Hydrology and Earth System Sciences* 14 (2010) 1401–1415.
- 840 [58] U. Strasser, M. Bernhardt, M. Weber, G. Liston, W. Mauser, Is snow
841 sublimation important in the alpine water balance?, *The Cryosphere* 2
842 (2008) 53–66.
- 843 [59] M. Hoffman, A. Fountain, J. Achuff, 20th-century variations in area
844 of cirque glaciers and glacierets, rocky mountain national park, rocky
845 mountains, colorado, usa, *Annals of Glaciology* 46 (2007) 349–354.

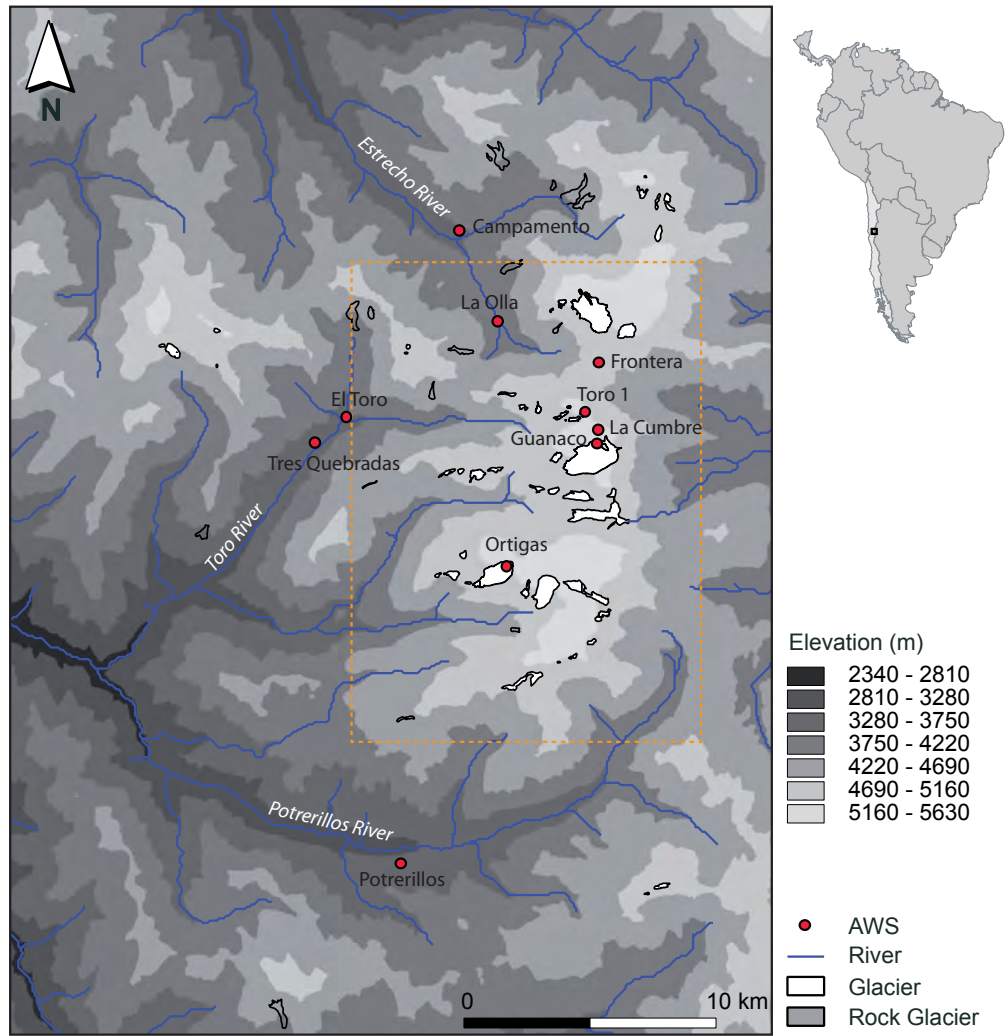


Figure 1: Map of the study area showing the location of the automatic weather stations (AWS). The map has the same extent as the computational grid. El Colorado AWS is not shown as it lies outside of the modeling grid (located 11 km west from western edge, at the same latitude of Campamento AWS). The rectangle in dotted orange line indicate the glacier area as used in Fig. 4.

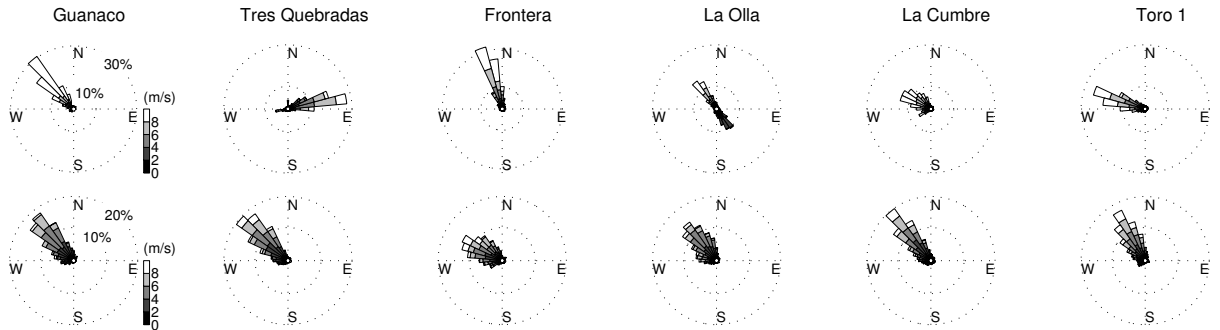


Figure 2: Wind roses between 1-May-2008 and 30-Nov-2008 for 6 weather stations. Top row: measurements, bottom row: MicroMet simulations.

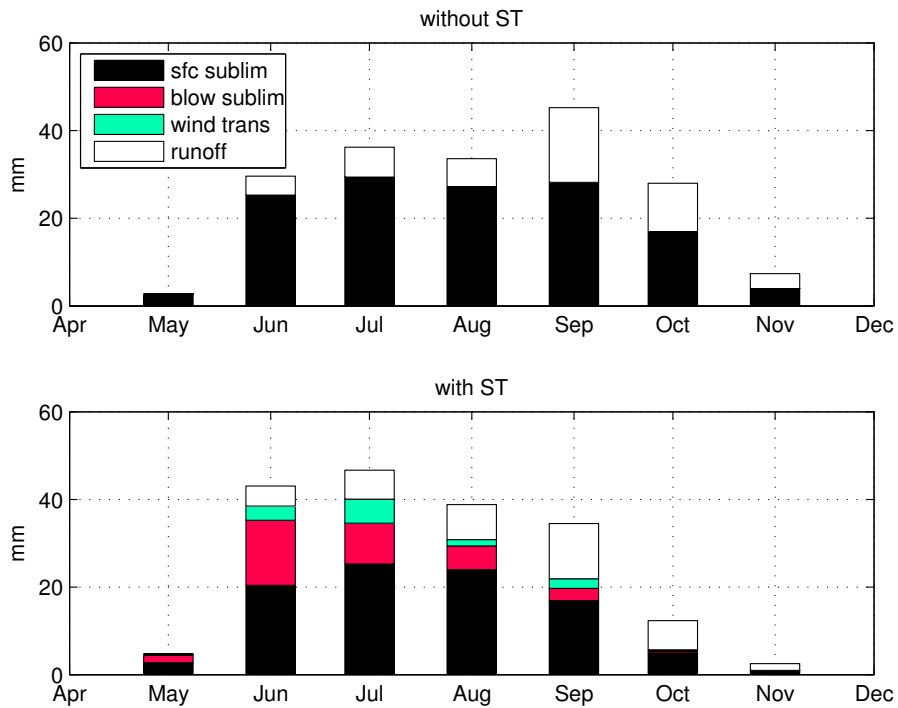


Figure 3: Comparison of model snow mass budgets without and with SnowTran (ST). Legend: sfc sublim: surface-static sublimation, blow sublim: sublimation of blowing snow, wind trans: wind transported snow, runoff.

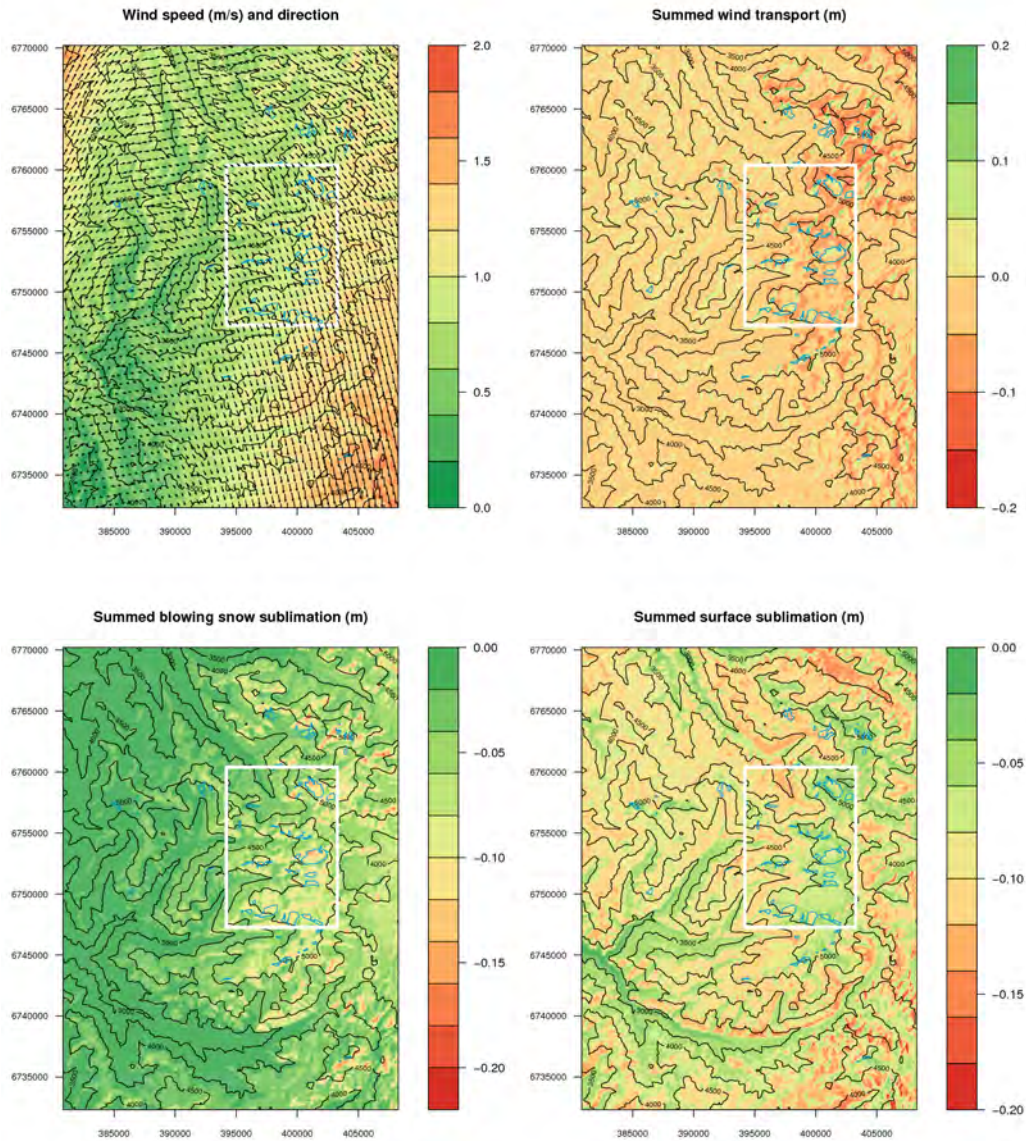


Figure 4: Maps of the model outputs over the full domain: mean wind field, total wind transported snow (saltation and suspension), sublimation of blowing snow and static-surface sublimation (in m w.e., all fluxes are cumulated over the simulation period). The glacier contours are drawn in blue. The axes are the northing (m) and easting (m) the WGS-84 UTM 19S projection.

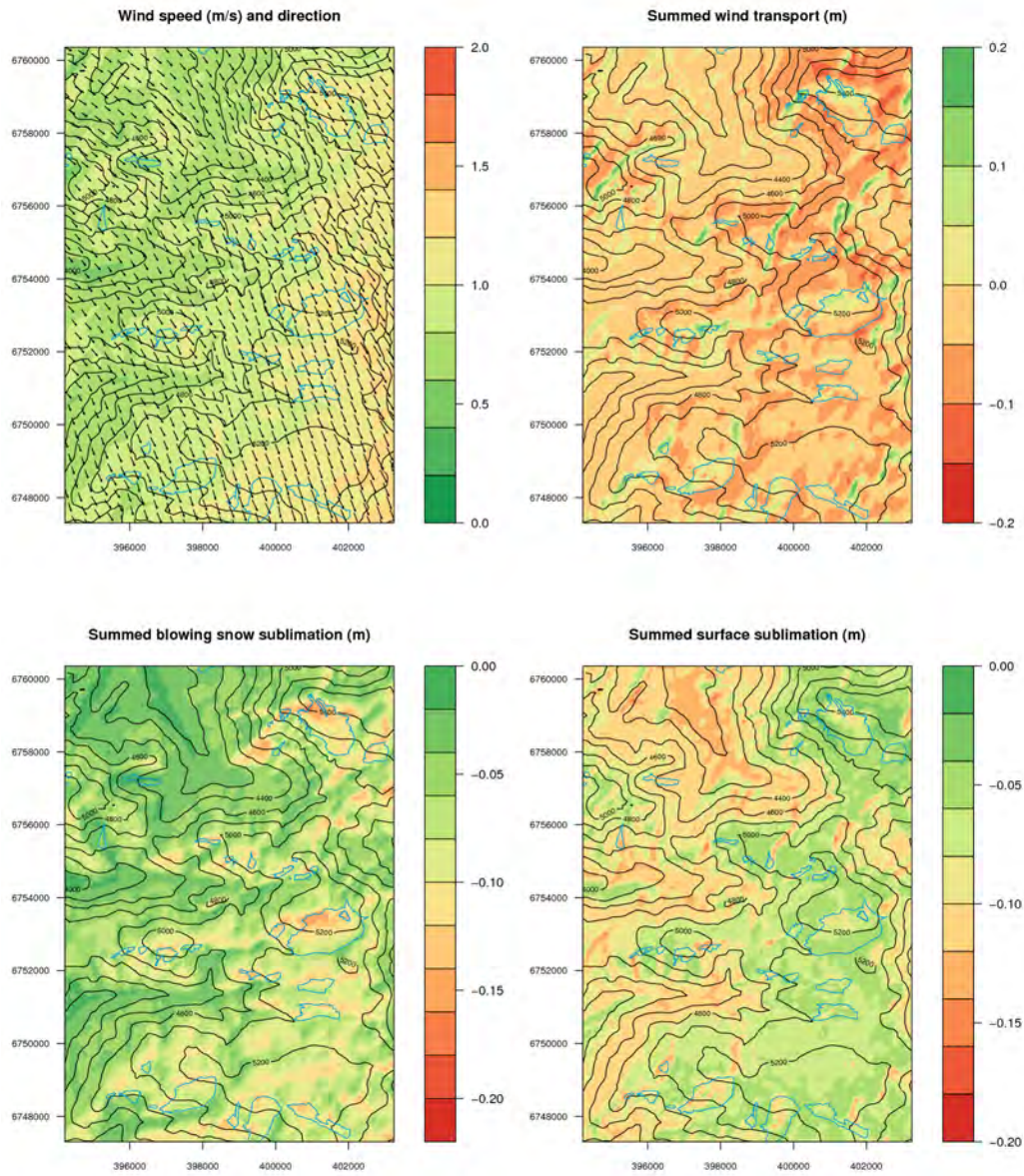


Figure 5: Same as Fig. 4 but zoomed over the glacier area.

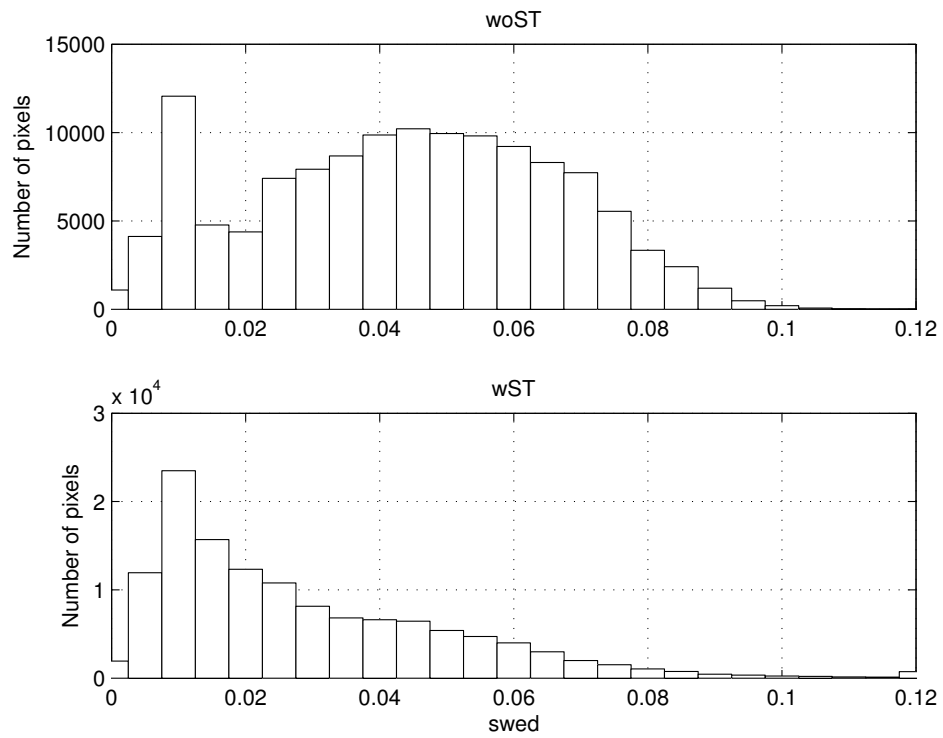


Figure 6: Distribution of the mean SWE depth (in m) calculated for each grid cell over the model run period (woST: without SnowTran, wST: with SnowTran).

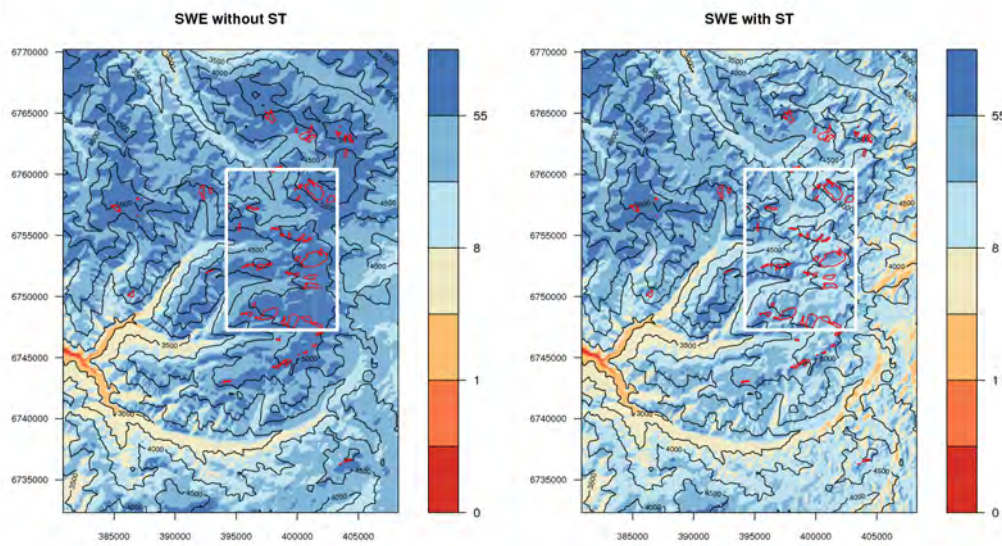


Figure 7: Maps of the mean simulated SWE for both model configurations (logarithmic scale in mm). The glacier contours are drawn in red.

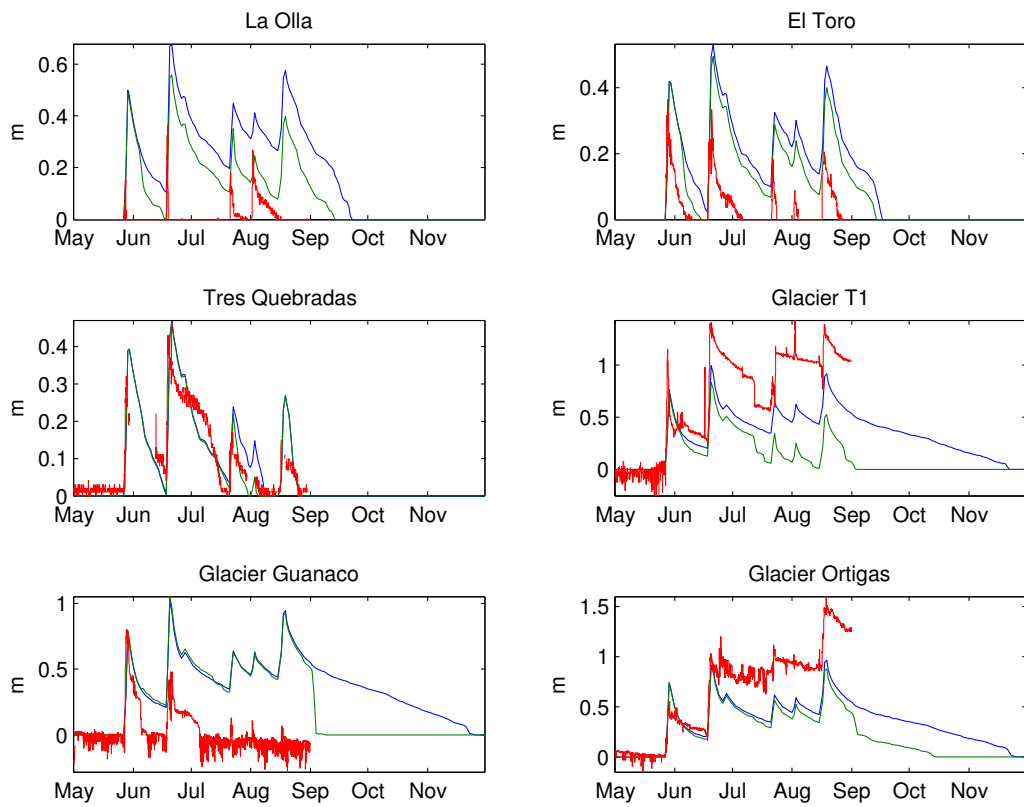


Figure 8: Simulated vs. observed snow depth at 6 stations. Legend: blue: SnowModel without SnowTran, green: with SnowTran, red: observations.



Figure 9: La Olla weather station (photograph taken on 21-7-2010)

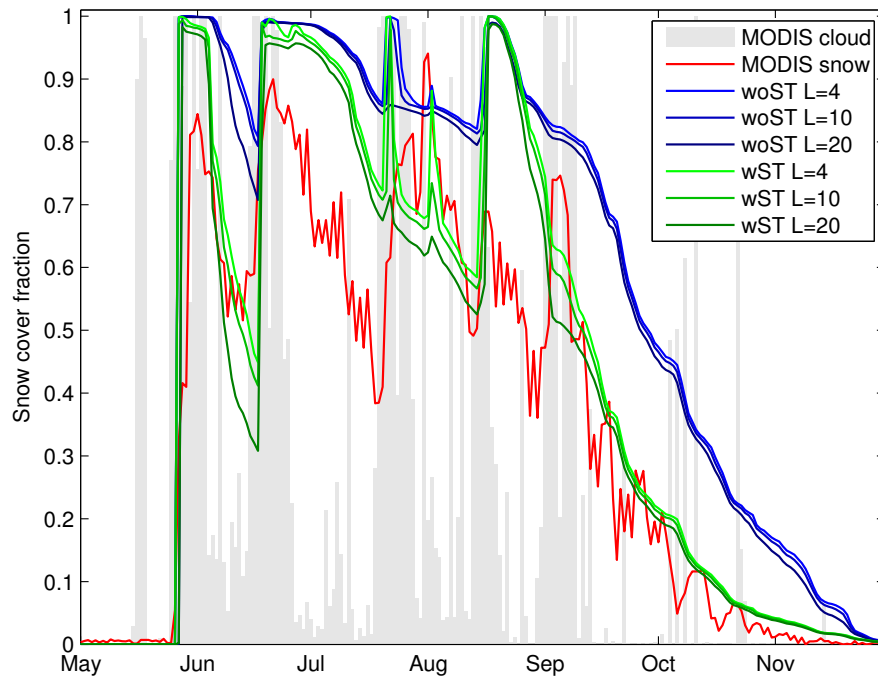


Figure 10: Snow coverage from SnowModel simulations and MOD10A1 (MODIS 500-m daily snow cover product). The snow cover area was computed for both simulations (without ST and with ST) using three different SWE thresholds (L indicated in the legend in mm, see Sect. 3.4). The fractional area of cloud cover is indicated in light gray. The total domain area is 1043 km² (Fig. 1).

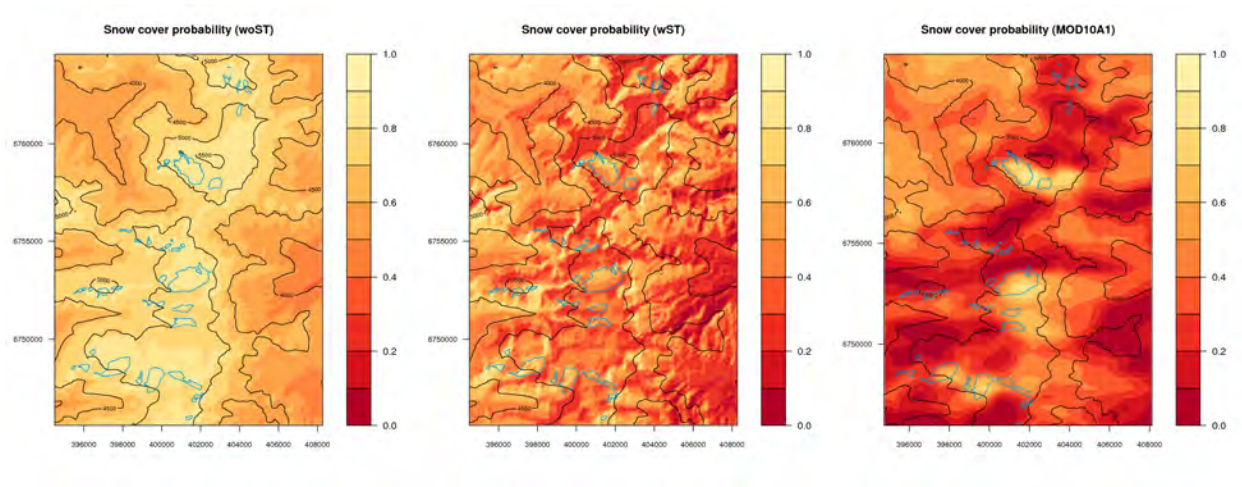


Figure 11: Simulated vs. observed snow cover probabilities over the simulation period in the glacier area.

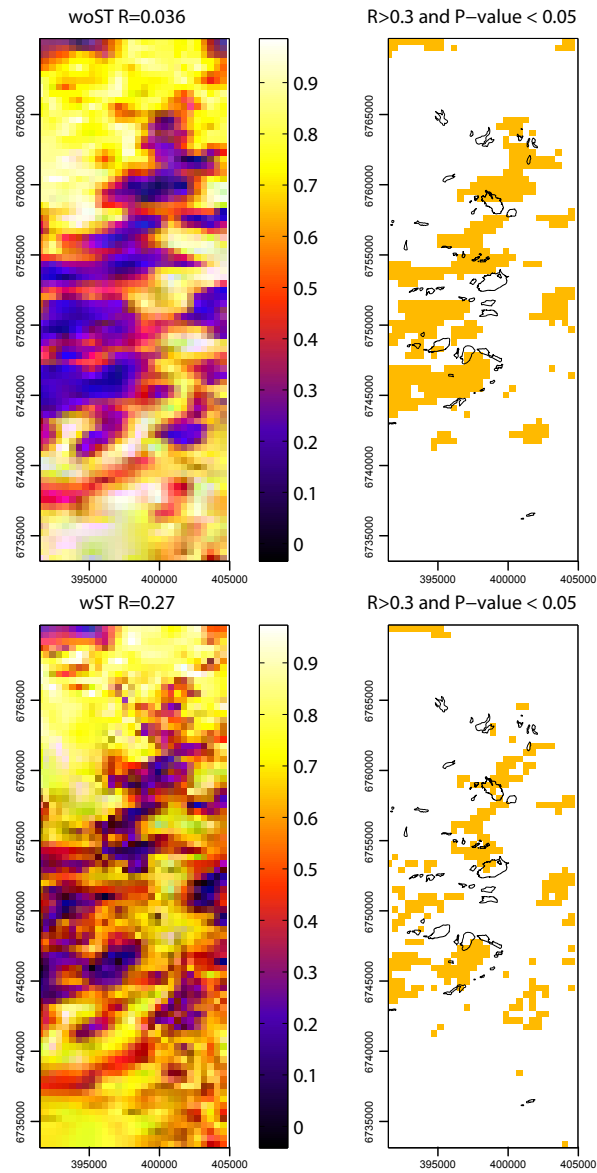


Figure 12: Left: Correlation maps between the simulated snow cover resampled to 500 m and MOD10A1 in the eastern part of the study area. The 2-D correlation coefficient (R) is indicated for both runs (SnowModel without or with SnowTran). Right: the area in white has a correlation coefficient $R > 0.3$ and a P -value < 0.05 (probability of no correlation lower than 5%).

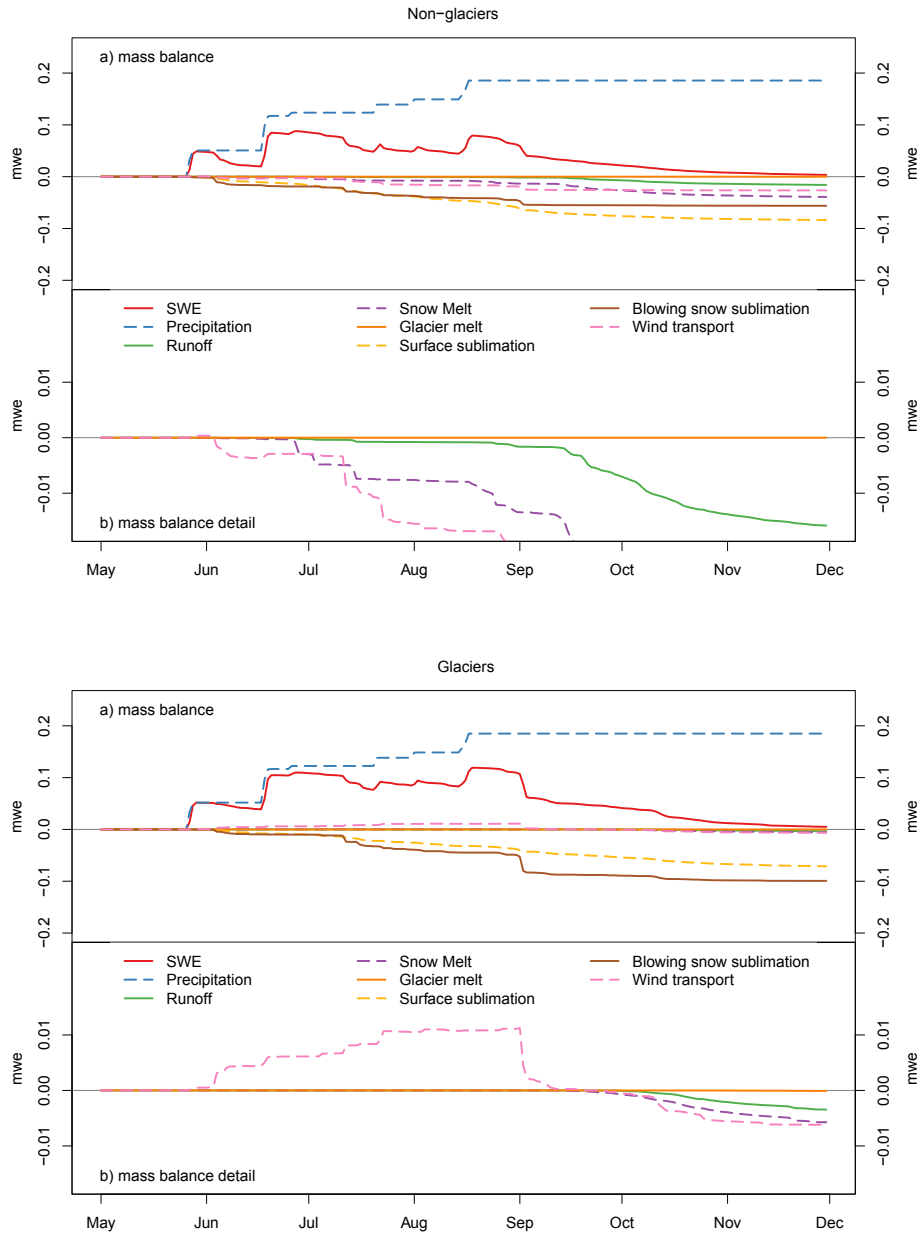


Figure 13: Snow mass balance components averaged over the glacierized area and the non-glacierized area above 4475 m a.s.l. (simulation with SnowTran-3D).

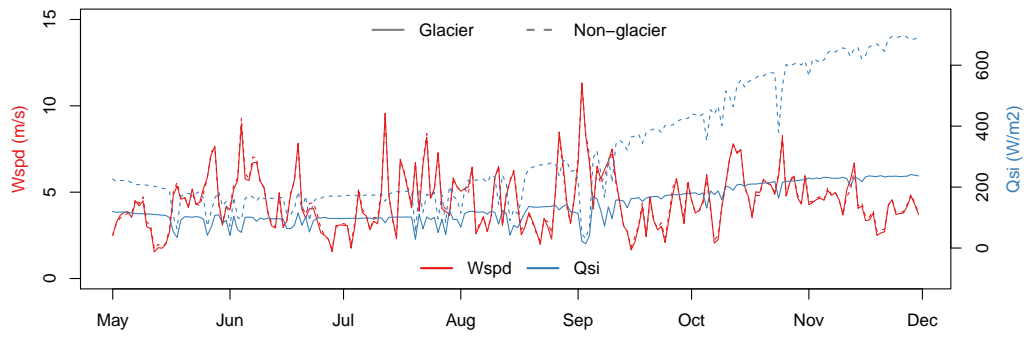


Figure 14: MicroMet simulated wind speed and incoming shortwave radiation averaged over glaciers (continuous line) and glacier-free areas above the lower glacier elevation (dashed line).

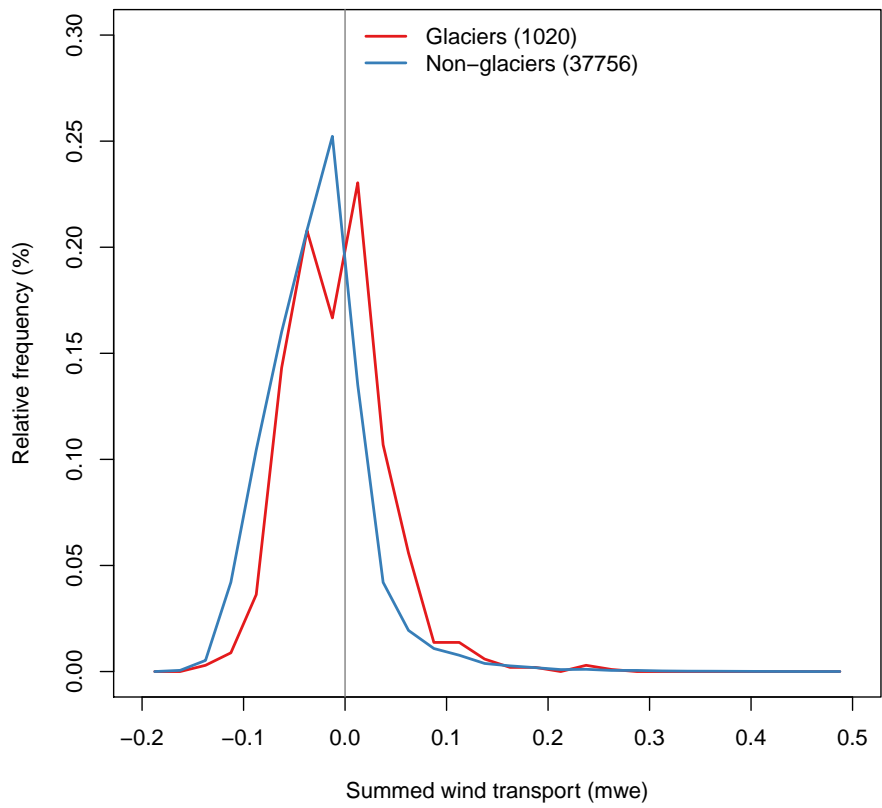


Figure 15: Frequency distribution of the transport rates simulated for the grid points located above 4475 m a.s.l. (frequencies calculated for 0.025 m w.e. bins).