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► **To cite this version:**

J I López-Moreno, N Callow, H Mcgowan, R Webb, A Schwartz, et al.. Marginal snowpacks: The basis for a global definition and existing research needs. *Earth-Science Reviews*, 2024, 252, pp.104751. 10.1016/j.earscirev.2024.104751 . hal-04571023

HAL Id: hal-04571023

<https://hal.science/hal-04571023v1>

Submitted on 12 Jun 2024

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1 **Marginal snowpacks: the basis for a global definition and existing research needs**

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19 **Abstract.** A marginal snowpack is a recent concept that refers to snow cover that is
20 relatively shallow and transient but still has important environmental and socioeconomic
21 functions. This class of snow cover influences environments over large areas of the world
22 and is very common in the Mediterranean climates, but also in the transition zone between
23 persistent seasonal and ephemeral snowpacks all over the world. However, a globally-
24 accepted definition to identify these environments has not been reached yet. Most of the
25 modelling and monitoring tools for snow have been developed in cold and alpine areas
26 with persistent snowpacks. The study and modelling of shallower snowpacks in milder
27 environments are complicated by their high temporal variability, frequently patchy nature
28 and typical coexistence with shrubs and forest. However, in recent years new remote
29 sensing tools and more complex modelling approaches and specific parametrizations are
30 facilitating their study. This paper provides a definition for marginal snowpacks,
31 identifying them as those with: (i) seasonal peak depths that only occasionally surpass 1.5
32 meters in favorable deposition zones such as wind drifts, ii) having typical seasonal
33 durations ranging from 60 to 120 days, and (iii) that are predominantly in an isothermal
34 state (on more than 75% of days) with high densification rates and several cycles of
35 accumulation-ablation during each snow season. We review the main existing research
36 challenges to improve scientific capabilities for their study and we discuss their
37 hydrological and environmental relevance at different spatial scales.

36 Keywords: Marginal snowpacks; remote sensing; snow simulation; environmental
37 impacts.

38

39 **1. Introduction**

40 Snow is listed as one of the essential climate variables to be monitored and studied to
41 support the work of the United Nations Framework Convention on Climate Change and
42 the Intergovernmental Panel on Climate Change (Bojinski et al., 2014). This is because
43 snow tightly controls the hydrology and seasonal cycles of ecosystems (plants and
44 animals) in mountain regions of mid and high latitudes (Musselman et al., 2021). In
45 addition, snow – its occurrence, quantity, spatial and temporal variability – has important
46 implications for land management and the economy of both mountains and downstream
47 areas through its major role in water resources, food production systems and
48 transportation (Qin et al., 2020). Hazard management challenges include heavy snowfall
49 events, avalanches and floods from rain-on-snow events (Haeberli and Whiteman, 2021;
50 McGowan et al., 2021; Musselman et al., 2018). Furthermore, winter tourism is becoming
51 one of the main income sources in mountain regions, with high vulnerability to this
52 section from interannual fluctuations that snow generally shows (Steiger et al., 2019).

53 Snow science has typically focused on cold, continental areas with well-developed and
54 seasonally persistent snowpacks. The main existing snow datasets, energy and mass
55 balance models, and snow parametrizations have been developed and tested in Canada,
56 Western United States, the European Alps and the former Soviet Union. In the last few
57 years there has been an increasing recognition of the need to understand and properly
58 monitor shallower and milder snowpacks composed of ephemeral and marginal snow
59 environments, like the ones developed in many areas under Mediterranean-type or mild
60 oceanic climates (Bilish et al., 2018; Fayad et al., 2017; López-Moreno et al., 2017;
61 Petersky and Harpold, 2018a). Ephemeral snowpacks are typically defined as those that

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62 persist for less than 60 consecutive days, are less than 50-100 cm in depth (depending on
63 different classifications), and have less than three different snow layers (Hatchett, 2021;
64 Petersky and Harpold, 2018b; Siirila-Woodburn et al., 2021; Sturm et al., 1995). The
65 concept of a marginal snow environment is more recent, having been introduced to
66 describe snow cover in the Australian Alps (Bilish et al., 2018, 2019; Schwartz et al.,
67 2020). Following earlier work (Bormann et al., 2013; Sanecki et al., 2006) that found that
68 the Australian snowpack did not sit within the ranges for any of the snow cover types in
69 the classification system of Sturm et al. (1995), these more recent studies showed that this
70 environment commonly has elements of both persistent and ephemeral snowpack
71 dynamics. While snow cover is typically continuous for several months, at the catchment
72 scale the snowpack lacks a stable accumulation season and melt takes place throughout
73 winter (Bilish et al., 2020, 2019). The term has since been applied to snow-affected
74 regions in other countries that are considered to lie between ephemeral and seasonal
75 persistent snowpacks but are so far lacking an accepted, well-defined classification.
76 Although the duration and depth of snow in environments with marginal snowpacks is
77 moderate, several studies have provided evidence of their impact on natural processes,
78 such as: water availability to montane and downstream areas (Huning and AghaKouchak,
79 2020); plant and animal phenology (Kelsey et al., 2021); the exchange of gases between
80 soils and atmosphere as well as the nutrient cycle (Tucker et al., 2016) among others.
81 However, how and to what extent a marginal snowpack actually affects those processes
82 is not yet well understood. In fact, there is no sound and spatially transferable knowledge
83 about snowpack properties (e.g., snow depth, water content, duration, etc.) that allow
84 consistent and repeatable characterization and evaluation of when a marginal snowpack
85 will have a significant influence on the aforementioned natural processes, and when its
86 presence and impact may be rather negligible.

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87 Marginal snowpacks are acutely vulnerable to climate warming due to their isothermal
88 characteristics and the mild temperatures in the environments where they develop (López-
89 Moreno et al., 2020) .We suggest that many of the current marginal snowpacks will
90 disappear or shift to an ephemeral state in the coming decades (Huss et al., 2017; Siirila-
91 Woodburn et al., 2021). Likewise, large areas currently occupied by persistent and cold
92 snowpacks will transition to marginal snowpacks. An exception could be sites where
93 precipitation patterns change sufficiently to overcome the general on-going warming
94 (López-Moreno et al., 2017).In addition, these environments are commonly located in
95 sub-tropical to mid-latitude locations, frequently in areas coexisting with vegetation (trees
96 and shrubs), and prone to receiving Light Absorbing Particles (LAP, such as dust)
97 transported by wind from snow-free areas. Episodes of LAP deposition on the snow
98 surface reduce its albedo, increasing energy inputs from solar radiation (Skiles et al.,
99 2018).

100 The combined effect of vegetation, increasing temperatures, and snow impurities may
101 interact, boosting the rapid changes experienced by marginal snowpacks within and
102 between snow seasons (accumulation-ablation cycles). Nevertheless, our current
103 understanding of these dynamics needs further research. There is current uncertainty as
104 to whether marginal snowpacks might exhibit certain specific responses to climate
105 forcing that differ from those of seasonal snowpacks. For example, while the melting of
106 persistent snowpacks occurs later in the season, under higher radiation inputs (Musselman
107 et al., 2017; Revuelto et al., 2014; Wu et al., 2018), marginal snowpacks develop and
108 ablate during the colder months when incoming solar radiation is still low (Bilish et al.,
109 2020). This suggests a lower sensitivity to changes in albedo (e.g., induced by LAPs) and
110 to increases in air temperature. This characteristic was suggested as an explanation for
111 the long-term series of snow duration and snow depth in the Pyrenees Mountains only

112 exhibiting a statistically significant decrease at elevations over 2100 m a.s.l., where a
113 persistent snowpack develops. At lower elevations where snow only develops in mid-
114 winter months, trends have remained almost stationary (López-Moreno et al., 2020b).

115 These challenges frame the need to better understand the characteristics and behaviour of
116 these marginal snowpacks in regions between seasonal and ephemeral snow. In the
117 subsequent sections we review the existing literature and then provide our perspective on
118 the research challenges, with the aim of: i) framing the concept of marginal snowpacks
119 with reference to previous definitions of snow type or snow environments with
120 comparable characteristics; ii) setting the basis for a global definition of marginal
121 snowpacks; iii) defining optimal monitoring needs to study marginal snowpacks and their
122 dynamics; and iv) tailoring modelling approaches to the specific characteristics of
123 marginal snowpacks.

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125 **2. Toward a global definition of marginal snowpacks**

126 Even if the concept of a marginal snowpack already exists and its use is starting to become
127 more common in the scientific literature (Bilish et al., 2018; 2019; 2020; López-Moreno
128 et al., 2020; Schwartz et al., 2020; Kraft et al., 2022) there is not yet a definitive and
129 accurate definition to provide clarity to use it in a consistent way globally (Bilish et al.,
130 2019). In fact, marginal snow has not been explicitly listed in the main existing snow
131 classification types, unlike ephemeral snowpacks (Sturm et al., 1995; Sturm and Liston,
132 2021). Marginal snowpacks have a longer duration and more significant environmental
133 influence than ephemeral snowpacks, but do not reach the temporal duration and the “one
134 peak” niveograph pattern generally exhibited by the other snow types defined in previous
135 snow classifications. The most widely-accepted classification of snow types, published
136 by Sturm et al. (1995) and revisited by Sturm and Liston (2021), clearly describes the

137 characteristics of ephemeral snow not exceeding 100 cm, generally associated with a
138 single storm event, wet and heavy snow lacking of stratigraphy due to high dominant
139 temperatures, and generally lasting less than 60 days over the ground; the rest of the
140 classifications refer to specific cold biomes (tundra, taiga) or to deeper and longer lasting
141 snowpacks like alpine and maritime snow.

142 The classes labelled in Sturm and Liston (2021) as “prairie” and “montane forest” share
143 some common characteristics with marginal snowpacks. However, these types are
144 geographically restricted to large plains and forested areas generally at latitudes over
145 50°N, while similar snow characteristics can also be observed at lower elevations or on
146 midlatitude mountains with rugged topography, and in both in open terrain and in shrub-
147 or forest areas. The “mountain” snow type is mentioned only briefly in the classification
148 of Sturm et al. (1995), as a special class, and few details are provided: “A highly variable
149 snow cover, depending on solar radiation effects and local wind patterns. Usually deeper
150 than associated type of snow cover from the adjacent low-lands”. While these properties
151 occur frequently in the environments referred to in the present work, they also feature in
152 colder mountainous environments and, in the absence of further information, do not
153 sufficiently describe the physical and dynamical characteristics of marginal snow.

154 Hammond et al. (2018) used the concept of “intermittent snow zones” to distinguish from
155 seasonal snowpacks using a threshold for annual snow persistence (SP, the fraction of
156 time that snow is present on ground) of 30%. Such a threshold could also envelope
157 marginal snowpacks, but it also includes ephemeral zones as there is no minimal SP limit.

158 A more precise separation was provided by Moore et al. (2015), who used the term
159 “transitional snow zone (TSZ)” as a class between the persistent snow zone (PSZ,
160 January-July $SP > 0.75$) and the intermittent snow zone (ISZ, January-July $SP < 0.5$) in the
161 Western US. Their results showed that the TSZ occupies almost the same extent as the

162 persistent snow zone. Despite this importance of the transitional snow zone, existing
163 literature overwhelmingly focuses on the persistent (seasonal) zones, while giving
164 increasing importance to ephemeral (intermittent) zones (Hatchett, 2021; Petersky and
165 Harpold, 2018a).

166 Another interesting concept that reflects the process of marginalization of persistent
167 seasonal snowpacks is the recently termed low-to-no-snow winters (Rhoades et al., 2022;
168 Siirila-Woodburn et al., 2021). These are defined statistically as years below the 30th
169 percentile in snow depth with respect to a baseline climate; but as occurred with the term
170 intermittent snow zone of Hammond et al. (2018), there is no minimal boundary to
171 capture the transition from seasonal persistent to ephemeral that represent the marginal
172 snowpacks.

173 Definitions only based on snow duration or snow probability as presented above may
174 present problems if applied globally. Sites with cold but relatively dry winters (e.g., arctic
175 snowpacks), or sites where short snowy and cold winters followed by a rapid increase in
176 spring temperature and/or radiation may host snowpacks with durations or depths that
177 exclude them from persistent seasonal snow zones, yet lack the dynamic nature (melting
178 events throughout the whole season) of marginal and ephemeral snowpacks. For this
179 reason, some definitions of snowpacks have included an air temperature criterion.
180 Concepts such as “at-risk snow” and “warm winters”, with temperatures above -2 °C and
181 0 °C respectively for any one of the core winter months (December-February/June-August
182 for N/S hemisphere respectively), have been suggested to identify snow areas that are
183 vulnerable to climate warming (Nolin et al., 2021; Nolin and Daly, 2006). Marginal
184 snowpacks likely develop between these temperature thresholds, but an accurate climatic
185 definition to complement snow metrics to define marginal snowpacks still needs specific
186 research.

187 We suggest that the definition of a marginal snowpack should include the following
188 characteristics: (i) with seasonal peak depths only occasionally surpass 1.5 meters in
189 favorable deposition zones such as wind drifts, ii) having durations ranging from 60 to
190 120 days, and (iii) that are predominantly in an isothermal state with high densification
191 rates and several cycles of accumulation-ablation during each snow season.

192 Simulated snow series in 24 mountain areas of the world reveal that marginal snowpacks
193 are predominantly found near the $+2 \text{ } ^\circ\text{C}$ isotherm at sites with precipitation $\geq 600 \text{ mm}$,
194 or at colder ($-2 \text{ } ^\circ\text{C}$) but drier sites. No marginal snowpacks would be found where
195 winter precipitation is less than 400 mm (Figure 1). Series were obtained using FSM2
196 model (Essery, 2015) driven by ERA5-Land data scaled to fixed winter (DJFM Northern
197 Hemisphere-JJAS for the Southern Hemisphere) precipitation (from 100 to 1200 mm)
198 and temperature values (from $-6 \text{ } ^\circ\text{C}$ to $+6 \text{ } ^\circ\text{C}$). Thus, marginal snowpacks are likely to be
199 found across the world at moderate elevations and in environments influenced by mild
200 mid-latitude climates with sub-tropical and maritime influences. Mediterranean
201 mountains in particular, have been recognized to often host these snowpack environments
202 (Fayad et al., 2017).

203 The perspective of this paper is that require a robust classification to identify
204 environments dominated by marginal snow should not only be based on subjective fixed
205 thresholds on snow and climate metrics, but also on their impact on local ecosystems. For
206 instance, some previous studies have suggested that ephemeral snowpacks impact the soil
207 and stream hydrology (Harrison et al., 2021; Petersky and Harpold, 2018a); however, it
208 is still unclear to what extent winter liquid precipitation could replace the snowmelt input
209 into the hydrological system without marked differences in the annual hydrograph. We
210 suggest the value of differentiating marginal from ephemeral snowpacks based on the
211 detection of an unequivocal signal of melting snow on the environment. In other words,

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212 marginal snowpacks must be of enough significance to be detectable in the interannual
213 variability of the soil and stream hydrology and the plant phenology of affected areas.
214 Additionally, runoff processes and the snowmelt input to soils may change significantly
215 as deeper persistent snowpacks transition to marginal snowpacks (Webb et al., 2020).
216 Previous hydrologic studies have shown that the heterogeneity of a snowpack can
217 strongly influence the hillslope-stream connectivity (Freudiger et al., 2017; Lundquist
218 and Dettinger, 2005), suggesting the spatially patchy nature of marginal snowpacks is
219 hydrologically significant. Snowmelt contribution to total runoff of marginal snowpacks
220 (from the dataset created for Figure 1) occupies an intermediate position between
221 ephemeral and seasonal snowpacks, and the snowmelt peak is clearly delayed with respect
222 to the former (Figure 2). However, it has not yet been clearly demonstrated to which
223 extent these impacts may be masked or replaced by the occurrence of liquid precipitation
224 during winter. The recently developed Snow Storage Index (SSI), representing the
225 temporal phase difference between daily precipitation and surface water inputs, is a
226 promising tool to study this topic (Hale et al., 2023). Monitoring the daily variation and
227 seasonal changes of natural tracers such as isotopes, electrical conductivity and
228 temperature of river flows may also provide clear guidance on the extent to which the
229 hydrology of a given catchment is controlled by snowmelt (López-Moreno et al., 2023;
230 Sprenger et al., 2022).
231 Coulthard et al., (2021) identified a clear snow signal in the yearly fluctuations of forest
232 growth and greenness in a study site that could be considered a marginal snow
233 environment. This is because snow melt provides extra moisture to the soil, soils remain
234 unfrozen due to the insulating effect of the snow, and climate conditions are not too harsh
235 to limit the growth of the trees. Monitoring vegetation phenology and productivity linked
236 to the snow cycles under different snow types is an obvious path to follow to improve our

237 understanding of snow-vegetation interactions (Jonas et al., 2008; Revuelto et al., 2022;
238 Sanmiguel-Vallelado et al., 2022; Trujillo et al., 2012).

239

240 **3. Monitoring needs for the study of marginal snowpacks**

241 Marginal snowpacks are more complicated to monitor than well-developed snowpacks.

242 As a snowpack becomes shallower and patchier, its main characteristics and physical

243 properties (depth, density, internal temperature, etc) become more variable and its

244 monitoring is more challenging (Sexstone et al., 2021). Marginal snowpacks have not

245 traditionally been subject to operational monitoring programs, resulting in a lack of

246 comprehensive historical datasets. In addition, errors assumed in deep and long lasting

247 snowpacks may be unacceptable in marginal snowpacks. Marginal snowpacks also need

248 dense observation networks or sampling strategies to deal with their high spatial and

249 temporal variability (Dickinson and Whiteley, 1972; López-Moreno et al., 2020c). An

250 example is given with snow cover derived from satellite optical images, one of the most

251 commonly-used remote sensing product for snow studies (Figure 3). This figure shows

252 the snow cover duration (SCD) in an area dominated by marginal snowpacks in the

253 Central Pyrenees derived from a combination of Sentinel-2 at 20 meters grid resolution

254 and Landsat 8, resampled to 20 meters (Gascoin et al., 2019), and MODIS at 500 meters

255 grid resolution. The figure shows that the two products tell different stories about the

256 spatial heterogeneity of the snow cover in these types of environments (see the mean SCD

257 in 4 selected points), and that MODIS may fail to provide adequate spatial resolutions in

258 such environments, as has been shown in previous studies (Bouamri et al., 2021; Pimentel

259 et al., 2017). For small study sites, time lapse cameras may offer very useful information

260 to represent and understand the very dynamic behaviour of shallow snow covers,

261 including their interaction with vegetation (Pimentel et al., 2015). Snow depths can be

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262 determined by installing snow poles in the view field (e.g. Bongio et al., 2021), or by
263 installing several cameras to accurately map snow depths from photogrammetric
264 reconstructions (Filhol et al., 2019; Liu et al., 2021). Self-recording temperature sensors
265 installed on the ground surface can be also an efficient method to identify snow cover and
266 snow-free periods (Lundquist and Lott, 2008; Navarro-Serrano et al., 2019).

267 Current methods for the measurement by satellite of snow depth in mountains are likely
268 not relevant for shallow and patchy marginal snowpacks as snow depth from satellite
269 photogrammetry has typical errors between 0.5 m and 1 m (e.g., Pléiades, WorldView;
270 Deschamps-Berger et al., 2020; Eberhard et al., 2021) similar to high-resolution altimetry
271 (ICESat-2; Deschamps-Berger et al., 2022; Enderlin et al., 2022). Snow depth retrievals
272 from synthetic aperture radar (Sentinel-1) have a spatial resolution of at best 100 m and
273 are subject to large errors over wet snowpack, a common state of marginal snowpacks
274 (Lievens et al., 2022). Finally, satellite-based passive microwave radiometer data for
275 snow water equivalent estimations are masked over complex terrain (i.e. mountains) and
276 are thus not available for most marginal snowpack environments (Luoju et al., 2021).

277 In the last decade, snow science has benefited from the flourishing of new affordable
278 remote sensing techniques that are suitable for capturing the complex dynamics of
279 marginal snowpacks. Terrestrial Light Detection And Ranging (LIDAR) and Unmanned
280 Aerial Vehicles (UAV) photogrammetry provide centimeter-scale resolution and
281 accuracy to analyse from the plot (10^0 m²) to the small (10^4 m²) scales (Bühler et al., 2016;
282 Goetz and Brenning, 2019; Jacobs et al., 2021; Revuelto et al., 2021b). Thus, UAV can
283 provide very detailed patterns of snow distribution (Figure 4), in this case for the area in
284 the vicinity of point 1 in Figure 3. The snow depth maps obtained clearly show that spatial
285 variability is governed by wind redistribution around vegetation with scouring on the
286 windward side and deposition on the lee side. Airborne LIDAR with UAV has also shown

287 very good capabilities to map shallow snow depths even in the presence of vegetation
288 (Harder et al., 2020; Jacobs et al., 2021; King et al., 2023). As mentioned above, for larger
289 scales, high spatial and temporal resolution satellites such as Sentinel-2 have
290 demonstrated high capabilities to monitor very dynamic snowpacks (Gascoin et al.,
291 2020), including sparsely forested areas (Muhuri et al., 2021). Promising workflows for
292 marginal snowpacks were recently proposed (Premier et al., 2021; Revuelto et al., 2021a;
293 Richiardi et al., 2023) for the downscaling of MODIS sensor retrievals (500 m grid size,
294 available since 2002) to 20 m resolution, using Sentinel-2 acquisitions starting in 2015.
295 This procedure enables the representation of the spatial variability of marginal snowpacks
296 while taking benefit of the length and revisit times of the MODIS dataset.
297 Remote sensing techniques can also be powerful tools to analyze the relationships
298 between snow depth / persistence and vegetation activity (Revuelto et al., 2022; Thapa et
299 al., 2021; Wang et al., 2022). Thus, multispectral sensors mounted on UAVs and satellites
300 may provide valid assessments of vegetation activity for different spatial scales, while
301 phenocams (Aasen et al., 2020; Julitta et al., 2014) are a promising tool adding sub-hourly
302 information on vegetation activity that improves the capabilities to accurately discern the
303 different role of marginal and ephemeral snowpacks on vegetation.

304
305 **4. Tailoring modelling approaches to the specific characteristics of marginal**
306 **snowpacks.**

307 As most existing snow models have been developed with a focus on cold climates and/or
308 seasonal snowpacks, they will likely need updating to include the properties of marginal
309 snowpacks. All of these properties are related to the relatively mild climatological
310 conditions where they develop. Below we describe some of the main identified needs.

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311 4.1 The partitioning of the snow energy balance differs from snowpacks that have been
312 studied in colder environments. The heterogeneity of marginal snowpacks can result in
313 increased complexity when examining and modelling their energy balance as localized
314 effects, such as those resulting from bare ground, vegetation, and fine-scale aspect
315 differences, can have significant impacts on fluxes. Marginal snowpacks have relatively
316 low cold content due to climatological conditions and relatively warm snowfall events,
317 which creates highly dynamic ablation characteristics spatiotemporally. Shortwave
318 radiation flux generally contributes the highest amount of energy to these snowpacks
319 (Fayad et al., 2017; Schwartz et al., 2020), similar to snowpacks of other classifications,
320 but the event-driven nature of marginal snowpacks means that specific contributions can
321 depend heavily on a season’s synoptic weather patterns (Schwartz et al. 2020). Turbulent
322 fluxes, particularly sensible heat flux, have more substantial control on marginal
323 snowpack energy balance due to warmer air temperatures in these climates, particularly
324 during the ablation season (Fayad et al., 2017). Soil heat flux, which is often neglected
325 in cold environments, may represent between 5% and 20% of the total energy inputs,
326 making it necessary to have a good representation of this flux in marginal snow
327 environments. Because a marginal snowpack is relatively thin, transmitted solar radiation
328 may be absorbed by the darker soil substrate and the snowpack can be warmed from
329 below through ground heat flux (Bilish et al., 2018; Knox et al., 2012; van der Valk,
330 2019). Snow mass and energy simulations in these environments also need to carefully
331 consider lateral energy fluxes, especially in areas of patchy snowpack (Harder et al., 2017;
332 Liston, 1995; Mott et al., 2018; van der Valk, 2019). Heat flux from tree trunks has also
333 been shown as a significant source of accelerated snow melt rates in a marginal snowpack
334 (Schwartz et al., 2021, 2020). Rain-on-Snow (RoS) events can cause a particular rapid
335 melt at any time of year due to their increased turbulent fluxes and precipitation flux to

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336 marginal snowpacks (López-Moreno et al., 2021; Schwartz et al., 2021). Therefore, while
337 marginal snowpacks do share some energy balance characteristics with those of colder
338 climates (e.g., shortwave radiation being the dominant flux to the snowpack), turbulent
339 fluxes, soil heat flux, and precipitation heat flux for these snowpacks need to be more
340 carefully considered.

341 4.2 Marginal snowpacks are heavily impacted by vegetation. Vegetation affects snow
342 distribution in many environments by: i) intercepting the new fallen snow; ii) acting as
343 an obstacle for wind redistribution creating wind- and leeward patterns; and iii) altering
344 the radiation input through shadow effects for incoming shortwave radiation and through
345 the emission of longwave radiation to the surroundings (Lundquist et al., 2013; Revuelto
346 et al., 2015; Sanmiguel-Vallelado et al., 2022; Schwartz et al., 2020; Webb, 2017). There
347 is evidence from limited available research to suggest these vegetation effects can become
348 exacerbated in marginal snow zones. Firstly, the mild conditions where marginal
349 snowpacks develop favour the presence of vegetation compared to alpine snowpacks.
350 Also, the redistribution of snow due to snow-vegetation interactions, which can be
351 quantified through an upwind vegetation index (V_x , Bilish et al., 2019), may boost the
352 already high snow variability over terrain typical of medium and low snow depth zones
353 (Sexstone et al., 2021). In addition, as the climate is warmer the emission of longwave
354 radiation is increased meaning that heating dominates the shadow effects (see Figure 5 as
355 example), while the interception by the canopy is reduced (Lundquist et al., 2013). It has
356 also been noted that most of the intercepted snow instead of being unloaded in the
357 subsequent days, is melted and water drops accelerate melting beneath the canopy
358 (Sanmiguel-Vallelado et al., 2020). Thus, warmer winter temperatures exacerbate the
359 differences in snow depth when forest stands and surrounding opening areas are
360 compared (Lundquist et al., 2013; Sanmiguel-Vallelado et al., 2022).

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361 Shrubs have a great impact on shallow snowpacks, affecting snow accumulation and
362 ablation patterns at very fine spatial scales (Figure 6). While the effect of forests on snow
363 has been intensively researched worldwide and very advanced observing and modelling
364 capabilities have been developed (Krogh et al., 2020; Mazzotti et al., 2022, 2021;
365 Musselman et al., 2015; Webster et al., 2016a, 2016b), there are no studies yet, to the
366 authors' knowledge, about how shrubs interact with snow in these mild climates. We
367 suggest that many of the shrubs may act as young and dense trees in a similar manner to
368 the studied Snow Gum forests in the Australian Alps after bushfires, with reduced
369 interception capacity and high emission of energy to surrounding snowpacks (Schwartz
370 et al., 2021, 2020). There are types of shrubs typical of Mediterranean environments of
371 low height and high density that might create small cold pools at the base protecting the
372 snowpack from the ground heat flux, a question that deserves focused research. Thus,
373 new parametrization schemes designed for terrain covered by shrubs depending on their
374 type and structure (species, density and height) have great potential to improve snow
375 modelling capabilities in these ecosystems.

376 4.3 The uncertain effect of snow impurities on melt rates.

377 The effect of LAP on melting rates of marginal snowpacks should not differ from reported
378 impacts on other snow types (Skiles et al., 2018), but for isothermal snowpacks the
379 response should be translated to more rapid melt of the isothermal marginal snowpack.
380 Namely, the combined effect of reduced albedo and increased absorption of solar
381 radiation by the impurities such as leaves, soot and dust should translate to increase
382 heating of the snow surface thereby enhancing melt relative to cold snowpacks (Bilish et
383 al., 2018; Schwartz et al., 2020). However, as marginal snowpacks do not develop late in
384 spring and incoming radiation in winter is relatively low, the total impact on the radiative
385 budget could be moderate (Dumont et al., 2020). This is observed in a simulation of the

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386 snowpack for a marginal-type and a long lasting-type snow year in the Atlas Mountains
387 (Morocco) with three different albedo parametrizations (Figure 7A). The figure shows
388 that under colder conditions the simulations provide very different outcomes, while
389 simulations in milder climatic conditions suggest that the marginal snowpack is the least
390 sensitive to albedo parametrization. Nonetheless, the balance between these two potential
391 opposing drivers of melt requires further research.

392 4.5) Uncertainty in the phase of precipitation.

393 Given that marginal snowpacks often develop close to the 0°C winter isotherm, much of
394 the precipitation falls at the boundary of the rain and snow phases (Alonso-González et
395 al., 2021). In addition, the total snow accumulated in these environments in a whole
396 season often relies on a few larger snowfall events, so misrepresenting the phase in even
397 a few precipitation events may lead to large errors in the simulation of snowpack
398 compared to seasonal and colder snowpacks. Similar to the analysis made while exploring
399 the sensitivity to changes in albedo (Section 4.4), the simulated snow series in the Sierra
400 Nevada mountains in Spain, using various temperature thresholds and precipitation phase
401 determination methods, indicate that during a colder year with a persistent snowpack, the
402 simulated snow series exhibit almost identical values (Figure 7B). Under a milder year
403 with a shallower and shorter-duration snowpack (marginal snow conditions), the different
404 approaches to estimating precipitation phase produced markedly different snow depth
405 time series.

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407 **5. Conclusions and outlook**

408 The aim of this paper has been to present the current gaps in knowledge, the challenges
409 and suggest focus areas to advance our understanding of marginal snowpacks. We outline

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410 the importance and a case for marginal snowpacks to be considered as a unique type of
411 snow, that lies at the transition between ephemeral and longer-lasting seasonal
412 snowpacks. In this paper we propose that a marginal snowpack must include the following
413 characteristics: (i) with seasonal peak depths only occasionally surpass 1.5 meters in
414 favorable deposition zones such as wind drifts, ii) having durations ranging from 60 to
415 120 days, and (iii) that are predominantly in an isothermal state (on more than 75% of
416 days) with high densification rates and several cycles of accumulation-ablation during
417 each snow season. We have shown evidence that a marginal snowpack can develop in a
418 relatively wide variety of climatic conditions, mostly where the mean winter temperature
419 ranges from -4 to +2 °C and precipitation is greater than 400 mm. Thus, they can occupy
420 large areas not only in Mediterranean-type climates, but also extending across the mid-
421 latitudes and fringing the sub-tropical regions across the world. Performing large scale
422 simulations of snowpack under current and future climatic conditions is a critical area for
423 the future research. Related to this task to determine which areas under climate change
424 scenarios will likely shift to ephemeral snowpacks, and which consolidated seasonal
425 snowpacks may transition into marginal snowpacks. Such simulations will provide
426 insight about their degree of sensitivity to climate change and presence of LAP on their
427 surface that at this time is still unclear. Resolving this likely requires advances in our
428 understanding of sources of heat flux (ground and trees) and the role of vegetation in
429 modulating processes of accumulation and ablation. Representing the present and future
430 distribution of marginal snowpacks also needs to use the best observational and modelling
431 approaches tailored to deal with the very high temporal and spatial variability that they
432 exhibit, and to capture some specific conditions of their energy and mass balance, as well
433 as the interaction with vegetation and shrubs that have not been considered in the
434 scientific literature yet. This proposed work will greatly benefit from the establishment

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435 of more experimental sites to study snowpacks and their environmental consequences in
436 mild mountain areas, and in doing so will contribute to a more complete representation
437 of the whole continuum from ephemeral to cold and persistent seasonal snow
438 environments.

439 **Acknowledgement:**

440 This study was funded by the project HIDROIBERNIEVE (CGL2017-82216K) and
441 MARGISNOW (PID2021-124220OB-100), both funded by the Spanish Ministry of
442 Science and Innovation.

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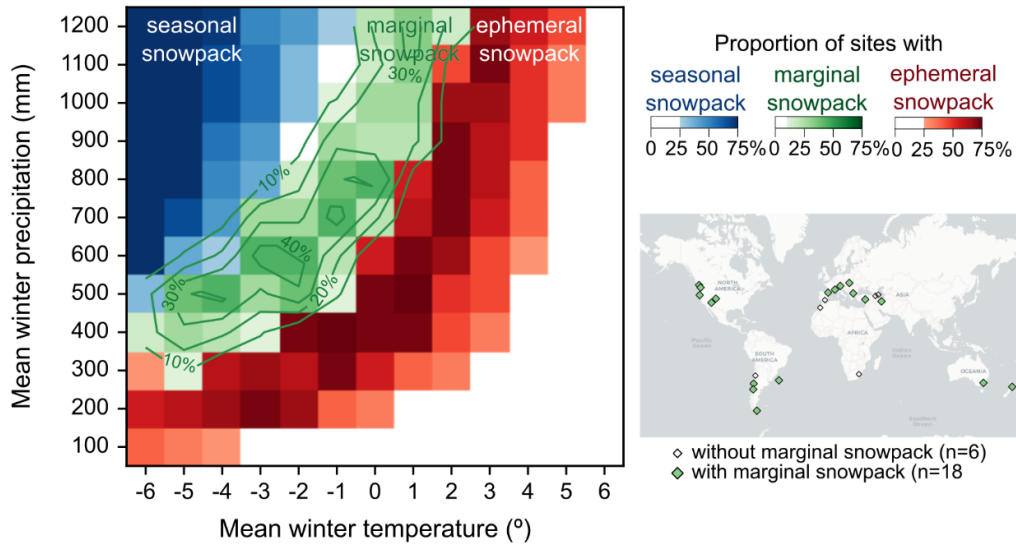
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817 **Figure 1.** Probability of finding seasonal, marginal (depth peak is lower than 1.5 meters,
 818 snow duration ranges between 60 and 120 days and snowpack is isothermal on more than
 819 75% of days) and ephemeral among 24 locations of the world (right plot) for different
 820 mean winter precipitation and temperature values (DJFM (JJAS) in Northern (Southern)
 821 Hemisphere). Results were obtained by simulating (with FSM2 model (Essery, 2015))
 822 snow series driven by ERA5-Land data scaled to fixed winter (DJFM (JJAS) in Northern
 823 (Southern) Hemisphere) precipitation (from 100 to 1200 mm) and temperature values
 824 (from -6 to +6).

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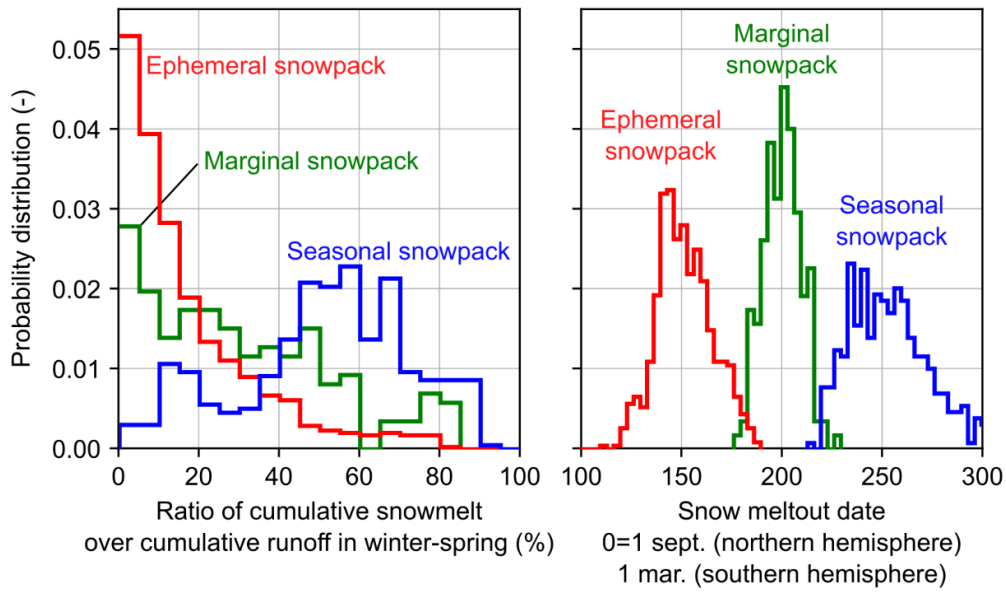
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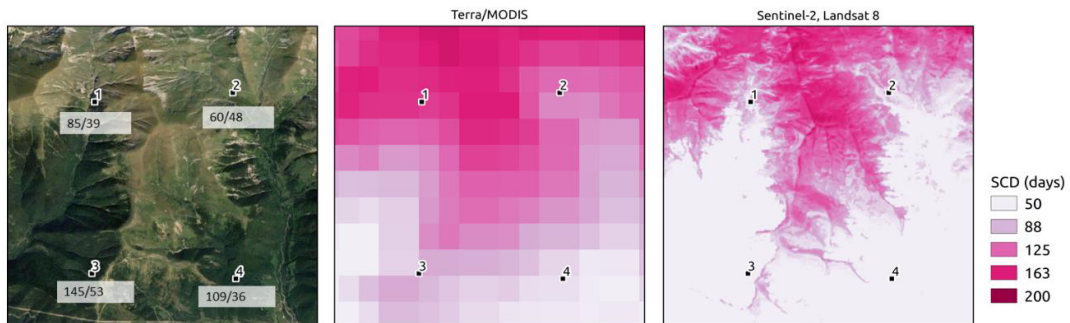
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Figure 2. Probability of finding different ratios of cumulative snowmelt over cumulative runoff during winter and spring period -January to June Northern Hemisphere, July to December Southern Hemisphere-(left) and probability distribution of snow melt-out date among the 25 sites simulated locations shown in Figure 1.

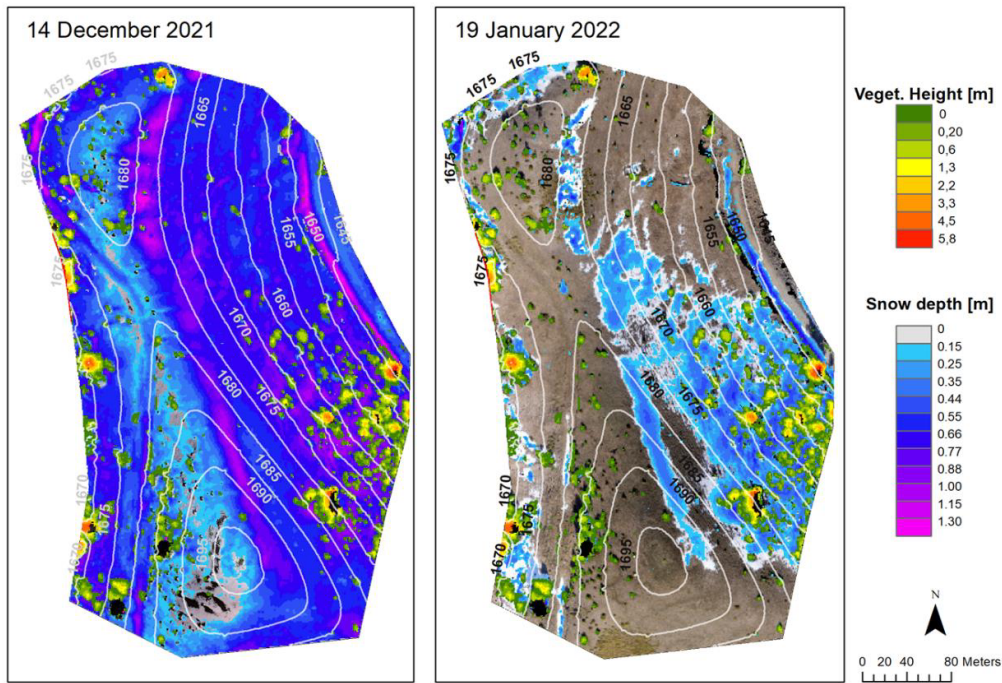
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859 **Figure 3.** Average annual snow cover duration (SCD) for the period 2017-2021 for a
860 typical marginal snowpack site in the Pyrenees derived from MODIS (500 m grid size)
861 and a composite of Sentinel-2 and Landsat 8 (30 meters). Numbers in the left plot inform
862 of the number of days with snow duration derived from MODIS/Sentinel2&Landsat8 for
863 4 selected points.

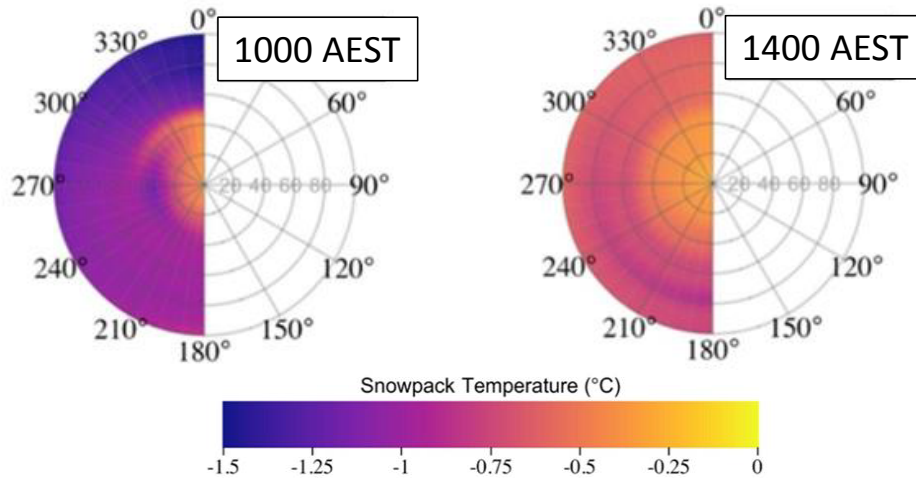
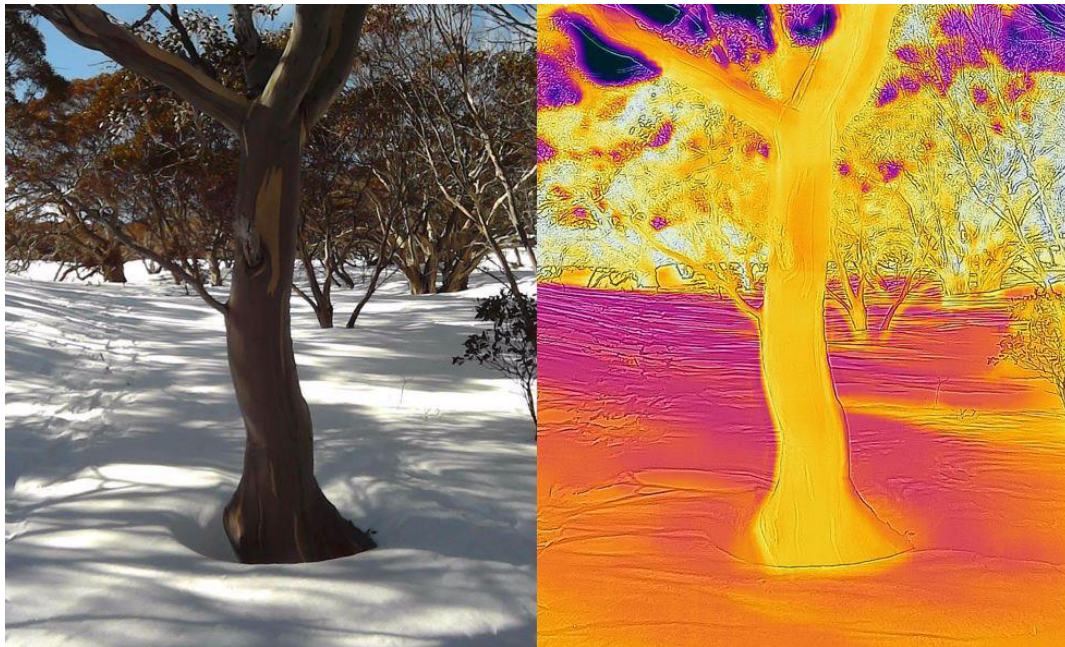
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Figure 4. Snow depth and vegetation height for two different dates mapped with structure from motion technique based on photos from unmanned aerial vehicle in the plot 1 of this figure.



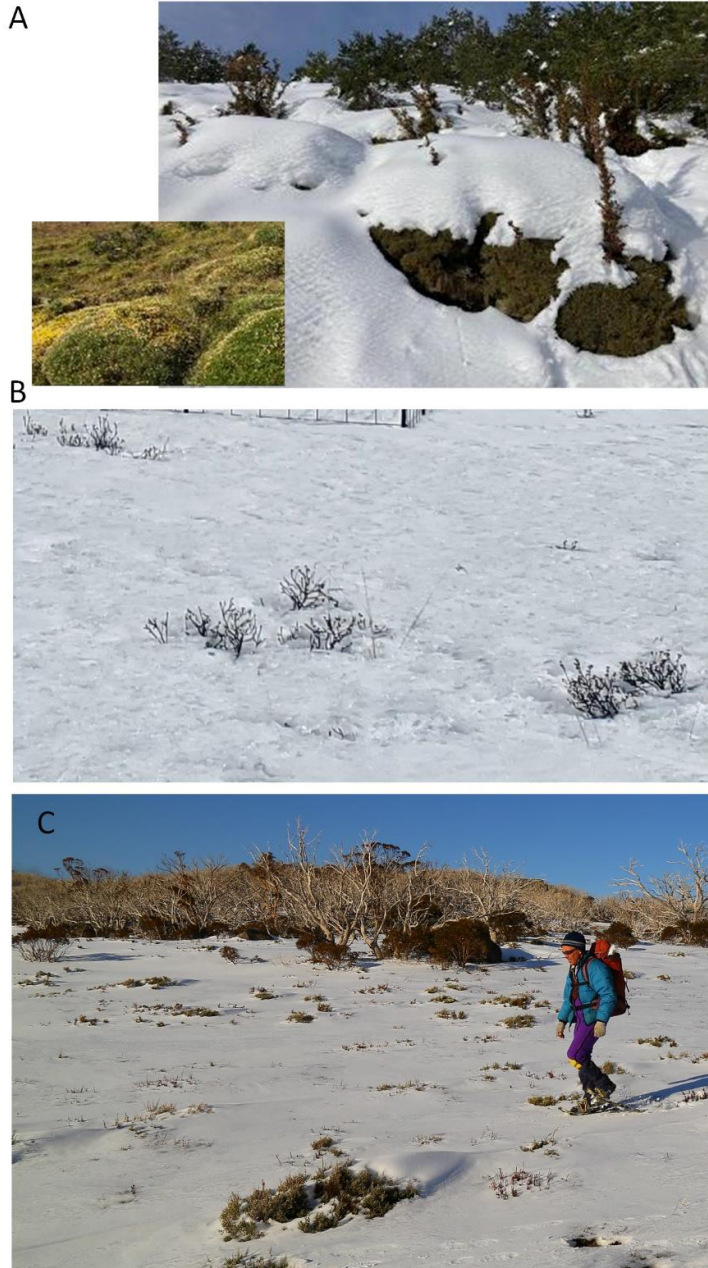
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892 **Figure 5.** Thermal emissivity from vegetation in a Snow Gum forest in the Snowy
 893 Mountains (Australia). Polar plots show average snow temperature around a monitored
 894 tree (from Schwartz et al., 2021) at 10 AM (mean air temperature $-0.4\text{ }^{\circ}\text{C}$) and 2 PM
 895 (mean air temperature $0.7\text{ }^{\circ}\text{C}$) Australian Eastern Standard Time (AEST) showing how
 896 thermal emission increases as the local environment warms.

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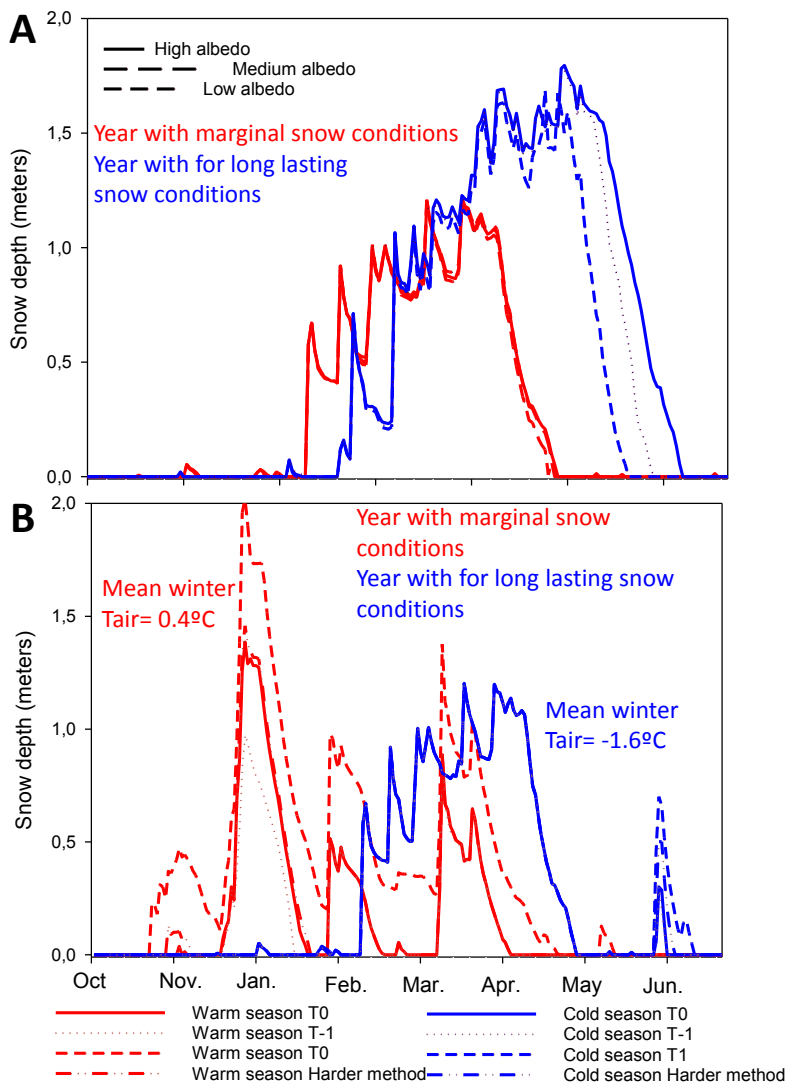


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901 **Figure 6.** A: Snowpack interacting with Mediterranean shrubs (*Buxus sempervivens*,
902 *Juniperus comunis* and *Echinopartum horridum*) in the Spanish Pyrenees. There is no
903 precedent literature on how these species affect snowpack dynamics. B: Preferential melt
904 around the shrubs that were poking through the snow surface (~1 m snowpack) in Jemez
905 mountains in New Mexico. C: Emergent shrubs interacting with snow accumulation in
906 the Snowy Mountains Australia.

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909 **Figure 7.** Simulated snowpack for two contrasted years with the Cold Region
 910 Hydrological Model (Pomeroy et al., 2022) using A: Richard Albedo module in the high
 911 Atlas of Morocco using three levels of minimum albedo (0.2, 0.3 and 0.4) and three
 912 constant albedo decay time for melting snow (0.05, 0.07 and 0.09 day⁻¹); and B: different
 913 temperature thresholds and methods to determine precipitation phase in the Sierra Nevada
 914 mountains (Spain). Under colder conditions the simulations provide similar snow depth
 915 time series, in contrast to simulations in milder climatic conditions.

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Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: