



HAL
open science

Snow hydrology in Mediterranean mountain regions: A review

Abbas Fayad, Simon Gascoin, G. Faour, J.I. López-Moreno, Laurent Drapeau,
Michel LE PAGE, Richard Escadafal

► **To cite this version:**

Abbas Fayad, Simon Gascoin, G. Faour, J.I. López-Moreno, Laurent Drapeau, et al.. Snow hydrology in Mediterranean mountain regions: A review. *Journal of Hydrology*, 2017, 551, pp.374–396. 10.1016/j.jhydrol.2017.05.063 . hal-02351628

HAL Id: hal-02351628

<https://hal.science/hal-02351628v1>

Submitted on 7 Jan 2025

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.

Accepted Manuscript

Review papers

Snow hydrology in Mediterranean mountain regions: a review

Abbas Fayad, Simon Gascoin, Ghaleb Faour, Juan Ignacio López-Moreno,
Laurent Drapeau, Michel Le Page, Richard Escadafal

PII: S0022-1694(17)30411-0

DOI: <http://dx.doi.org/10.1016/j.jhydrol.2017.05.063>

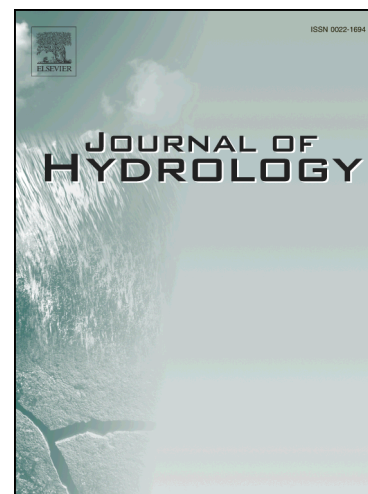
Reference: HYDROL 22062

To appear in: *Journal of Hydrology*

Received Date: 24 October 2016

Revised Date: 23 May 2017

Accepted Date: 24 May 2017



Please cite this article as: Fayad, A., Gascoin, S., Faour, G., López-Moreno, J.I., Drapeau, L., Page, M.L., Escadafal, R., Snow hydrology in Mediterranean mountain regions: a review, *Journal of Hydrology* (2017), doi: <http://dx.doi.org/10.1016/j.jhydrol.2017.05.063>

This is a PDF file of an unedited manuscript that has been accepted for publication. As a service to our customers we are providing this early version of the manuscript. The manuscript will undergo copyediting, typesetting, and review of the resulting proof before it is published in its final form. Please note that during the production process errors may be discovered which could affect the content, and all legal disclaimers that apply to the journal pertain.

1 **Snow hydrology in Mediterranean mountain regions: a review**

2 Abbas Fayad^{1,2,*}, Simon Gascoin¹, Ghaleb Faour², Juan Ignacio López-Moreno³, Laurent Drapeau¹,
3 Michel Le Page¹, and Richard Escadafal¹

4
5 ¹Centre d'Etudes Spatiales de la Biosphère (CESBIO), UPS/CNRS/IRD/CNES, Toulouse, France

6 ²National Council for Scientific Research/Remote Sensing Center (CNRS/RSC), Beirut, Lebanon

7 ³Pyrenean Institute of Ecology (CSIC), Department of Geoenvironmental Processes and Global
8 Change, Zaragoza, Spain

9 * Correspondence: abbas.fayad@gmail.com

10 **Abstract**

11 Water resources in Mediterranean regions are under increasing pressure due to climate change,
12 economic development, and population growth. Many Mediterranean rivers have their headwaters in
13 mountainous regions where hydrological processes are driven by snowpack dynamics and the specific
14 variability of the Mediterranean climate. A good knowledge of the snow processes in the
15 Mediterranean mountains is therefore a key element of water management strategies in such regions.
16 The objective of this paper is to review the literature on snow hydrology in Mediterranean mountains
17 to identify the existing knowledge, key research questions, and promising technologies. We collected
18 620 peer-reviewed papers, published between 1913 and 2016, that deal with the Mediterranean-like
19 mountain regions in the western United States, the central Chilean Andes, and the Mediterranean
20 basin. We find a large amount of studies in the western United States that form a strong scientific
21 basis for other Mediterranean mountain regions. We found that: (1) the persistence of snow cover is
22 highly variable in space and time but mainly controlled by elevation and precipitation; (2) the
23 snowmelt is driven by radiative fluxes, but the contribution of heat fluxes is stronger at the end of the
24 snow season and during heat waves and rain-on-snow events; (3) the snow densification rates are
25 higher in these regions when compared to other climate regions; and (4) the snow sublimation is an
26 important component of snow ablation, especially in high-elevation regions. Among the pressing

27 issues is the lack of continuous ground observation in high-elevation regions. However, a few years of
28 snow depth (HS) and snow water equivalent (SWE) data can provide realistic information on
29 snowpack variability. A better spatial characterization of snow cover can be achieved by combining
30 ground observations with remotely sensed snow data. SWE reconstruction using satellite snow cover
31 area and a melt model provides reasonable information that is suitable for hydrological applications.
32 Further advances in our understanding of the snow processes in Mediterranean snow-dominated
33 basins will be achieved by finer and more accurate representation of the climate forcing. While the
34 theory on the snowpack energy and mass balance is now well established, the connections between
35 the snow cover and the water resources involve complex interactions with the sub-surface processes,
36 which demand future investigation.

37 **Keywords: Snowpack; Snow hydrology; Mountain hydrology, Mediterranean climate**

38

39 **1. Introduction**

40 Mountain regions are a major source of surface water and groundwater recharge in the
41 world (Viviroli et al., 2007; Dettinger, 2014). The water balance in mountainous regions is
42 defined by the interactions between the climate, cryospheric, and hydrological systems (de
43 Jong et al. eds. 2005; DeWalle and Rango, 2008). In mountainous regions that are under the
44 influence of the Mediterranean climate (Bolle 2003; Lionello et al. 2006), the wet-winters
45 and hot and dry-summers climate, orographic enhanced precipitation, variability of
46 temperature and the partitioning of rain and snow with elevation, and the high seasonal
47 variability of the snow cover make the hydrologic processes in these mountainous regions
48 significantly different from those found in other cryospheric regions and or dry or wet
49 climates. Under the influence of the Mediterranean climate, an important fraction of the
50 precipitation occurs during winter months (e.g., Demaria et al., 2013a; López-Moreno et al.,
51 2013a; Valdés-Pineda et al., 2014), with the highest elevation areas receiving most of this

52 winter precipitation as snow while the mid-elevation areas have a mixed precipitation regime
53 (McCabe et al., 2007; Surfleet and Tullos, 2013; Guan et al., 2016). Winter precipitation is
54 orographically enhanced along with elevation (Dettinger et al., 2004; Behrangi et al., 2016;
55 Derin et al., 2016). The snowmelt from the Mediterranean mountain occurs in the spring and
56 summer when precipitation is otherwise scarce, and thus, this snowmelt is an essential water
57 resource for many communities living in the surrounding low land regions (Morán-Tejeda et
58 al., 2010; López-Moreno et al., 2008a, 2014).

59 The Mediterranean mountain regions include the countries around the Mediterranean
60 Sea (e.g., Morocco, Spain, France, Italy, Bulgaria, Croatia, Greece, Turkey, and Lebanon),
61 the western US (California), and the mid-latitude area of the central Chilean Andes. In almost
62 all these regions, agriculture is an important source of income and employment, and
63 snowmelt provides runoff during the crop-growing season when irrigation is the most needed.
64 However, the sustainability of the water resources is threatened by the pressure of a growing
65 population, increasing irrigation, and climate change (e.g., Barnett et al., 2008). While
66 Mediterranean region have been considered as climate change “hot spots” since the first
67 IPCC reports (Milly et al., 2005; Giorgi, 2006; Nohara et al., 2006; Nogués-Bravo et al.,
68 2007; Giorgi and Lionello, 2008; Loarie et al., 2009; Kyselý et al., 2012; Kapnick and
69 Delworth, 2013; Morán-Tejeda et al., 2014; Prudhomme et al., 2014; Harpold and Molotch,
70 2015; Vano et al., 2015; Kumar et al., 2016), there is also new evidence that the rate of
71 atmospheric warming increases with elevation (Kotlarski et al., 2015; Pepin et al., 2015),
72 which strengthens the concern about the climate change in Mediterranean mountain regions.
73 The impact of atmospheric warming is expected to be strong in snow-dominated watersheds
74 since snow accumulation and ablation are highly sensitive to air temperature (Beniston, 2003;
75 Barnett et al., 2005; Howat and Tulaczyk, 2005; Brown and Mote, 2009; Cooper et al., 2016).
76 The main consequence on warming is a shift in the hydrological regimes from a snow-

77 dominated regime towards a rain-dominated regime (Berghuijs et al., 2014; Goulden and
78 Bales, 2014). For example, in the western US, areas with elevations between 2000 to 2800 m
79 are the most sensitive to global warming (Maurer et al., 2007). Regions in the western US
80 where the average winter-wet-day minimum temperature increased by +3 °C are witnessing a
81 reduction in the winter-total snowfall to precipitation ratio (Knowles et al., 2006). Most
82 Northern-Hemisphere's snow-dependent regions are likely to experience increasing stress
83 from low snow years within the next three decades (Diffenbaugh et al., 2012). Areas with an
84 average winter temperature between -4 and -2 °C are expected to witness shifts towards
85 earlier streamflow peaks (changes that exceed 45 days relative to those from 1961–1990)
86 (Maurer et al., 2007). Similar results were reported in the Southern Alpine river basins
87 (Zampieri et al., 2015). The Mediterranean climate is also characterized by a high inter-
88 annual variability, although the underlying mechanisms depend upon the specific region.
89 North and South American Mediterranean regions are under the influence of the climatic
90 variability of the Pacific Ocean, while the Mediterranean climate in Europe and North Africa
91 is relatively connected to the North-Atlantic climatic variability (López-Moreno et al.,
92 2013a).

93 Research on the seasonal snow and snow hydrology in mountains is well established
94 and several authors have already produced review articles or chapters on the following: (1)
95 the physical properties of the snowpack (e.g., Armstrong and Burn (eds) 2008; Kinar and
96 Pomeroy, 2015; Sturm, 2015); (2) remote sensing of snow (Dozier and Painter, 2004; Seidel
97 and Martinec 2004; Dozier et al., 2009; Dietz et al., 2012; Frei et al., 2012; Deems et al.,
98 2013; Lettenmaier et al., 2015; Sturm, 2015; Tedesco (ed.) 2015); (3) spatial distribution of
99 the snow water equivalent, SWE (Dozier et al., 2016); (4) snow and mountain hydrology
100 (e.g., Seidel and Martinec 2004; de Jong et al. (eds.) 2005; Bales et al., 2006;; Armstrong and
101 Burn (eds) 2008; DeWalle and Rango 2008; Varhola et al., 2010; Hrachowitz et al., 2013;

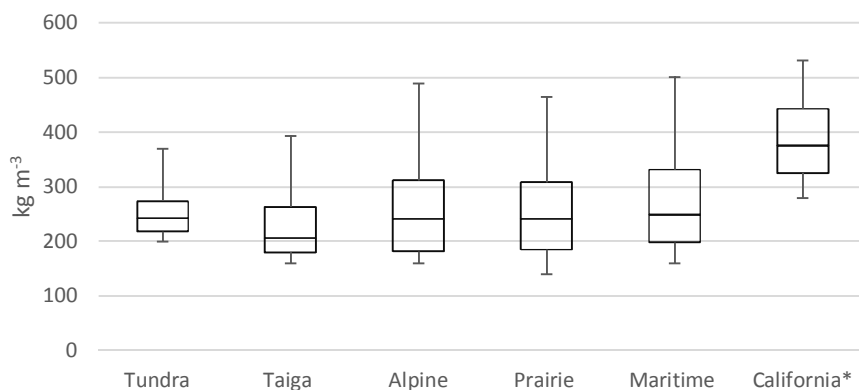
102 Bierkens, 2015; Sturm, 2015); (5) snow spatial representation in hydrologic and land-surface
103 models (e.g., Clark et al., 2011); and the (6) projected climate impact on the cryospheric and
104 hydrological systems in mountains (e.g., Beniston, 2003; de Jong et al. (eds.) 2005; Huber et
105 al. (eds.) 2005; Vicuña and Dracup, 2007; Viviroli et al., 2007; Brown and Mote, 2009;
106 Stewart, 2009; García-Ruiz et al., 2011; Diffenbaugh et al., 2012; Kapnick and Delworth,
107 2013; Beniston and Stoffel, 2014; Pepin et al., 2015; Sturm 2015; Wu et al., 2015; Meixner et
108 al., 2016).

109 Snow processes are driven by meteorological forcing (energy and mass fluxes) and
110 land surface physiography (topography and vegetation). Therefore, the snowpack presents
111 different characteristics depending on the region. The standard snow classification that was
112 introduced by Sturm et al., (1995) defines seven classes of seasonal snow according to their
113 physical properties: Tundra, Taiga, Alpine, Maritime, Ephemeral, Prairie, or Mountain. The
114 “Mediterranean snow” can be observed as a subset of the Maritime class, and it is
115 characterized by a warmer snowpack, a shorter snow season, and a higher variance in both
116 the intra-annual snow depth and mean monthly snow density compared to the Tundra, Taiga,
117 and Prairie snow regions (Brown and Mote, 2009; Sturm et al., 2010; Bormann et al., 2013)
118 (Fig. 1). In comparison with the Tundra and Taiga regions, the snowpack in Mediterranean
119 mountains is characterized by higher mean annual snow densities and higher annual
120 densification rates (Bormann et al., 2013; Trujillo and Molotch, 2014) (Fig. 1).

121 To our knowledge, no review to date has explicitly addressed the characterization of
122 snow hydrologic processes related to snow in one of the major snow regions. Given the
123 significance of the snowmelt as a water resource in Mediterranean regions, we considered
124 that a review of the previous snow studies undertaken in Mediterranean mountain regions is
125 needed. This review may be helpful, for example, in defining a new research program in this

126 climate region, which is highly sensitive to global warming and where snowmelt is an
 127 important contributor to the hydrologic cycle.

128 More specifically this review seeks to answer the following questions: (1) what are
 129 the major forcing variables and controls that drive the snow dynamics in Mediterranean
 130 mountain regions? (2) To what extent are we able to estimate the spatiotemporal properties of
 131 snowpack (i.e., snow cover areas (SCA), snow height (HS), and snow water equivalent
 132 (SWE))? (3) What are the current limitations and opportunities associated with available
 133 observational networks and methods used to assess the snowpack dynamics and hydrologic
 134 responses in these mountain regions?



135 Fig. 1. Variation in the mean monthly snow density (Oct-June) (kg m^{-3}) adopted from Brown and Mote (2009) for the major
 136 climate regions. *California monthly snow density means (Jan-June) are based on long-term monthly data records (more
 137 than 20 years) retrieved from 46 snow courses and 26 SNOTEL stations (data are available online at
 138 wcc.nrcs.usda.gov/snow/). The average snow depth and standard deviation, not shown, were as follows: Tundra (43.8 cm,
 139 24.7 std dev), Taiga (59.6, 22.7), Alpine (130, 82.5), Prairie (88.5, 72.8), and Maritime (176.6, 149.9) (Sturm et al., 2010),
 140 and the average for California calculated from long term monthly snow courses and SNOTEL data was 146.1 cm (std dev =
 141 97.5).
 142

143

144 We collected 620 peer-reviewed articles published between 1913 and 2016, which
 145 dealing with the snowpack and snow hydrology in Mediterranean regions. From this large
 146 number of papers, we adopted a hybrid quantitative (metadata analysis from the papers) and

147 qualitative approach (literature review) to gain insight into the major issues, trends, and
148 advances in this already large and growing research field. We present the geographic extent
149 of the papers and the methodology to analyze them in section (2). The key indicators obtained
150 from the papers dataset are presented in section (3). The second part of the paper is devoted
151 to the review of the three key issues that emerge from this article database: Section (4)
152 addresses the characterization of the climatic forcing in snow-dominated Mediterranean
153 regions; Section (5) describes the main features of the snowpack obtained from ground
154 measurements and remote sensing techniques; Section (6) focuses on the studies dedicated to
155 the snowmelt modeling; and Section (7) draws conclusions and opportunities for future work.

156 We focused on papers that address snowfall, snowpack and snow hydrology processes
157 in Mediterranean mountains. We did not focus on the climate change impact studies, which
158 already represent an important body of the literature *per se*. Interested readers can refer to
159 Beniston (2003), Beniston and Stoffel, (2014), de Jong et al., (eds) (2005), and de Jong et al.,
160 (2012) for additional information regarding the potential impact of climate changes on
161 mountain hydrology and water resources in Mediterranean regions.

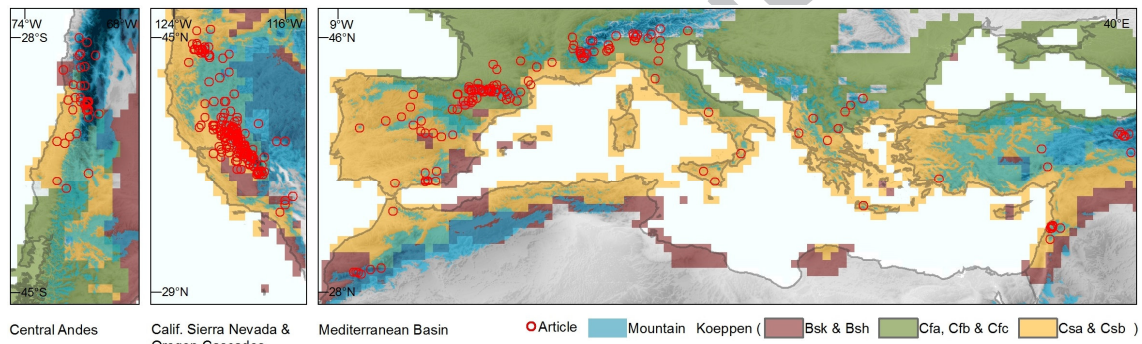
162

163 **2. Methods**

164 2.1. Geographic extent of the review

165 The Mediterranean climate is found on the western part of the continents between
166 latitudes 30° and 45° (Bolle (ed.), 2003). The land regions around the Mediterranean Sea
167 (southern Europe, Northern Africa and the Levantine region) form the largest area of this
168 type of climate. The Mediterranean climate is also found in the western Coastal US
169 (California, and western Oregon), and the central Chilean Andes (Fig. 2). Limited regions in
170 southern Australia and southern Africa are also classified as Mediterranean (not shown). A

171 combined Koppen (Kottek et al., 2006) and mountain classification scheme (Viviroli et al.,
 172 2007) was used to better distinguish the mountain regions associated with the Mediterranean
 173 climate (Fig. 2). The Koppen climate scheme defines five main groups and multi subtypes
 174 according to the long-time annual and monthly temperature means and precipitation totals. Of
 175 particular interest to this study are the Mediterranean (Csa, Csb) regions and the regions
 176 influenced by Mediterranean climate, such as the adjacent maritime zones (Cfb, Cfc) and the
 177 semi-arid regions (BSh, BSk). The Viviroli et al., (2007) scheme distinguishes a total of 15
 178 relief patterns by combining elevation and a relief roughness indicator, and it was used to
 179 distinguish between mountainous and lowland areas.



181 Fig. 2. Mediterranean mountain regions (a) Central Chile (b) western US and (c) Mediterranean Basin. Mountain regions
 182 were derived using the Viviroli et al., (2007) scheme based on the global multi-resolution terrain elevation data
 183 (GMTED2010) at 15-arc second resolution (Danielson et al., 2011), and they are shown in light blue; the three main distinct
 184 climates portray the Mediterranean (Csa, Csb) shown in light orange, oceanic and maritime climates (Cfb, Cfc) in dark olive,
 185 and the semi-arid regions (BSh, BSk) in plum (Kottek et al., 2006). The red dot indicates the coordinates associated with
 186 each paper in the database.

187

188 2.2. Bibliographic sources

189 We used the website of the three major scientific publishers (Elsevier, Wiley, and
 190 Springer), Google Scholar, ReadCube, and open access journals websites to find articles from
 191 the early 20th century to the present, in which snow, hydrology, and mountain hydrology and

192 climatology appeared in the title or abstract, or as a keyword. Only articles published in peer-
193 reviewed journal with an impact factor greater than one and articles related to the
194 Mediterranean regions presented above were considered. A second round of screening
195 focused on reading the abstract and identifying articles where snow properties, snow
196 hydrology, and mountain hydroclimatology are considered as part of the article's main
197 objectives. As much as possible, we avoided papers where snow was addressed in a marginal
198 context. Hundreds of articles were identified during the initial screening. A total of 620
199 articles, (published in 82 different journals) (Fig. 3a.), were retained after the second
200 screening. A table with the metadata for the articles is provided as supplementary file (A1).

201 We identified a list of 35 different indicators that correspond to key research areas
202 (Supplementary material A2). These were classified under three major groups (science,
203 methods, and data) and subdivided into different categories. The first group focuses on
204 science and it includes three categories: (1) meteorology and climatology in mountains (e.g.,
205 mountain climate, climate change and variability, climatology and meteorology, and
206 hydrometeorology (inc. hydroclimatology), (2) snow (e.g., snow hydrometeorology (inc.
207 climatology), snow properties, and snow hydrology) and (3) hydrology (e.g., mountain
208 hydrology, hydrology in snow-dominated basins, and hydrogeology in mountains). The
209 second group focuses on the following methods: (4) methods used to quantify the snow cover
210 extent (e.g., remote sensing of snow); methods used to describe the spatial distribution of
211 snowpack indicators (e.g., spatial statistics and trends in climate, snowpack, and hydrology);
212 and methods used to simulate the main characteristics of snow accumulation, snow duration,
213 and snowmelt processes (e.g., snow energy and mass balance simulation, hydrological
214 modeling). The third group emphasizes the following: (5) data (i.e., length of data used,
215 source and type of data (i.e., ground observations, projections, and reanalysis), and spatial
216 scales (extent of the study area and elevation range). Each article was associated with a pair

217 of longitude and latitude coordinates, which represent the approximate centroid of the study
218 area highlighted in the paper, and each article was reported on a map that shows both the
219 Koppen climate classes and the mountain regions, as defined by Viviroli et al., (2007) (Fig.
220 2).

221 Using our personal criteria, each article was classified under one or two major science
222 topics (see categories 1-3 above) and a methodological approach (see category 4 above). We
223 then combined both in a single label. For instance, Maurer et al. (2007) addressed streamflow
224 trends in snow-dominated regions, where climate change, hydrology, snow, and streamflow
225 timing were all considered. Hence, since the article emphasizes on the use of a hydrologic
226 model for streamflow in mountain regions, the paper was categorized under the “trends in
227 snowpack and hydrology, using distributed hydrological model”.

228

229 **3. Description of the articles database**

230 **3.1. Mountain ranges**

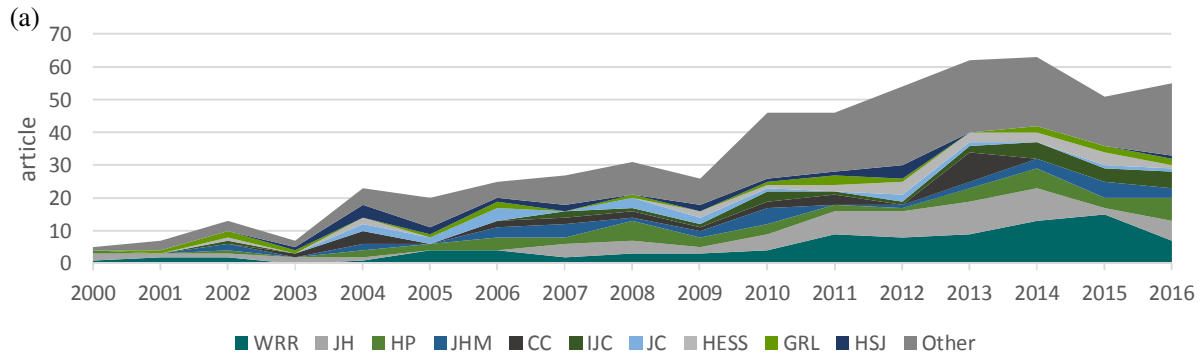
231 Mountain regions covered in this review include the following (Fig. 3b): (1) the
232 coastal regions of western United States (Bales et al., 2006) including the Oregon Cascade
233 (Sproles et al., 2013) and California Sierra Nevada Mountains (Guan et al., 2013a; Molotch
234 and Meromy, 2014); (2) the central Andes that cover two of Chile’s major natural regions –
235 Chile’s central and southern zones (Favier et al., 2009; Cortés et al., 2011; Valdés-Pineda et
236 al., 2014); the major mountain chains around the Mediterranean Sea (López-Moreno et al.,
237 2011a), namely; (3) Spanish (López-Moreno et al., 2014), and French (Gascoïn et al., 2015),
238 Pyrenees; (4) Spanish Sierra Nevada Mountains (Pimentel et al. 2015); (5) French and Italian
239 Maritime Alps (Dedieu et al., 2014) – which are under the influence of the Mediterranean
240 climate (Durand et al. 2009); (6) Turkey and the Armenian Plateau (Tekeli, 2008); (7) Mount

241 Lebanon and Anti Lebanon Ranges (Mhaweji et al., 2014); and (8) Moroccan Atlas
242 (Marchane et al., 2015). Little information was found on other Mediterranean Sea mountains
243 (López-Moreno et al., 2011a), such as the Iberian Peninsula Mountains (Morán-Tejeda et al.,
244 2014), Italian Apennines (Martelloni et al., 2013), Southern Calabrian mountains in Italy
245 (Senatore et al., 2011), Julian Alps (Italy and Slovenia), Dinaric Alps (mostly over Croatia
246 and Bosnia and Herzegovina), Bulgarian mountains (Brown and Petkova, 2007), Pindos
247 (Greece), Rhodope (Greece), and Taurus (Turkey).

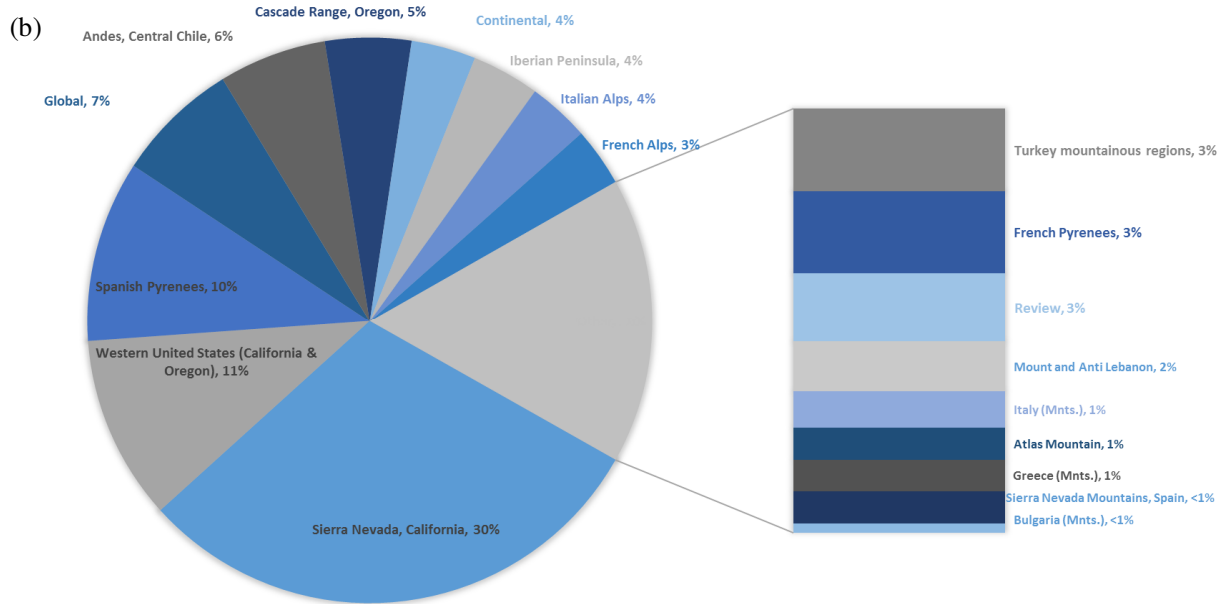
248 3.2. Bibliometric analysis

249 Papers that covered local and regional scale studies accounted for ~90% (of all 620
250 papers), the remaining (~10%) were global studies and review papers. The majority of all
251 articles (90.5%) were published between 2000 and 2016 inclusive, and half of all articles
252 (53.4%) were published over the past five years (2011-2016) (Fig. 3a). The remaining
253 (<10%, not shown) were published between 1913 and 1999, of which ~85% were published
254 between 1990 and 1999. Approximately 66.5% of all articles were published in 10 journals
255 (Fig. 3a). Over the past 16 years (2000-2016), papers covering the California, Sierra Nevada
256 Mountains amounted to 30% of the local and regional scale studies (41% when the regional
257 scale studies over the western United States are included). Spanish Pyrenees (10%) and the
258 central Chilean Andes (6%) were among the most studied mountain regions (Fig. 3b). Figure
259 3c highlights the yearly number of published papers in the first three major Mediterranean
260 regions (2000-2016).

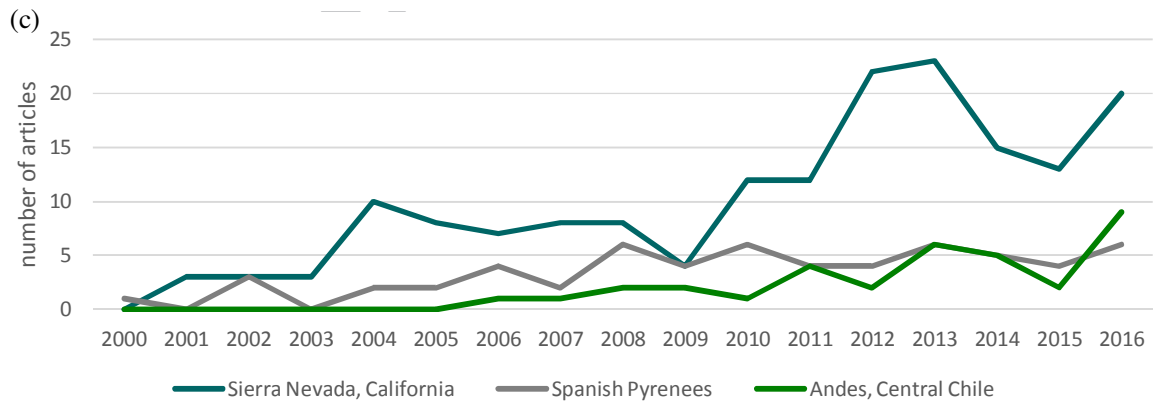
261



262



263



264

265 Fig. 3. Key bibliometric indicators were the following (from top to bottom): (a) cumulative yearly number of
 266 publications per journal (based on 561 articles published between 2000 and 2016); (b) Distribution of studies by
 267 major mountain regions shown; and (c) number of yearly published papers in California (excluding western US
 268 regional studies) (30%), Spanish Pyrenees (10%), and central Chilean Andes (6%).

269 3.3. Thematic analysis

270 The papers cover multiple scales: (1) experimental sites and small catchments (Storck
271 et al., 2002; Franz et al., 2010; López-Moreno et al., 2010, 2013b; Bales et al., 2011; Liu et
272 al., 2013; Raleigh et al., 2013; Harpold et al., 2014; Giroto et al., 2014; Revuelto et al.,
273 2016a; Marti et al., 2016); (2) snow-dominated basins (Lundquist et al., 2010; Powell et al.,
274 2011; Rousselot et al., 2012; Smith et al., 2013; Welch et al., 2013; Cortés et al., 2014; Franz
275 et al., 2014; Telesca et al., 2014; Marchane et al., 2015); (3) multiple basins, mountain
276 ranges, and regional scales (Painter et al., 2009; López-Moreno et al., 2011a; Pavelsky et al.,
277 2011; Guan et al., 2013b; Núñez et al., 2013; Slater et al., 2013; Stewart, 2013; Avanzi et al.,
278 2014; Hüsler et al., 2014; Cornwell et al., 2016); and (4) continental scales and the global
279 scale (e.g., Nohara et al., 2006; Pepin et al., 2015). The studies provide information on (1)
280 mountain climatology and meteorology (Bonfils et al., 2008; Herrero and Polo, 2012;
281 Pavelsky et al., 2012; Lute and Abatzoglou, 2014; Lundquist et al., 2015a; Guan et al., 2016);
282 (2) long-term hydroclimatology and snowpack trends in mountains (López-Moreno and
283 García-Ruiz, 2004; Hamlet et al., 2005; Mote et al., 2005; Stewart et al., 2005; Masiokas et
284 al., 2006; McCabe et al., 2007; Pierce et al., 2008; Das et al., 2009); (3) meteorological
285 forcing and topographic controls on snowfall and snowpack in mountains (Anderton et al.,
286 2004; Guan et al., 2010; Rice et al., 2011; Musselman et al., 2012; Trujillo et al., 2012;
287 Wayand et al., 2013; Ayala et al., 2014; Molotch and Meromy, 2014; Hinkelman et al., 2015;
288 Lapo et al., 2015; López-Moreno et al., 2015; Harpold, 2016); (4) snowpack properties
289 (Mizukami and Perica, 2008; Perrot et al., 2014; Trujillo and Molotch, 2014); (5) snow
290 accumulation and ablation (Harpold et al., 2012; Meromy et al., 2013; Guan et al., 2013a;
291 Avanzi et al., 2014; Sade et al., 2014); (6) snowmelt runoff (Tekeli et al., 2005a; Herrero et
292 al., 2009; Şorman et al., 2009; Franz and Karsten, 2013; Liu et al., 2013; Jepsen et al.,
293 2016a); and (7) different hydrological (Aguilar et al., 2010; Kourgialas et al., 2010;

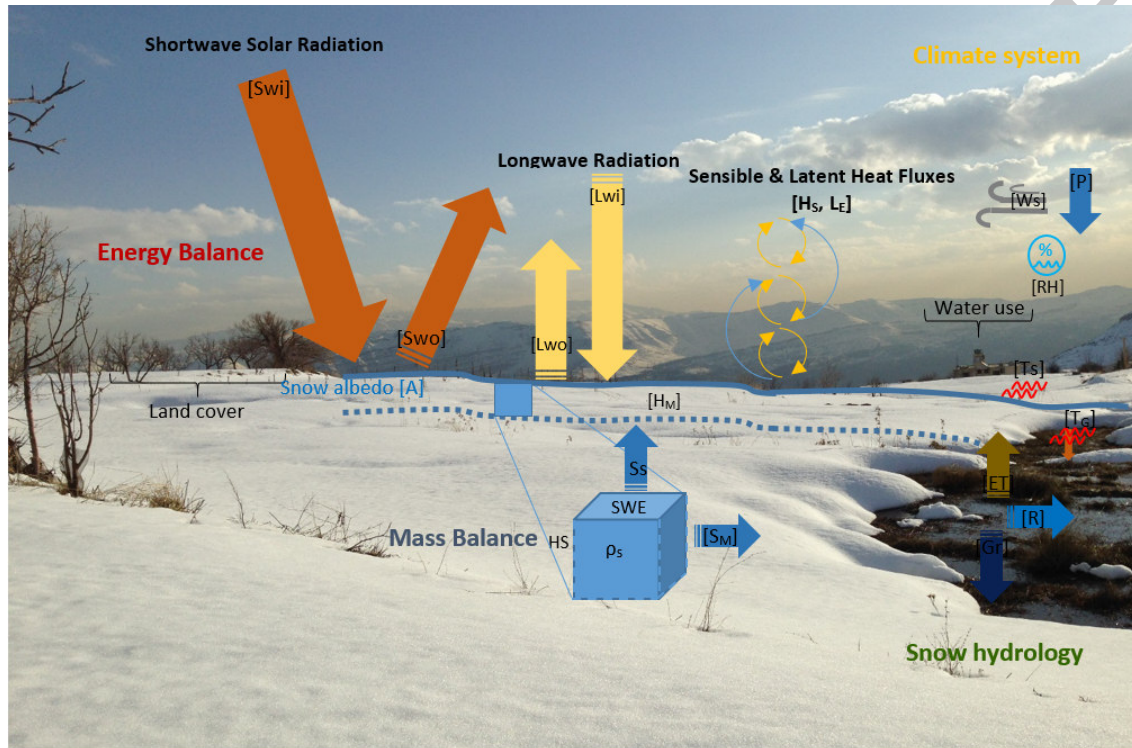
294 Lundquist and Loheide, 2011; Goulden et al., 2012; Schlaepfer et al., 2012; Harpold et al.,
295 2015; Penna et al., 2015; Harpold, 2016); and (8) hydrogeological processes (Tague and
296 Grant, 2009; Lowry et al., 2010) in snow-dominated mountain regions.

297 Given the variety of the topics covered in the literature, we found that the most
298 relevant approach for synthesizing them is to treat the three main vertical levels of the
299 hydrosystem from the atmosphere to the bedrock separately: (1) climate forcing to the
300 snowpack, (2) snowpack spatio-temporal variability, and (3) snowmelt hydrology and
301 hydrogeology. A synthesis on climate forcing, snowpack dynamics, and hydrological
302 processes is presented in Table 1 and further discussed in detail under sections 4-6,
303 respectively. Figure 4 summarizes the key elements of the energy fluxes and mass balance in
304 a typical Mediterranean mountain context.

305 Early studies published prior to the '90s emphasized on mountain meteorology,
306 ground observations of the snowpack, and the theoretical aspects of snow energy balance and
307 snowmelt-runoff models. The time period between 1990 and 1999 witnessed a diversification
308 in the topics with a focus on the quantification of the snow water equivalent, snow
309 interception in forests, hydrology and hydrogeology in snow-dominated basins –including
310 hydrochemical analysis of snowmelt runoff. In this period, the first studies on the changes in
311 snowpack and streamflow under global warming were published. Few studies were based on
312 remote sensing (5%).

313 After 2000, the number of scientific publications increased exponentially each five
314 years. Such a growth rate is higher than the doubling time for natural sciences, which is
315 estimated at 8.7 years (Bornmann and Mutz, 2015). Figure 5 summarizes the number of
316 published papers (2000-2016) based on their key category. The main scientific area was the
317 effect of meteorological and climatological variables on the snow hydrology that accounted

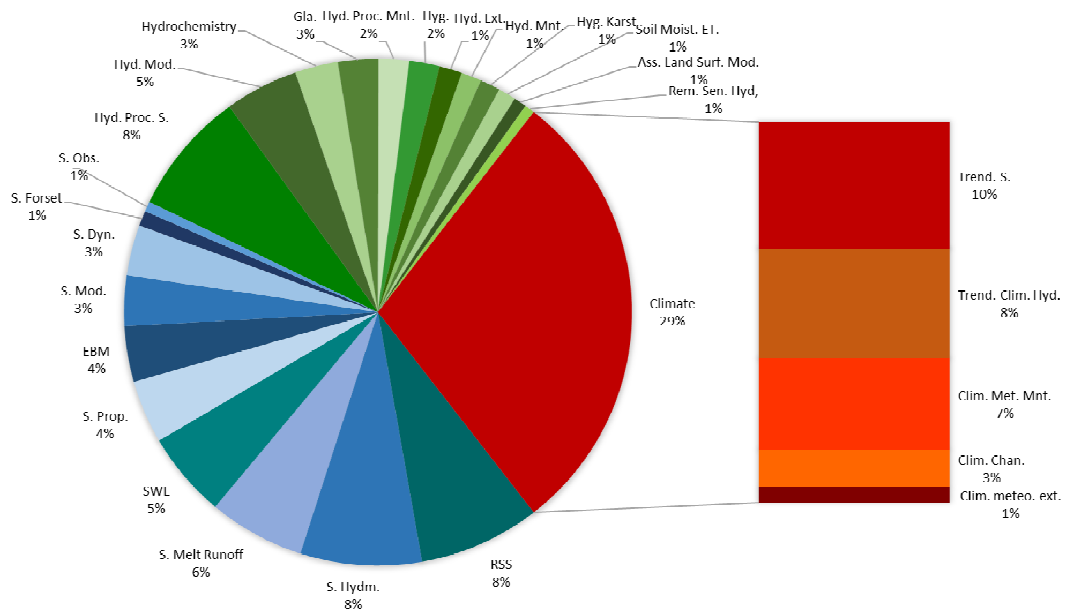
318 for 29% of the studies (Fig. 5), of which about a half were dedicated to assessing climate
 319 change impacts on the hydrology and the snowpack. 25% and 7% of the studies were
 320 dedicated to hydrology and hydrogeology, respectively. The snowpack modeling accounted
 321 for 13% of the studies, and the snow remote sensing accounted for 8% (Fig. 5).



322
 323 Fig. 4. Major climate forcing and snow processes in Mediterranean-like mountainous regions with emphasis on
 324 the specific objectives shown here for mountain hydrology and snowpack dynamics. Where SWi and SWo are
 325 incoming and outgoing shortwave radiation, respectively; Lwo and Lwi are the emitted and incoming longwave
 326 radiation, respectively; P is precipitation, Ws is wind speed, and RH is relative humidity; HM is sensible heat
 327 flux; Ts is surface temperature and Tg is ground temperature; HS is snow depth, ds is snow density, and SWE is
 328 snow water equivalent; Ss is snow sublimation and Sm is snow melt; ET is evapotranspiration, R is surface
 329 runoff, G is subsurface and groundwater flow. The background image was taken in Laqlouq at 1850 m a.s.l.
 330 (Mount-Lebanon) on February 20th, 2016 (courtesy of the author).

331

332



333

334 Fig. 5. Distribution of papers by science groups and key sub-categories with emphasis on climate forcing to the
 335 snowpack (29% of all studies, shown in red), snow studies (39%, blue), and snowmelt hydrology and
 336 hydrogeology (32%, green). S. is snow; Trend S. indicates a study that emphasizes on addressing climate
 337 change impacts on snow. RSS indicates a paper that focuses on remote sensing of snow. EBM indicates a study
 338 that describes and tests an energy balance model (see appendix A2 for a detailed list of indicators)

339

340

341

342

343

344

345

346

347

348

349

350

351

352

353

354

355

356

357

358 Table 1. Summary of key science topics identified in the literature; in addition, the table lists major variables,
 359 scales, and sources of uncertainty.

Topic	Main variables of interest	Main source of data	Main methods	Major sources of uncertainty
Climate forcing to the snowpack	Near-surface meteorological variables (air temperature, air humidity, precipitation, longwave and shortwave radiation); latent and sensible heat	Ground observations (automatic weather stations); reanalysis data	Mesoscale atmospheric model (e.g., WRF); assimilation techniques; downscaling; spatial interpolation	Lack of weather stations at high-elevation; high spatial variability of the climate in mountains; lack of long time series; snowfall undercatch by precipitation gauges; few radiation and flux measurements
Snowpack spatio-temporal variability	Snow cover area, snow depth, snow density, snow water equivalent, snow albedo	Field measurements; Automatic weather stations, space borne remote sensing products; terrestrial remote sensing (Lidar, camera)	Temperature index model; regression analysis; modeling of snowpack mass and energy balance	Spatial variability of snow depth; inter-annual variability of SWE; difficulty to sample large areas in the field; cloud and canopy obstruction in optical remote sensing; large errors of SWE retrievals in complex topography by microwave remote sensing
Meltwater hydrology	Surface runoff, soil moisture, evapotranspiration, groundwater flow and recharge	Gauging stations; remote sensing; hydro-chemical testing for streamflow and groundwater recharge.	Water balance, hydrological and hydrogeological modeling.	Medium to high difficulty in conducting measurements; heterogeneity of mountain topography and land cover; mixed rain/snow regimes; lack of sub-surface measurements.

360

361 4. Climate forcing to the snowpack

362 The two processes that control snowpack dynamics in mountains are snow
 363 accumulation and ablation. The accumulation is mainly forced by snowfall and this mainly
 364 depends on precipitation and temperature (López-Moreno, 2005), while the ablation is driven
 365 by radiation and heat fluxes between the atmosphere, the snowpack and the underlying soil
 366 (Herrero et al., 2009). The near-surface wind also influences both accumulation and ablation
 367 (e.g., Gascoin et al., 2013) (see Sect. 5).

368 4.1. Near-surface meteorological observations

369 The minimum meteorological data to run a temperature index snowmelt model are the
370 precipitation and the air temperature (DeWalle and Rango, 2008). A typical 1D (vertical)
371 snowpack energy balance model requires additional data of air relative humidity, incoming
372 shortwave and longwave radiation and wind speed. The wind direction is only useful to
373 simulate wind drift and lateral heat advection (e.g., Burns et al., 2014), in case of a patchy
374 snow cover (e.g., Liston, 1995). However, information on the spatial distribution of the main
375 meteorological variables remains incomplete in Mediterranean mountains, such as in most of
376 the world's mountains (e.g., Bales et al., 2006). This has been attributed to the following:

377 (1) The sparseness of the automatic weather stations (AWS) networks (Horel and
378 Dong, 2010; Gottardi et al., 2012; Valdés-Pineda et al., 2014; Henn et al., 2015). Even in
379 well-monitored regions, most of the AWS are usually below 3000 m a.s.l, although meltwater
380 production generally increases with elevation (Favier et al., 2009).

381 (2) The number of variables being measured at the AWS (Raleigh et al., 2016). A
382 survey based on 1318 AWS across the western US, where meteorological data and either
383 SWE or snow depth are measured, indicated that near-surface forcing variables of air
384 temperature and precipitation are among the most sampled (99-83%), whereas wind speed,
385 humidity (often as relative humidity RH), and incoming shortwave radiation are measured
386 24-36% of the time. Incoming longwave radiation is the least measured (1.4%). Nearly 99%
387 of all AWS do not measure all six forcing variables (Raleigh et al., 2016).

388 (3) Biases and uncertainties that arise from observational data. AWS are prone to data
389 logging failure; some sensors require periodic calibration and the data must undergo specific
390 quality control given the harsh climatic conditions encountered in high-elevation areas
391 (Estévez et al., 2011; Filippa et al., 2014; Lundquist et al., 2015a).

392 Radiative and turbulent fluxes in Mediterranean mountain regions can be calculated
393 from meteorological and incident solar radiation and thermal radiation observations (e.g.,
394 using pyranometers and pyrgeometers) at experimental sites (e.g., Marks et al., 1992). There
395 are few flux tower locations (e.g., Goulden et al., 2012; Burns et al., 2014) and specific
396 research sites, such as the CUES in California, which feature a full range of sensors for
397 measuring the snow energy balance (Bair et al., 2015). Flux towers equipped with eddy
398 covariance system and specific stations equipped with pyranometers and pyrgeometers
399 remain the two options for measuring the sensible heat, latent heat, and radiative fluxes.
400 However, most of the available flux towers are generally located at flatter lowland areas and
401 provide little information needed to evaluate fluxes in snow ablation in complex mountain
402 regions (Bales et al., 2006; Raleigh et al., 2016). Studies that address snow energy balance in
403 snow-dominated regions (e.g., Sproles et al., 2013; Mernild et al., 2016a) rely on solving the
404 energy balance solely from meteorological observations (e.g., Liston et al., 1999; Herrero et
405 al., 2009). This has resulted in the current availability of limited information for validating
406 the contribution of radiative and turbulent fluxes (Lapo et al., 2015; Raleigh et al., 2016).

407 4.2. Precipitation

408 In Mediterranean mountain regions, more than 80% of the annual precipitation falls
409 during winter (November to March for the Northern Hemisphere and May to September in
410 the Southern Hemisphere) (Mazurkiewicz et al., 2008; Demaria et al. 2013a; López-Moreno
411 et al. 2013a). Mountain regions such as the Sierra Nevada, California receive 75-90% of
412 winter precipitation in the form of snow (Jepsen et al., 2012). Mountain regions tend to
413 receive more precipitation than surrounding lowland areas due to the orographic
414 enhancement (Favier et al., 2009; Neiman et al., 2014; Lundquist et al., 2015a; Derin et al.,
415 2016).

416 The assessment of the distribution in precipitation amounts in mountain regions and
417 an accurate identification of the precipitation type (snow or rain) emerge as the most
418 uncertain factors in the literature (Gottardi et al., 2012; Neiman et al., 2014; Dettinger, 2014;
419 Buisan et al., 2014; Derin et al., 2016). Uncertainties in the precipitation distribution over
420 mountain regions are associated with: (1) snow gauge undercatch (Sevruk et al, 1991;
421 Rasmussen et al., 2012), (2) precipitation phase determination (e.g., Harpold et al., 2017), (3)
422 methods for estimating spatial precipitation distribution, including the precipitation lapse
423 rates (Lundquist et al., 2015a; Henn et al., 2017), and (4) the heterogeneity of the
424 precipitation network (Favier et al., 2009; Rice and Bales, 2010; and Gottardi et al., 2012).
425 Wind-induced precipitation undercatch affects the accuracy of precipitation data and is more
426 pronounced for solid precipitation than for liquid precipitation (Rasmussen et al., 2012;
427 Buisan et al., 2016; Smith et al., 2016; Pan et al., 2016). Measurement errors due to gauge
428 undercatch frequently range between 20% and 50% (Rasmussen et al., 2012). The factors that
429 govern snow undercatch are related to the gauge setting (i.e. shielded and unshielded) (Colli
430 et al., 2015), snowflake characteristics (Theriault et al., 2012), and wind speed (Rasmussen et
431 al., 2012). Despite its importance little information was found in the literature on snow
432 undercatch in Mediterranean regions.

433 Precipitation phase determination is often done as post-processing given that most
434 gauges do not detect the phase. The precipitation phase is required to determine the water
435 equivalent during the accumulation season, but also to properly correct precipitation
436 undercatch, and for investigating rain-on-snow events which contribute to the snowpack
437 ablation. Determining precipitation phase from ground observation can be achieved using: (1)
438 thresholds for temperature (e.g., air, dewpoint, and wet bulb) (see Marks et al., 2013), (2)
439 linear transition, range, and sigmoidal curve methods based on near-surface air temperature
440 (e.g., Harpold et al., 2017), and (3) psychrometric energy balance method (Harder and

441 Pomeroy, 2013). Despite the availability of these methods, one of the major limitation for the
442 proper determination of precipitation phase from ground data is attributed to the lack of
443 meteorological observations for stations in near locations to the precipitation gauges (Harpold
444 et al., 2017).

445 Rain-on-snow events are not uncommon in Mediterranean mountains (Guan et al.,
446 2016). These events help in warming the snowpack and add very high sensible heat to the
447 snowpack through condensation, which accelerates melting and sometimes triggers
448 catastrophic floods (McCabe et al., 2007; Surfleet and Tullos, 2013). In the western US, rain-
449 on-snow-events appear to be partly driven by the El Niño–Southern Oscillation (ENSO), the
450 Pacific Decadal Oscillation (PDO) (McCabe et al., 2007; Lute and Abatzoglou, 2014) and
451 atmospheric rivers (Trujillo and Molotch, 2014; Guan et al., 2016). To our knowledge, the
452 impacts of rain-on-snow events were not specifically addressed in regions other than the
453 western US. The analysis of rain-on-snow events remain challenging and warrant future
454 investigation (Wayand et al., 2015).

455 Uncertainties associated with the spatial distribution of precipitation increases with
456 elevation, where differences between datasets ranged between 5 to 60%, exceeding 200 mm
457 yr⁻¹ on average, were reported across the western US (Henn et al., 2017). Different
458 methodologies were developed to compute the integrated precipitation in high-elevation
459 watersheds (Valery et al., 2010) and to generate gridded precipitation maps from daily
460 ground observation (see Demaria et al., (2013b) and Lundquist et al., (2015a) for a list of
461 gridded precipitation products). The emergence of gridded precipitation products over the
462 2000s has boosted the research in snow hydrology and facilitated the upscaling of point-scale
463 studies. Precipitation grids are invaluable data for distributed hydrological modeling in both
464 the operational and research context, e.g., to perform climate change impact studies at the
465 scale of river basins (Mernild et al., 2016b). While the overall accuracy of gridded

466 precipitation products has been deemed satisfactory, the biases increase with elevation
467 (Mizukami et al., 2011; Lundquist et al., 2015a). Precipitation-gauge undercatch, a poor
468 knowledge of wind patterns to correct the undercatch, and the lack of in situ input data are
469 sources of errors in the gridded precipitation products (Dettinger, 2014; Lundquist et al.,
470 2015b; Mizukami and Smith, 2012). In addition, temporal inconsistencies in multi-year
471 gridded precipitation biases tend to increase the uncertainty in simulating hydrological
472 responses in snow-dominated basins (Mizukami and Smith, 2012).

473 Acquiring precipitation and snowfall from high-resolution satellite-based rainfall
474 (SBR) products (e.g., TRMM and GPM) in mountain regions (Derin et al., 2016), such as the
475 western US (Behrangi et al., 2016), and northeastern Spain (Kenawy et al., 2015), is still
476 hindered by the facts that (1) capturing solid precipitation is practically challenging for
477 TRMM and results are highly biased over snow surfaces, (2) precipitation satellites tend to
478 underestimate the wet season and overestimate dry season precipitation rates over land and
479 should be corrected using in situ measurements, and (3) the performance of gauge correction
480 to SRB is less effective in mountain regions and depends on the representativeness of the
481 observation networks.

482 Over the past decade there had been an increase in the use of assimilation techniques
483 and the downscaling of atmospheric model (e.g., Vionnet et al., 2016, Mernild et al., 2016a).
484 These different techniques to estimate precipitation using a combination of ground
485 observations, numerical weather prediction, and remote sensing observations are still not
486 complete and the generated gridded data is at coarser and medium resolution at best (e.g.,
487 Quéno et al., 2016). There is more work needed to understand how atmospheric circulation
488 (Jin et al., 2006; Lundquist et al., 2010) and the complex topography at the finer scales
489 (López-Moreno et al., 2015) affects precipitation and snowfall and both topics are interesting
490 field of research. An intercomparison between different gridded precipitation datasets (e.g.,

491 Lundquist et al., 2015a; Henn et al., 2017) across different mountain regions is needed.
492 Reducing the bias in precipitation estimates along altitude and enhancing the spatial
493 resolution of gridded precipitation could be the next breakthrough in mountain hydrology.

494 4.3. Air temperature

495 The air temperature is the most important factor that determines the precipitation
496 phase (rain or snow), and it is strongly correlated to the snowmelt rate (Jin et al., 2006; Mote,
497 2006; Brown and Petkova, 2007; Kapnick and Hall, 2010). During the melting season in the
498 mid-elevation regions of the Spanish Pyrenes, the increase in the daily snowmelt rates was
499 correlated with the increase in the observed daily temperature (López-Moreno and Latron,
500 2008). In many low and mid-elevation Mediterranean mountain regions, changes in the
501 surface air temperature had been previously identified as the major driver for the reduction in
502 the amount of precipitation that falls as snow, the decline in the snow water equivalent, and
503 shifts towards earlier snowmelt (Stewart et al., 2005; Bonfils et al., 2008; Demaria et al.
504 2013a; Pagán et al., 2016).

505 Similar, to all other meteorological variables, uncertainties associated with measuring
506 the air temperature arise from the lack of AWS in remote and high-elevation mountain areas
507 (Raleigh et al., 2016). However, air temperature is the climatic variable that is the most often
508 available from in situ and gridded-products. In comparison with precipitation, the in-situ
509 measurements of temperature are much less biased and the interpolation methods are more
510 robust. From the papers we could examine, the uncertainty on the precipitation data is
511 generally considered as a more important issue.

512 4.4. Radiation and heat fluxes

513 In Mediterranean mountain regions, the snowpack melt energy is dominated by the
514 radiative fluxes (shortwave and longwave) (Marks and Dozier, 1992; López-Moreno et al.,

515 2012). The net radiative flux accounts for approximately 70-80% of the energy for snow melt
516 in regions, such as Sierra Nevada California, Oregon Cascades, Spanish Pyrenees, and the
517 Armenian Plateau (Marks and Dozier, 1992; Şensoy et al., 2006; Mazurkiewicz et al., 2008;
518 López-Moreno et al., 2008b; Hinkelman et al., 2015). However, this contribution varies
519 significantly over the time and the location. For instance, the net radiation contribution to
520 melt at three different sites in the Oregon cascades was found to range between 49 and 80%
521 (Mazurkiewicz et al., 2008). Similar results were found in the Armenian Plateau, which
522 indicates that the net radiation fluxes and turbulent fluxes account for 70 to 30% of the melt
523 energy, respectively (Şensoy et al., 2006). Sensible and latent heat transfers were found to be
524 of similar magnitude with an opposite sign, and therefore they tend to cancel each other in
525 some sites during the now-melt season (Marks and Dozier, 1992; Jepsen et al., 2012). A
526 significant amount of snow is lost through sublimation in Mediterranean mountains,
527 approximately 20% of the total snowpack ablation depending on the location, and this
528 amount increases at the end of the snow season (Beaty, 1975; Marks and Dozier, 1992;
529 Jepsen et al., 2012). The net turbulent flux tends to increase during the melt season. Its
530 contribution to snowmelt during the entire season was found to range between 0 to 19% in a
531 mountain basin in Sierra Nevada, California (a mean of 10% with a standard deviation of 6%
532 over a time period of 12 years) (Jepsen et al., 2012). The contribution of the turbulent energy
533 fluxes was found to increase under rain-on-snow events, and it accounts for up to 42% of
534 snowmelt during such events (Mazurkiewicz et al., 2008). The contribution of turbulent
535 fluxes (i.e., latent and sensible heat fluxes) to melt energy was found to be slightly higher in
536 warmer Mediterranean regions (Atlas Mountain, Iberian Peninsula and Eastern
537 Mediterranean) (Schulz and de Jong, 2004; Herrero et al., 2009; Sade et al., 2014). Under
538 extreme weather conditions (i.e., episodic strong low-humidity winds, clear skies, intense
539 solar radiation, and sudden increases in temperatures), sublimation accounted for up to 40%

540 of the total loss in snowpack in Sierra Nevada, Spain (Herrero et al., 2009), and similar
541 results were reported for the Atlas Mountain (Schulz and de Jong, 2004) and Mount Hermon
542 (Sade et al., 2014).

543 In the absence of radiation sensors (pyranometer and pyrgeometer), the incoming
544 radiation can be estimated using (1) empirical relationships with surface air temperature and
545 relative humidity (Jepsen et al., 2012; Lundquist et al., 2013) or (2) solar and longwave
546 surface irradiance data from synoptic satellite products (Jepsen et al., 2012; Hinkelman et al.,
547 2015). However, computing radiative fluxes using empirical methods can lead to
548 overestimation errors of up to 50% in the snowmelt rates, which indicates the need for
549 enhanced methods that combines satellite products and ground observations (e.g., Hinkelman
550 et al., 2015). The application of such products to Mediterranean mountains should account for
551 the fact that shortwave and longwave radiations vary significantly with elevation, terrain
552 geometry and the forest cover (Aguilar et al., 2010; Raleigh et al., 2013, Lundquist et al.,
553 2013).

554 Sensible and latent heat exchange are influenced by surface air temperature, water
555 vapor, and wind speed (Marks and Dozier, 1992; Kim and Kang, 2007; Jepsen et al., 2012).
556 Most of these variables exhibit high spatial variability over the complex mountainous
557 topography (Marks and Dozier, 1992), which makes it difficult to achieve reliable estimates
558 of the contribution of snowmelt from heat fluxes at most sites. Furthermore, while the surface
559 air temperature is measured at most AWS, information on wind speed and humidity are often
560 lacking, and thus, this hinders the calculation of sensible heat fluxes (Raleigh et al., 2016).

561 Our understanding of the energy exchange between the snowpack and the atmosphere
562 in mountains is incomplete. The installation of more complete meteorological stations
563 (including longwave/shortwave sensors and turbulent heat measurement systems) in

564 mountains is needed in order to better characterize the different components of the energy
565 balance. However, this requires solving the issue that eddy covariance systems are not
566 considered reliable in complex terrain.

567 **5. Snowpack**

568 5.1. In situ observations

569 Historical studies on snow properties and the quantification of the water that falls as
570 snow are more than 300 years old (Grew, 1673), and the importance of snow cover on
571 climate was first highlighted by Woeikof (1885). The first published investigations of
572 snowfall, HS, snow density, SWE and snow melt, and the first method for field sampling of
573 snow and snow instrumentation in California can be dated to the late 19th and early 20th
574 centuries (e.g., Church, 1913). Monthly snowfall observations in California date back to 1878
575 (Christy, 2012). Over the past two decades, there has been a significant increase in the
576 number of studies that investigates HS, snow density, and SWE through manual field
577 sampling (Bocchiola and Groppelli, 2010; Sturm et al., 2010; López-Moreno et al., 2013b;
578 Bormann et al., 2013; Ayala et al., 2014), HS measurements using (acoustic) snow depth
579 gauges, SWE measurements with snow pillows, and snow density measurements from HS
580 and SWE observations (e.g., SNOTEL network) (e.g., Rice and Bales, 2010; Meromy et al.,
581 2013; Luce et al., 2014).

582 The main variable of interest for snow hydrologists is the SWE, which is obtained by
583 multiplying the snow height by the snow density. The snow height is typically measured with
584 a calibrated snow probe and it is easier to estimate than the snow density, which requires a
585 more elaborate field-work (e.g., Bocchiola and Groppelli, 2010; Sturm et al., 2010; López-
586 Moreno et al., 2011b). Field measurements are usually biased with observational errors
587 (Lundquist et al., 2015b) and uncertainty about the representativeness of in-situ snow depth

588 and density measurements (López-Moreno et al., 2011b, 2013b). Improving the in-situ
589 accuracy of snow course measurements can be achieved by increasing the rate of data
590 sampling along the snow course and minimizing human errors. Findings in the Spanish
591 Pyrenees indicated that increasing the number of in-situ measurements (i.e., using at least five
592 snow depth measurements at 5-10 meter intervals) could ensure a bias of less than 10% when
593 estimating the average snow depth at plots of 100 m² (López-Moreno et al., 2011b). The
594 snow density exhibits less variability than the snow depth (López-Moreno et al., 2013b),
595 which implies the need for fewer snow density measurements along each course. Such
596 findings support the US snow courses sampling guidelines, which indicates the need for 10
597 point measurements of HS, SWE, and density at 30 meter interval (over a 300 m transect)
598 (Rice and Bales, 2010). The same applies for snow sampling approaches in other regions
599 (e.g., Watson et al., 2006; Jost et al., 2007). However, collecting in-situ probe measurements
600 at larger scales remains challenging. Steeps slopes and high-elevation areas (above 3000 m
601 a.s.l) are unsafe and not easily accessible. Airborne and terrestrial Lidar now enable the
602 measurement of HS with a centimetric accuracy at a much higher resolution than manual
603 surveys (Sect. 5.2.4). However, these techniques remain costly and do not provide continuous
604 observation of HS, such as AWS. A terrestrial time-lapse camera is a cost-effective device
605 used to monitor the snow cover variability in both space and time, but its use is restricted to
606 small spatial scales (less than 1 km²) (Revuelto et al., 2014). As a result, it is difficult to
607 capture the temporal variability of the HS and SWE by field sampling. On the other hand,
608 continuous AWS measurements of snow depth and SWE remain site specific, and most of the
609 time, they fail to capture the spatial variability of the snowpack due to the spatial
610 heterogeneity of the climate and terrain with respect to the network density (Bales et al.,
611 2006; Gottardi et al., 2012; Raleigh et al., 2016).

612 Some regions are equipped with advanced snow observatories and the data are easily
613 accessible (e.g., SNOTEL in the western US) while other mountain regions, such as the
614 Pyrenees, are well covered by ground stations but the data are to be collected from various
615 agencies and are not always publicly distributed (e.g., Gascoin et al., 2015). The
616 implementation of snow observatories based on the principles of open data is en route in
617 regions such as Lebanon where snow observations are recently being collected (e.g., Fayad et
618 al., 2017). Extending the ground-based observation networks remains crucial in mountain
619 regions that remain under-sampled. However, it is as important to share these data to foster
620 their use by the scientific community and among water stakeholders.

621 5.2. Remote sensing of seasonal snow cover

622 The snow cover extent, albedo, height, and water equivalent are the main remote
623 sensing products for snow hydrology, but they have very different levels of accuracy and
624 resolution. Here, we only briefly present the main products that were used in our list of
625 papers. Interested readers can refer to Dietz et al. (2012) and Frei et al. (2012) for further
626 information on snow remote sensing.

627 5.2.1. Optical remote sensing of the snow cover

628 The NASA MODIS Aqua/Terra daily snow products (collection 5 MOD10A1 and
629 MYD10A1 (Hall et al., 2002)) are the most widely used. These products have provided the
630 binary snow-covered area (SCA) and fractional SCA (fSCA), and the snow albedo at a 500 m
631 resolution since 2000 for Terra and 2002 for Aqua. The SCA product allows the calculation
632 of the snow cover duration (SCD), snow cover start date (SCS) and snow cover melt-out date
633 (SCM). The SCA and fSCA allow the calculation of the snow coverage in a watershed.
634 MODIS snow products were tested and applied in the Sierra Nevada California (Painter et al.,
635 2009; Molotch and Meromy, 2014), Pyrenees (Gascoin et al., 2015), Southern Alps (Dedieu

636 et al., 2014), Moroccan Atlas (Marchane et al., 2015), Armenian Plateau (Tekeli et al., 2006),
637 and Mount Lebanon (Telesca et al., 2014).

638 The main limitation of optical snow products is the obstruction by cloud cover. A
639 cloud removal algorithm must be run to generate meaningful snow climatology from MODIS
640 snow products (Gascoin et al., 2015; Marchane et al., 2015). There are also errors related to
641 sensor viewing geometry and forest canopy obstruction (Dozier et al., 2008; Gao et al., 2010;
642 Dietz et al. 2012; Raleigh et al., 2013; Kostadinov and Lookingbill, 2015).

643 In addition to the MOD10 family, there are more sophisticated approaches to retrieve
644 sub-pixel fSCA, grain size, and albedo from MODIS using spectral unmixing techniques
645 (Painter et al., 2009). The validation of the fSCA against higher resolution snow cover maps
646 data obtained from Landsat ETM+ over the Sierra Nevada California, in particular, indicates
647 their better accuracy compared to the MOD10A1 products (Dozier et al., 2009; Painter et al.,
648 2009; Rittger et al., 2013). The accuracy of the fSCA is lower in forested areas, which
649 suggests that there is a need for future research in this direction (Raleigh et al., 2013;
650 Kostadinov and Lookingbill, 2015).

651 Snow cover extent and snow climatology had also been derived from AVHRR data at
652 a spatial resolution of 1 km for the Alpine region (1985–2011) (Hüsler et al., 2014) and the
653 Armenian Plateau (Tekeli et al., 2005a). Finally, Cortés et al., (2014) proposed and tested a
654 sub-pixel approach for mapping snow and ice cover over the central Andes using spectral
655 unmixing of Landsat imagery at a spatial resolution of 30 m (1986–2013).

656 Future improvement of snow cover representativeness from optical remote sensing
657 could include better cloud removal and enhanced snow cover mapping in forested regions.
658 Daily SCA from MODIS are hindered by their spatial resolution of 500m which is too coarse
659 to capture snow variability in heterogenous mountain slopes, in regions where snow is
660 ephemeral, and at the end of the season when snow becomes patchy. The Sentinel-2 mission

661 with its 20 m spatial resolution and 5 days revisit time is expected to provide better accuracy
662 for mapping SCA in the heterogenous mountain regions.

663 5.2.2. Remote sensing of SWE

664 The retrieval of SWE from spaceborne passive microwave (PM) sensors involves a
665 coarser resolution (~25 km) and limited accuracy (Dietz et al., 2012; Frei et al., 2012;
666 Vuyovich et al., 2014; Dozier et al., 2016). Overall, PM sensors tend to underestimate SWE.
667 For example, from April 1st 2014 SWE estimates, the passive microwave AMSR2 sensor
668 underestimated the SWE by 40-75% compared to other SWE retrieval methods (i.e.,
669 interpolation from snow pillows and SCA, calculation using SCA and NLDAS, and modeling
670 using SNODAS) (Dozier et al., 2016). Examples from the Mediterranean regions include the
671 use of AMSR2/AMSR2 over the contiguous US (Vuyovich et al., 2014), California (Li et al.,
672 2012), the Armenian Plateau (Tekeli, 2008; Şorman and Beser, 2013), and Mount Lebanon
673 (Mhawej et al., 2014), and the use of the Scanning Multichannel Microwave Radiometer
674 (SMMR) and Special Sensor Microwave Imagers (SSM/I) over the Andes (Foster et al.,
675 2009).

676 PM sensors have limited capability in capturing the SWE in regions with ephemeral
677 or patchy snow cover and regions with vegetation cover (Li et al., 2012; Vuyovich et al.,
678 2014), and they exhibit an overall tendency to underestimate SWE during snowfall and melt
679 seasons (Dozier et al., 2016). This was attributed to the high scattering in mountain regions
680 due to relief (Li et al., 2012) and the tendency of PMs to saturate at an SWE value of 120 mm
681 (for wavelengths, 18 GHz as the background signal and 37 GHz as the scattering signal)
682 (Dietz et al. 2012).

683 Despite these limitations of PMs, a number of studies demonstrated that PMs are able
684 to capture the overall seasonal variations of snow accumulation, melt timing, and season
685 length at the macro scale, and in contrast to imaging spectrometry, they are not affected by

686 cloud cover (Foster et al., 2009; Vuyovich et al., 2014). Coupling ground-observed data SCA
687 and PM sensed SWE is being investigated as an alternative for enhancing the SWE
688 estimation in Mediterranean regions (e.g., Vuyovich et al., 2014; Şorman and Beser, 2013).

689 5.2.3. Snow albedo

690 The importance of snow albedo in Mediterranean regions has been attributed to the
691 fact that most of the snowmelt is dominated by net radiation (Sect. 4.1). A decrease in snow
692 albedo results in an increased amount of absorbed shortwave radiation and eventually, an
693 enhancement in the snowmelt. Surface snow albedo changes in Mediterranean mountain
694 regions are associated with snowpack thickness (Tekeli et al., 2006), snow grain size and
695 surface wetness (Dozier et al., 2008, 2009), and snow impurities (mainly mineral dust and
696 organic particles) (Lee and Liou, 2012). In California's Sierra Nevada, the reduction in the
697 snow albedo during the melt season (March to April) is driven by the increase in surface
698 temperature and the increase in the deposition of absorbing aerosols. Both temperature and
699 aerosols contribute to the 61% decrease in snow albedo, and 26% of the albedo reduction was
700 attributed to the increase in the aerosol optical depth (Lee and Liou, 2012). Snow albedo can
701 be calculated by observing the incoming and reflected solar radiation at AWS. Given the lack
702 of in-situ observations, many studies have used optical remote sensing techniques. The
703 method to derive snow albedo from imaging spectrometry is well developed in literature
704 (e.g., Dozier and Painter, 2004; Seidel and Martinec 2004; Frei et al., 2012; Deems et al.,
705 2013; Tedesco (ed.) 2015). In the Mediterranean context, most studies were conducted in
706 Sierra Nevada, California using MOD10A1 or MODSCAG MODIS albedo products (Painter
707 et al., 2003; Dozier et al., 2009; Lee and Liou, 2012). In the Armenian Plateau, the
708 MOD10A1 albedo was found to be consistent with in situ measurements in terms of
709 magnitude and temporal variability, with a small positive bias due to differences in the
710 acquisition time (Tekeli et al., 2006). On the contrary, in the Spanish Sierra Nevada, the

711 coarse-resolution albedo products from MODIS and SPOT underestimated the in-situ snow
712 albedo due to the mixing effects of snow and snow-free patches in a MODIS pixel especially
713 during the melting periods (e.g., Pimentel et al., 2016).

714 Advances in airborne hyperspectral remote sensing have enabled the accurate
715 estimation of snow surface cover, grain size and albedo at a relatively higher cost (e.g.,
716 Painter et al., 2003). Future research areas in surface snow properties can be found in Dozier
717 et al. (2009), which indicates the need to better understand the spectral characteristics of
718 snow from remote sensing sensors, to further investigate the consequences of dust and other
719 impurities on snow reflectance, and to further investigate the coupling of snow properties and
720 snowpack energy via models (e.g., Oaida et al., 2015).

721

722 5.2.4. High resolution airborne and ground-based remote sensing

723 Over the past few years, a number of studies have used ground-based terrestrial laser
724 scanners (TLS) and airborne LiDAR to measure the snow depth at high spatial resolution
725 with decimetric accuracy (e.g., in California (Harpold et al., 2014; Kirchner et al., 2014;
726 Zheng et al., 2016), and the Spanish Pyrenees (Revuelto et al., 2014; López-Moreno et al.,
727 2015)). These technologies have enabled numerous fundamental advances in our knowledge
728 of the snow depth distribution (see Sect. 5.4). They also hold potential for operational snow
729 monitoring if their costs can be mitigated; otherwise, their application will remain restricted
730 to relatively small areas, as noted in the scientific literature ($<100 \text{ km}^2$). The NASA Airborne
731 Snow Observatory (ASO) (Painter et al., 2016) is a notable exception since it is run over
732 major water basins in the western US. ASO is composed of an imaging spectrometer and a
733 Lidar altimeter to measure the snowpack reflectance and depth from an aircraft. The SWE
734 maps are produced over 48 hours using the snow reflectance as a proxy for snow density

735 (Dozier et al. 2016). Recent alternatives were proposed to determine the snow depth at high
736 resolution and at a lower cost: (1) an unmanned aircraft vehicle photogrammetric survey, and
737 (2) high-resolution stereo satellite imagery (Marti et al., 2016).

738 5.3. Methods of HS and SWE regionalization

739 5.3.1. Regionalization

740 Spatial interpolation (regionalization) techniques are required to estimate the
741 snowpack water equivalent at the catchment scale. Various statistical models based on the
742 terrain characteristics were proposed to compensate for the low spatial density of snow
743 course surveys and ground station observations. Spatially distributed HS estimates from
744 observations in Mediterranean mountain were represented using: linear regression models,
745 classification trees, generalized additive models (GAMs), regression tree models (e.g.,
746 Molotch et al., 2005), and combined tree classification with GAM residuals (e.g.,
747 López-Moreno and Nogués-Bravo, 2006; López-Moreno et al., 2010). Similarly, but at
748 much lower scale, the assimilation of snow cover area maps derived from time-lapse camera
749 images time series was shown to give good results in small Mediterranean pilot catchments,
750 where the snow cover is highly variable and sometimes ephemeral (Pimentel et al., 2015;
751 Revuelto et al., 2016b).

752 5.3.2. SWE reconstruction

753 Dozier et al. (2016) reviewed the methods to generate spatially distributed SWE as
754 follows: (1) spatial interpolation from ground based networks only using statistical models,
755 such as decision trees (Anderton et al., 2004); (2) constrained interpolation by remotely
756 sensed SCA (Giroto et al., 2014); (3) SWE reconstruction using snow modeling (e.g.,
757 Raleigh and Lundquist, 2012; Guan et al. 2013b); and (4) reconstruction using data

758 assimilation (Cortés et al., 2016) (see Sect. 6.1) and backmelt calculations (e.g., Raleigh and
759 Lundquist, 2012), which may be combined with time-lapse photography (Revuelto et al.,
760 2016a). The increase in the reliance of SWE reconstruction had been motivated by the
761 assumption that knowledge of melt energy fluxes would be superior to knowledge of
762 precipitation accumulation (Cline et al., 1998; Jepsen et al., 2012; Slater et al., 2013).

763 SWE reconstruction estimates the total volume of snow based on backward
764 calculation of the amount of ablation that occurred prior to the complete removal of snow
765 (Cline et al., 1998). The SWE reconstruction process, as described by Cline et al., (1998), is
766 performed at each pixel by (1) determination of fSCA, (2) computation of the snowmelt
767 energy, and (3) determination of the initial SWE at the beginning of the melt season.

768 Several snowpack models for SWE reconstruction are constantly being tested and
769 enhanced for application in Mediterranean regions, and they range in complexity from (1)
770 simple temperature index models (Daly et al., 2000; Rice et al., 2011; Biggs and Whitaker,
771 2012), to (2) enhanced degree day models (DDMs) that account for net radiation, snow
772 albedo (e.g., Molotch and Bales, 2006), and tree cover (Biggs and Whitaker, 2012), and (3)
773 modified DDMs (based on a modified SRM (Martinec, 1975) (Tekeli et al., 2005b; Şensoy
774 and Uysal, 2012), to (4) energy balance models (Cline et al., 1998; Jepsen et al., 2012;
775 Raleigh et al., 2016; Boudhar et al., 2016; Cornwell et al., 2016), and (5) models that perform
776 both forward and backward reconstruction (Raleigh and Lundquist, 2012; Revuelto et al.,
777 2016a).

778 SWE reconstruction models have proven to be suitable for many Mediterranean
779 regions such as the Andes (Cornwell et al., 2016), Sierra Nevada California (Shamir and
780 Georgakakos, 2006; Rice et al., 2011; Raleigh et al., 2016), Oregon cascades (Sproles et al.,
781 2013), Pyrenees (Gómez-Landesa and Rango, 2002), Alps (Thirel et al., 2012), Turkey
782 (Tekeli et al., 2005b), and the Atlas Mountains (Boudhar et al., 2016).

783 The uncertainty associated from SWE reconstruction arises from the probable error
784 propagation in model forcing especially in areas where dense observing network are not
785 available (Lundquist et al., 2015b; Dozier et al., 2016). Another source of uncertainty is
786 attributed to the retrieval and spatial resolution of SCA and fSCA from imaging spectrometer
787 (e.g., AVHRR and MODIS) (Sect. 5.2) and return time period (e.g., 16 days for Landsat)
788 (Slater et al., 2013). The Sentinel-2 mission with its 5 days repeat cycle offers the prospect of
789 improving the SWE reconstruction results in regions where the snow cover variability is high
790 (Marti et al., 2016).

791 SWE reconstruction methods based on the use of depletion curves that relate
792 fractional snow cover area to average SWE should consider that there is a hysteresis in the
793 SWE-fSCA relationship (Luce and Tarboton, 2004; Magand et al., 2014; Gascoin et al,
794 2015). In fact, a given snow cover fraction generally corresponds to a smaller snow mass at
795 the beginning of the snow season to that found at the end of the season. This is due to the
796 snowpack evolution along the season, where snow wind redistribution and snowmelt
797 occurring at preferential locations, tend to increase the heterogeneity in the SWE spatial
798 distribution.

799 The success of the spatial interpolation techniques for the estimation of HS and SWE
800 should encourage the implementation of regular snow surveys and automatic snow stations in
801 less monitored mountain regions, such as the Andes, Atlas Mountains, and Mount Lebanon.
802 In the absence of ground measurements, methods based on SCA data assimilation into an
803 energy balance snow model are the most promising since they rely on publicly available
804 remote sensing and climate datasets (reanalyses) with global coverage (e.g., Kapnick and
805 Delworth, 2013).

806 5.4. Snowpack spatial variability

807 5.4.1. Snow height spatial variability

808 Results from the aforementioned studies indicate that in Mediterranean mountain
809 regions, the spatial distribution of the snow height is driven by meteorological forcing
810 (López-Moreno 2005; Svoma, 2011; Mizukami and Smith, 2012; Bormann et al., 2013; Luce
811 et al., 2014) and topography (elevation, slope, aspect and related radiation parameters) (e.g.,
812 Elder et al., 1998; Anderton et al., 2004; López-Moreno and Nogués-Bravo, 2006; Rice et
813 al., 2011; Molotch and Meromy, 2014; Revuelto et al., 2014). Canopy interception (e.g.,
814 López-Moreno and Latron, 2008; Revuelto et al., 2015; Zheng et al., 2016) plays a secondary
815 role in comparison with other snow regions because most of the snowpack accumulates
816 above the tree line in many Mediterranean mountains. Forest regions are present at mid-
817 altitude mountain regions (2000-2600 m a.s.l) in California (e.g., Rice and Bales, 2010;
818 Musselman et al., 2012), Oregon (Kostadinov and Lookingbill, 2015), and the Pyrenees (e.g.,
819 Gascoin et al., 2015). Snow redistribution due to wind is probably an important process
820 (Gascoin et al., 2013), and it is one of the less explored fields of research in Mediterranean
821 regions. This may be due to the lack of accurate information needed to create reliable wind
822 fields over complex topography. Snow models run using high-resolution meteorological
823 forcing are still unable to capture wind snow redistribution, which usually occurs at the sub-
824 pixel scale (e.g., Quéno et al., 2016). However, the wind redistribution may be less important
825 in Mediterranean mountains than in colder regions due to the higher snowpack densification
826 rates. Table 2 summarizes the contribution of climate forcing and mountain controls
827 potentials in explaining snow distribution and depth, and the level of uncertainty in
828 Mediterranean mountain regions.

829 For example, in Sierra Nevada California, Elder et al., (1998) obtained a model that
830 could explain up to 70% of the observed variance in HS using the elevation, net radiation and
831 slope as predictors. According to Molotch and Meromy, (2014), snow cover persistence is
832 driven by mountain controls where elevation (the most explanatory variable) and climate
833 controls of precipitation and temperature determined most of the snow variability. Vegetation
834 and slope ranked second in explaining part of the snow cover variability, whereas shortwave
835 solar radiation and the terrain aspect were of tertiary importance. Similar findings were
836 reported in the Spanish Pyrenees, which indicates that elevation and solar radiation explain a
837 high percentage of the variance in HS (Anderton et al., 2004; López-Moreno and
838 Nogués-Bravo, 2005).

839 Similar findings based on high-resolution airborne lidar were reported from an
840 experiment over a micro-scale snow dominated basin (with an elevation range of 1500–3300
841 m) in the Sierra Nevada, California; the experiment indicated that 43% of snow-depth
842 variability can be explained by elevation, and another 14% is related to the slope, aspect and
843 canopy penetration fraction (Zheng et al., 2016). A ground-based terrestrial laser scanner in
844 the Pyrenees demonstrated that the high resolution topographic position index and maximum
845 upwind slope are more statistically significant ($\alpha < 0.05$) in explaining the intra-annual snow
846 variability compared to the elevation and slope (Revuelto et al., 2014). Snow variability at
847 this scale is further influenced by mountain curvature, whereas the aspect and the computed
848 incoming radiation were found to be less statistically significant when correlated with intra-
849 annual snow variability (Revuelto et al., 2014).

850 Despite these encouraging results, to date, there is no accepted universal law to derive
851 HS or SWE from a set of predictors that can be obtained anywhere. This is because the link
852 between the terrain parameters and the snow distribution is not fully explained at the small
853 scale (e.g., Molotch et al., 2005; López-Moreno et al., 2010, 2015; Revuelto et al., 2014;

854 Zheng et al., 2016). This quest is hindered in particular by (1) the high inter-annual snow
 855 variability in Mediterranean regions, since most studies rely on 1-2 years of sporadic
 856 observations (e.g., Anderton et al., 2004; López-Moreno et al., 2010; Zheng et al., 2016), and
 857 (2) the increase in the scale dependency of the model results (e.g., the importance of
 858 elevation) as the grid cell size increases (López-Moreno et al., 2010).

859 The presence of vegetation, especially forest, adds to the ambiguity in explaining
 860 topographic control because it modifies meteorological variables, such as wind and the
 861 incoming radiation, with difference intensities, which depends on the canopy density, trees
 862 trunks and crow size (e.g., Musselman et al., 2012; Harpold et al., 2014; Zheng et al., 2016).
 863 The snow depth can be significantly reduced by 20% to 80% in forested areas compared with
 864 open sites due to interception and the sublimation or melting of the intercepted snow
 865 (Revuelto et al., 2015; Szczypka et al., 2015). Information on the impact of vegetation cover
 866 on snow interception in Mediterranean mountain regions and elsewhere (Varhola et al., 2010)
 867 remains limited and warrants future research (López-Moreno and Latron, 2008; Musselman
 868 et al., 2012; Raleigh et al., 2013; Revuelto et al., 2015; Zheng et al., 2016).

869 Table 2. Main variables influencing the snow depth spatial distribution

Variable	Control Level
Elevation [1-5, 7-9]	Medium to very high
Slope [1-5, 7-9]	Low to high (micro); High (meso-macro)
Curvature [5, 8-9]	High at micro
Exposure [3-5, 7-8]	Low at micro to medium at the micro scale
Radiation [1-3, 5, 7-9]	Low to medium (micro); High (macro)
Relative elevation [2, 5, 8]	Low to very high
Upwind slope [3, 5, 7, 9]	High at micro
Canopy interception [4, 6]	Medium to high

870 Radiation: potential incoming solar radiation; Relative elevation (inc. topographic position index (TPI) and
 871 combined TPI); Upwind slope: maximum upwind slope.

872 Scale (micro 1–102 km²; meso 102–104 km²; macro > 104 km²)

873 Sources: [1] Elder et al., 1998; [2] López-Moreno and Nogués-Bravo, 2005, 2006; [3] Anderton et al., 2004;
 874 [4] Zheng et al., 2016; [5-6] Revuelto et al., 2014, 2015; [7] Molotch et al., 2005; [8] López-Moreno et al.,
 875 2010; and [9] López-Moreno et al., 2015.

876

877 5.4.2. Snowpack density

878 Over most parts of the maritime US, the snowpack density was found to be highly
879 correlated with total precipitation (Svoma, 2011). The variability in snow densities is also
880 driven by the average air temperature during days with no snowfall, the mean snowfall
881 density, the fractional precipitation that falls as snow (Svoma, 2011) and melt-refreeze events
882 (Bormann et al., 2013). At the slope scale, densification processes are further influenced by
883 solar radiation, slope, vegetation cover, and wind exposure (Bormann et al., 2013, Elder et
884 al., 1998).

885 However, the observed spatial variability of the snowpack density in Mediterranean
886 regions is much lower than the spatial variability of the snow height (Mizukami and Perica,
887 2008; López-Moreno et al., 2013b). As a result, the number of density measurements
888 required to derive the SWE may be lower than the number of HS measurements. This has
889 important implications for the monitoring of the snowpack since density measurements in the
890 field are time consuming. Similarly, year-to-year changes are significantly higher for the HS
891 than for the snowpack density (Mizukami and Perica, 2008; Bormann et al., 2013). However,
892 the density should be carefully measured at the start and end of each season when its intra-
893 annual variance is maximal (Sturm et al., 2010; López-Moreno et al., 2013b; Bormann et al.,
894 2013; Trujillo and Molotch, 2014). The low inter-annual variability of snow density also
895 holds potentials in Mediterranean regions. Climatological values of snow density can be
896 estimated with confidence using few years of measurements (Anderton et al., 2004;
897 Mizukami and Perica, 2008; Meromy et al., 2013), combined with regular HS measurements,
898 to estimate the SWE for hydrological applications in mountains (Mizukami and Perica,
899 2008).

900 5.4.3. SWE

901 Long-term records of SWE (> 50 years) indicate that the maximum snow
902 accumulation is higher and the snow season is shorter in the Oregon Cascades and the
903 California Sierra Nevada than in continental mountain ranges (Trujillo and Molotch, 2014).
904 In the western US, the April 1st SWE (a proxy of the annual peak of SWE) and the snow
905 residence time (SRT) are highly correlated with daily temperature and precipitation (Luce et
906 al., 2014). Hence, the observed decrease in SWE in this region was linked to the regional
907 increase in temperature, and the results were qualitatively consistent with observed trends in
908 temperature and precipitation at nearby stations (Mote, 2003). In the southern Italian Alps,
909 the SWE average and variances are known to a good degree of approximation if continuous
910 information on the accumulated SWE, snow depth, and density are known (Bocchiola and
911 Rosso, 2007). Smaller scale studies in California and Central Andes indicate a higher
912 influence of the slope and maximum upwind slope (Molotch et al., 2005; Welch et al., 2013;
913 Ayala et al., 2014). The influence of the theoretical incoming radiation increased during the
914 melt season, which is in agreement with energy balance model studies (Molotch et al., 2005;
915 Ayala et al., 2014) (Sect. 4). We do not detail the spatial variability of the SWE since it is
916 largely inherited from the HS, as presented above.

917 **6. Snowmelt hydrology and hydrogeology**

918 Once snowmelt occurs, the snowpack water is channeled through surface outflows
919 and streams, and it undergoes evapotranspiration, subsurface flow and groundwater recharge
920 via deep percolation (e.g., Knowles and Cayan, 2004; Franz et al., 2010; Lundquist and
921 Loheide, 2011; Smith et al., 2013; Manning et al., 2012; Godsey et al., 2014). Given the
922 spatio-temporal variability of the climatic conditions that were highlighted in the previous
923 sections, the closure of the hydrologic budget in Mediterranean snow-dominated basins

924 remains challenging (e.g., Ralph et al., 2016). In addition, several authors point to a limited
925 understanding of surface and sub-surface hydrologic processes in mountains (Bales et al.,
926 2006; Smith et al., 2013).

927 6.1. Snowmelt modeling

928 6.1.1. Snow melt models

929 Different snowmelt models were applied in the Mediterranean context with
930 significantly varying levels of details between the models. Following DeWalle and Rango
931 (2008), these models can be classified under three categories: (1) statistical snowmelt-runoff
932 methods (e.g., Stewart et al., 2005), (2) temperature index or degree day models (TIM/DDM)
933 (e.g., Null et al., 2010), and (3) physically based distributed-snowmelt models or energy
934 balance models (EBM) (e.g., Herrero et al., (2009) in the Spanish Sierra Nevada, Şensoy et
935 al., (2006) in the Karasu basin, Turkey, and Mernild et al. (2016a) in the Andes). The
936 distinction between these boundaries seems to be fading in the literature as there is a
937 tendency towards the use of heterogeneous modeling approaches, and a continuum now
938 exists between the three categories. Martelloni et al., (2013) proposed and tested a modeling
939 scheme, over the Italian Apennines, that is considered as an intermediate approach between
940 temperature index and physically based models. Sproles et al., (2016) used a modified
941 snowmelt runoff model (SRM), which was run using MODIS SCA data, to investigate
942 snowmelt forecasts in the data-poor regions of the Chilean Andes.

943 Major sources of uncertainty in snow melt simulation arise from (1) the error in the
944 input data (particularly precipitation), (2) reliance on DDM (due to limited information on
945 incoming and reflected radiation and fluxes), which usually translates into the lack of
946 accounting of snow sublimation, and (3) the model parameterization regarding rain/snow
947 separation and turbulent fluxes (Franz et al., 2010; He et al., 2011; Raleigh and Lundquist,

948 2012; Slater et al., 2013; Avanzi et al., 2014). Snow model intercomparison studies in
949 Mediterranean mountain regions (Franz et al., 2010; Slater et al., 2013) and elsewhere
950 (Molotch and Margulis, 2008; Essery et al., 2013; Bavera et al., 2014) indicate that while
951 very large differences can exist between models (different melt algorithms), proper
952 simulation of snowmelt is highly associated with the proper parameterization of models (e.g.,
953 Smith et al., 2013) and the model's ability to solve SWE with high confidence (e.g., Franz et
954 al., 2010). To the best of our knowledge the only snow-hydrological model comparison
955 studies, which include Mediterranean catchments, are the studies of Franz et al., (2010) and
956 Valéry et al. (2014a, 2014b). We believe that there is a need for testing and comparing
957 different snow models and carrying out meaningful intercomparison exercises across
958 different Mediterranean mountain regions. The reader is advised to look at model
959 parameterizations and sensitivity (Clark et al., 2011; Garcia et al., 2013), the intercomparison
960 in forested snow regions (e.g., Essery et al., 2009; Rutter et al., 2009), the influence of soil
961 moisture response on snow distribution and melt (Bales et al., 2011; Kerkez et al., 2012;
962 Harpold et al., 2015), single model SRM multi-site comparison (e.g., Martinec and Rango,
963 1986; Seidel and Martinec, 2004; DeWalle and Rango, 2008), ensemble model simulations
964 (e.g., Franz et al., 2010; Essery et al., 2013), and the snow model intercomparison project
965 (MIP) (e.g., DMIP (Smith et al., 2013) and SNOWMIP2 (Essery et al., 2009)).

966 6.1.2. Large-scale land surface models and assimilation techniques

967 The modeling of large-scale distributed cryospheric processes had been made possible
968 through the application of the following: (1) finer scale land surface models with snow
969 schemes (e.g., Boone et al. 2004; Livneh et al., 2010; Brun et al., 2013; Magand et al., 2014;
970 Singh et al., 2015); (2) physically based simulations using mesoscale WRF model (Caldwell
971 et al., 2009; Pavelsky et al., 2011, 2012; Wayand et al., 2013; Liou et al., 2013; Franz et al.,
972 2014; Oaida et al., 2015); (3) blending snow sensor observations and remote sensing data

973 with snowmelt model simulations (e.g., Guan et al. 2013a; Rittger et al., 2016), and using
974 data assimilation (e.g., Franz et al., 2014; Giroto et al., 2014) of ground and remote sensing
975 data with Land Surface Model (Zaitchik and Rodell, 2009; Hancock et al., 2013) and Snow
976 Data Assimilation System (SNODAS) (Guan et al., 2013a; Vuyovich et al., 2014); and (4)
977 reanalysis of ground data (Gottardi et al., 2012; Avanzi et al., 2014), remote sensing data
978 (Margulis et al., 2016), and land surface data (e.g., Durand et al., 2009; Vidal et al., 2010;
979 Rousselot et al., 2012; Rutz et al., 2014).

980 While such techniques can capture large-scale variability in the cryospheric system,
981 most of these techniques are still hindered by (1) limited ground data and dependence on the
982 representativeness of the observation network (e.g., Livneh et al., 2010; Guan et al., 2013a;
983 Balsamo et al., 2015; Dozier et al., 2016); (2) uncertainties in the quality of forcing data
984 (surface meteorological and radiative forcing) (Livneh et al., 2010; Pavelsky et al., 2011;
985 Gottardi et al., 2012; Liou et al., 2013; Guan et al., 2013a); (3) model parameterization and
986 the number of model simplifications of physical phenomena (Livneh et al., 2010); (4)
987 limitations in mountain environments (Gottardi et al., 2012; Wayand et al., 2013; Wrzesien et
988 al., 2015), which are attributed to the downscaling of surface forcing over topographically
989 complex areas (Livneh et al., 2010; Guan et al., 2013a); (5) fSCA data retrieval gaps due to
990 cloud contamination (Guan et al., 2013a); (6) lack in accounting for the spatial variability
991 snow of albedo (Livneh et al., 2010; Guan et al., 2013a); (7) accounting for canopy/forest
992 cover (Livneh et al., 2010; Guan et al., 2013a); and (8) tendency towards reporting earlier
993 snowmelt/depletion (Pavelsky et al., 2011; Wrzesien et al., 2015) and higher biases observed
994 during snow depletion (Wrzesien et al., 2015) ablation seasons (Guan et al., 2013a).

995

996 6.2. Snowmelt contribution to runoff and groundwater

997 While rainfall defines most of the hydrograph shape in the mid to low mountain
998 regions, the streamflow in higher elevation areas (typically above 2000 m a.s.l.) is dominated
999 by snowmelt (López-Moreno and García-Ruiz 2004; Wayand et al., 2013; Jepsen et al.
1000 2016a). In the western US, snowmelt-dominated rivers reach their highest sustained flow
1001 during the spring melt season, whereas rain-dominated rivers achieve their highest sustained
1002 flows during the winter rainy season (Lundquist and Cayan, 2002). Streamflow was estimated
1003 to peak 2-4 weeks earlier in transitional rain-snow-dominated basins compared to snow-
1004 dominated basins (Ashfaq et al., 2013; Liu et al., 2013). Processes controlling the water
1005 transfer through overland, subsurface and groundwater flow are reasonably well understood
1006 (e.g., Jefferson et al., 2008; Tague and Grant, 2009; Smith et al., 2013; Wayand et al., 2013).
1007 However, the effect of the snowpack dynamics on those processes is one of the foremost
1008 challenges in the hydrology of Mediterranean mountains.

1009 6.2.1. Snowmelt runoff

1010 The simulation of the streamflow in snow-dominated Mediterranean regions was
1011 successfully achieved using lumped rainfall-runoff models with a snowmelt routine (e.g.,
1012 Karpouzou et al., 2011), a distributed statistical model that combines remote sensing SCA and
1013 ground observation (e.g., Gómez-Landesa and Rango, 2002; Powell et al., 2011; Akyurek et
1014 al., 2011; Biggs and Whitaker, 2012), and a physically based distributed hydrologic model
1015 that balances both surface energy and water budgets and accounts for snowmelt using
1016 snowpack energy balance routines, such as the variable infiltration capacity (VIC) model
1017 (Maurer et al., 2007) and the Distributed Hydrology Soil Vegetation Model (DHSVM) (e.g.,
1018 Wayand et al., 2013; Cristea et al., 2014). Apart from the modeling approach, the relationship
1019 between snowmelt and streamflow in Mediterranean snow-dominated regions has also been

1020 successfully addressed by the empirical analysis of streamflow data against observed SWE
1021 (Lundquist et al., 2004) and tracer tests (Liu et al., 2013).

1022 There is a global agreement that the total annual runoff volume will decrease, in
1023 regions such as California, under a warming climate (Jepsen et al., 2016a). Changes in snow-
1024 fed streamflow volume are controlled by the (1) annual snow mass (total snowfall) and melt
1025 rates (e.g., Lundquist et al., 2005; Franz and Karsten, 2013; Morán-Tejeda et al., 2014;
1026 Godsey et al., 2014), and (2) subsurface processes (Liu et al., 2013; Jepsen et al., 2016a).
1027 Controls driven by (1) soil moisture and water holding capacity (Costa-Cabral et al., 2013),
1028 (2) vegetation cover (Biggs and Whitaker, 2012; Cristea et al., 2014), (3) evapotranspiration
1029 (Lundquist and Loheide, 2011; Goulden et al., 2012; Godsey et al., 2014), and (4)
1030 groundwater storage (Godsey et al., 2014) are usually site specific and vary depending on soil
1031 type (e.g., soil water holding capacity), and the groundwater storage capacity and flow time
1032 (e.g., the low capacity and faster travel time in Karst). A study carried in a snow–rain
1033 transition mountain region in the Southern Sierra Nevada, California indicated that
1034 streamflow generation is controlled by subsurface flow (average relative contribution to
1035 streamflow discharge was greater than 60%), snowmelt runoff including rain on snow (less
1036 than 40%), and fall storm runoff (less than 7%), whereas soil water in the unsaturated zone
1037 and regional groundwater were not significant contributors to streamflow (Liu et al., 2013).
1038 In the Spanish Pyrenees, using a single multiple regression model, the contribution of
1039 snowpack to spring runoff was estimated to be a 42% for the 1955-2000 period (López-
1040 Moreno and García-Ruiz, 2004). In the Anti Lebanon Mountain, the karst formation has a
1041 short-term influence characterized by an intra-annual patterns of fast spring discharges
1042 (Koeniger et al., 2016).

1043 Regional long-term trends in the snowmelt-generated streamflow in California are
1044 believed to be controlled by long-term decadal changes and spring warming temperature

1045 trends (e.g., Stewart et al., 2005; Maurer et al., 2007). Whereas, the inter-annual variations of
1046 snowmelt and streamflow timing are driven by regional temperature fluctuations and
1047 precipitation anomalies (Stewart et al., 2005). It is clear that temperature and precipitation
1048 alone cannot explain the entire variability in snowmelt onset and streamflow peak timing and
1049 that changes are also influenced by elevation (Maurer et al., 2007; Biggs and Whitaker, 2012;
1050 Wayand et al., 2013) and shifts in snowfall-snowmelt patterns in regions, such as California
1051 (Godsey et al. 2014), and the Spanish Sierra Nevada (Morán-Tejeda et al., 2014). In
1052 Mediterranean regions, a shift in streamflow timing would have profound implications on
1053 water management by reducing the available water resources in late spring and summer when
1054 the precipitation is low (e.g., Stewart et al., 2005; Tanaka et al., 2006; López-Moreno et al.,
1055 2008b; Vicuña et al., 2011). In California, changes in snowmelt and streamflow onset timing,
1056 at the micro- and mesoscale, were found to respond non-linearly to the increase in
1057 temperature (Lundquist and Flint, 2006). Snowmelt-driven streamflow timing, at smaller
1058 scales, is strongly dominated by solar radiation and the combined effect of solar radiation
1059 exposure (a function of aspect, elevation and time of the year) and temperature (a function of
1060 elevation and shading) (Lundquist and Flint, 2006). These results highlight the need to
1061 account for solar radiation, meteorological forcing, and topography when addressing
1062 snowmelt and streamflow responses in Mediterranean-like regions (Wayand et al., 2013).
1063 Diurnal snow-dominated streamflow patterns are also sensitive to the basin size (Lundquist et
1064 al., 2005). At the micro-scale ($< 30 \text{ km}^2$), travel times through the snowpack dominate
1065 streamflow timing, whereas in mesoscale basins ($>200 \text{ km}^2$), streamflow peaks are more
1066 consistent, with little or no variation, due to snowpack heterogeneity and the longer travel
1067 percolation times through deeper snowpacks and stream channels.

1068 6.2.2. Snowpack control on soil moisture and evapotranspiration

1069 The role of the soil water holding capacity in controlling soil moistures and
1070 evapotranspiration is usually site specific (Christensen et al., 2008; Maurer et al., 2010; Bales
1071 et al., 2011; Schlaepfer et al., 2012; Tague and Peng, 2013; Harpold et al., 2015; Jepsen et al.,
1072 2016a, 2016b). The interaction between snowmelt and soil moisture is subject to soil physical
1073 properties (texture) and soil depth (Schlaepfer et al., 2012; Bales et al., 2011; Harpold, 2016).

1074 At present, little information is available on soil water holding capacities at high
1075 elevations (e.g., Christensen et al., 2008; Bales et al., 2011; Costa-Cabral et al., 2013).
1076 Information on the soil water potential and water table depth is useful to explain the runoff
1077 generation processes (Latron and Gallart, 2008). An increase in temperature would not only
1078 reduce the snow accumulation but also increase the soil water storage and evapotranspiration
1079 in snow-dominated basins (Maurer et al., 2010; Tague and Peng, 2013; Wu et al., 2015). The
1080 acquisition of soil moisture data in snow-dominated mountain regions would aid a better
1081 understanding and forecasting snowmelt runoff (Kerkez et al., 2012).

1082 A number of studies investigated evapotranspiration in snow-influenced
1083 Mediterranean mountains, mostly in California Sierra Nevada (Leydecker and Melack, 2000;
1084 Dettinger et al. 2004; Bales et al., 2011; Lundquist and Loheide, 2011; Tague and Peng,
1085 2013; Costa-Cabral et al., 2013; Goulden and Bales, 2014; Jepsen et al., 2016b; Harpold,
1086 2016), Sierra Nevada Spain (Aguilar et al., 2010), and Southern Italy (Senatore et al., 2011).
1087 The interplay between snowmelt and evapotranspiration was most of the time addressed
1088 using modeling approaches that do not explicitly account for snowpack dynamics (e.g.,
1089 Aguilar et al., 2010; Lundquist and Loheide, 2011; Tague and Peng, 2013; Jepsen et al.,
1090 2016a).

1091 In Mediterranean regions, high-elevation areas are usually snowmelt-dominated
1092 whereas lower-regions are evapotranspiration/infiltration-dominated (Lundquist and Cayan,
1093 2002). Evapotranspiration tends to be low during the winter season through the beginning of
1094 the melt season due to the presence of the snow cover and at late summer and autumn due to
1095 soil dryness. During the melt season, the combined effect of increasing air temperatures and
1096 solar radiation tends to accelerate snowmelt, enhance water availability in soil, and increase
1097 surface temperature, which results in increased evapotranspiration (Leydecker and Melack,
1098 2000). The inter-annual evapotranspiration is controlled by elevation and aspect, which
1099 define the amount of incoming solar radiation (Goulden et al., 2012; Lundquist and Loheide,
1100 2011). Evapotranspiration in mid-altitude regions is usually water-limited, i.e., controlled by
1101 the precipitation (Christensen et al., 2008; Lundquist and Loheide, 2011), whereas in higher
1102 snow-dominated regions, it is relatively energy-limited, i.e., it responds more strongly to
1103 temperature variations (Christensen et al., 2008; Lundquist and Loheide, 2011; Schlaepfer et
1104 al., 2012; Godsey et al., 2014; Jepsen et al., 2016a). Based on a number of papers reported in
1105 Jepsen et al., (2016a), the evapotranspiration in Sierra Nevada California under a warming
1106 climate, has an overall tendency to increase (medium confidence) in snow-dominated
1107 regions, and some regions are either susceptible to warming or expected to experience a
1108 slight decrease.

1109 6.2.3. Groundwater recharge

1110 Groundwater studies in Mediterranean mountain are most of the time presented at the
1111 basin scale and they provide little information on the link between snowpack dynamics and
1112 groundwater processes. Groundwater recharge in snow-dominated regions is dominated by
1113 the timing of the snowmelt (early or late spring) and the subsurface flow (Tague and Grant,
1114 2009). In groundwater-dominated watersheds, the aquifer storage and the slow recession can
1115 help in sustaining discharge during the summer dry periods even under a negative yearly

1116 water balance (Jefferson et al., 2008). Despite its importance, the lack of extended studies has
1117 resulted in the availability of negligible information on the extent of snowpack control on
1118 groundwater resources in most Mediterranean mountains (e.g., Palmer et al., 2007; Lowry et
1119 al., 2010, 2011; Liu et al., 2013; Valdés-Pineda et al., 2014). The separation between rain-
1120 fed and snow-fed groundwater recharge is still incomplete due to a number of factors: (1)
1121 lack of groundwater wells and monitoring networks, (2) complex geology especially in karst
1122 regions (e.g., Hartmann et al., 2014; Tobin and Schwartz, 2016), and (3) the complexity of
1123 subsurface flows in mountain regions (e.g., Knowles and Cayan, 2004; Tague and Grant,
1124 2009; Millares et al., 2009; Godsey et al., 2014). A comprehensive review on the different
1125 groundwater mechanisms and the importance of snow in groundwater recharge under
1126 projected warming scenarios over the western US can be found in the work of Meixner et al.,
1127 (2016).

1128 The link between snowmelt and groundwater spring discharge at the mesoscale in
1129 Mediterranean regions was addressed by using hydrochemical analysis. Studies on
1130 experimental snow-influenced micro- to mesoscale basins in Sierra Nevada California
1131 (Taylor et al., 2001; Friedman et al., 2002; Rademacher et al., 2005; Huth et al., 2004; Shaw
1132 et al., 2014), Oregon (Palmer et al., 2007), Serra da Estrela Mountain Portugal (Carreira et
1133 al., 2011), Sierra Nevada Spain (Fernández-Chacón et al., 2010), and the Southern Italian
1134 Alps (Penna et al., 2015) demonstrated the potentials for using stable isotopic analysis for
1135 hydrograph separation between snow-fed, rain-fed and groundwater-fed sources and to
1136 investigate flow paths (Bales et al., 2006), and the evolution of snowmelt (Taylor et al.,
1137 2001). Tracer tests were used to (1) separate between snowmelt runoff (including rain on
1138 snow) (Williams et al., 2001), subsurface flow and fall storm runoff (Liu et al., 2013; Perrot
1139 et al., 2014) and shallow evapotranspired groundwater from groundwater sources (Shaw et
1140 al., 2014), and (2) investigate meltwater-driven surface runoff and catchment transit time

1141 (e.g., McGuire and McDonnell, 2010). General chemical analyses also provided reliable
1142 information on the state of water residence time in springs (Rademacher et al., 2005). The
1143 karst aquifers are of particular relevance in the Mediterranean region since they represent a
1144 key source of freshwater supply for the people living in the Mediterranean basin (Doummar
1145 et al., 2014). The estimation of groundwater recharge from snowmelt in karst regions had
1146 been limited to mid and low latitude micro-scale snow-influenced mountainous regions with
1147 studies in southern Europe Spain (Andreo et al., 2004), Italy (Allocca et al., 2014), Greece
1148 (Novel et al., 2007), and the eastern Mediterranean regions of Mount Lebanon (Bakalowicz et
1149 al., 2007). A pioneering study in the mid-altitude mountain region in Crete showed promise
1150 for simulating the contribution of snowmelt to karst hydrosystems by coupling a karstic
1151 model and an energy balance snow model (Kourgialas et al., 2010).

1152 New opportunities for the separation between SWE, surface water reservoir storage,
1153 soil moisture, ET, and changes in groundwater storage have been made possible using the
1154 GRACE mission (Famiglietti et al., 2011; Scanlon et al., 2012) and finer-resolution land-
1155 surface models (Singh et al., 2015). The use of global position system (GPS) vertical land
1156 motion observations in the California Central Valley (Ouellette et al., 2013; Argus et al.,
1157 2014; Boniface et al., 2015) and Oregon (Fu et al., 2015) seems to show potential for
1158 estimating terrestrial water storage while accounting for snow accumulation and melt. While
1159 these studies are encouraging, they are still limited to the regional scale due to the coarse
1160 resolution of the GRACE observations (approximately 300 km).

1161 **7. Conclusion**

1162 The review of 620 papers published between 1913 and 2016 demonstrated that the
1163 science behind snowpack dynamics (energy and mass fluxes) and hydrological process in
1164 Mediterranean mountain regions is well developed. The number of studies that are dedicated

1165 to the snow in Mediterranean regions also reflects the societal importance of the topic in the
1166 context of climate change, economic development and population growth. The use of
1167 indicators helped in highlighting major snow hydrologic processes in Mediterranean
1168 mountains. In specific areas, such as in identifying major drivers for snowpack dynamics, it
1169 was difficult to draw definitive conclusions given the variety of approaches (e.g., different
1170 major drivers and methods). Our classification of Mediterranean mountains encompasses a
1171 large range of geologic and physiographic conditions. Despite the fact that the theory behind
1172 hydrologic processes in mountains is well established, drawing a common conclusion
1173 remains difficult beyond the case studies because the limited number of studies in this area of
1174 research area and the variety of approaches used (e.g., different models).

1175 Mediterranean snow-influenced regions are marked by a high inter- and intra-annual
1176 climate variability that shapes up most of the hydrologic processes. As a result, the snow
1177 depth, snow density, and snow water equivalent exhibit high inter- and intra-annual variance.
1178 In addition, the snowpack is affected by higher densification rates compared to other climate
1179 regions. The snowpack energy and mass balances are dominated by radiation fluxes, which
1180 account for most of the energy available for melt. The contribution of sensible and latent heat
1181 fluxes to ablation becomes prominent at the end of the snowmelt season. Snow sublimation
1182 is more pronounced in the high-elevation zones, whereas snowmelt dominates the warmer,
1183 low to mid-elevation regions. The role of snow metamorphism (grain size and albedo) on the
1184 melt onset is still an open field of research. There is also room for improving snow mapping
1185 in forests and assessing the impact of absorbed impurities on radiative exchange at the snow
1186 surface. In particular, the snowpack in the Mediterranean basin is exposed to the deposition
1187 of mineral dust from the surrounding desert areas in Middle East and North Africa.

1188 In Mediterranean mountain regions snowmelt are exposed to (1) periods of low
1189 precipitation or high temperature causing “snow drought” (Cooper et al., 2016), (2)

1190 heatwaves, (3) rain on snow events, and (4) and dust deposition on the snowpack. Increasing
1191 air temperatures will lead to a shift in precipitation regime with elevation (i.e., rain to snow
1192 and increase in rain-on-snow events). The dust deposition tends to enhance the snow melt by
1193 increasing the radiative exchange due to the decrease of snow albedo. Understanding
1194 snowmelt sensitivity to these climate variables is of primary importance to improving our
1195 knowledge on the hydrologic processes and water resources system responses in mountain
1196 regions and downstream areas.

1197 In situ networks are often too sparse given the aforementioned spatial variability and
1198 most of the monitoring stations only monitor few meteorological variables needed to solve
1199 the energy budget of the snowpack. The increasing availability of remote sensing data,
1200 especially in the visible domain, has enabled scientific breakthroughs, such as the
1201 reconstruction of the SWE at the mountain scale with a decametric resolution for the last 30
1202 years (Margulis et al., 2016). Limitations associated with passive microwave and radar are
1203 physically linked to the band width and are likely to remain in the near future. Moreover,
1204 airborne techniques (e.g., NASA's ASO (Painter et al., 2016)) are an option for acquiring
1205 highly detailed and direct estimates of HS and SWE once their high operational costs are
1206 reduced.

1207 Data assimilation portability to different regions is hindered by the reliance on larger
1208 data sets as input variables. In regions with limited ground-based observations, model outputs
1209 can be biased by an increased uncertainty. Similarly, the reliance on multiple other
1210 technologies (e.g., ground-based and remote sensing observations) makes the system highly
1211 dependent on the simultaneous availability of data from all systems (Guan et al., 2013a). The
1212 results using reanalysis of remote sensing data (Margulis et al., 2016) and physically based
1213 simulations run using the mesoscale WRF model (e.g., Caldwell et al., 2009; Wayand et al.,
1214 2013) seem to provide better results of SWE in regions with limited station data. One of the

1215 promising areas for research is the development of combined products, which include ground
1216 observations and remotely sensed data through data assimilation in snowpack models.

1217 Conducting snow measurements in less monitored regions such as Lebanon's
1218 mountains and the Atlas Mountains is required, and these investigations can make use of the
1219 extended knowledge gained from other Mediterranean regions. In the meantime, the models
1220 based on climate reanalysis and remote sensing data are more easily transferrable. Snow
1221 density and SWE spatiotemporal variability can be estimated, with an acceptable accuracy,
1222 using a few years of ground observation (e.g., Anderton et al., 2004; Mizukami and Perica,
1223 2008). Maintaining the existing in situ network is critical for monitoring the snowpack
1224 response to climate change. Free access to open software and snow and meteorological data
1225 in the western US has allowed an intense development of the snow science in this region.
1226 This review suggests that a similar open data, open code policy is the path forward for other
1227 Mediterranean regions. Although snow models, hydrological models and land surface models
1228 are increasingly distributed as open source software, data assimilation codes are less
1229 available. There is still need for more collaboration in terms of standardizing and sharing
1230 data. It is important, that snow observations, measurements and analysis are documented and
1231 archived in online snow data repositories (Kinar and Pomeroy, 2015) to serve as a source of
1232 information and provide data that can be used for research purposes and intercomparison
1233 projects.

1234 Advancing our understanding of hydrological processes in Mediterranean mountains
1235 is partly hindered by the sparse meteorological stations and hydrological gauging networks,
1236 and the large uncertainty in key variables, such as the stream flow in headwaters catchments
1237 (Avanzi et al., 2014; Lundquist et al., 2015b; Raleigh et al., 2016). In addition, there remain
1238 challenges in taking advantage of these advances in catchment hydrology because the
1239 response of the streamflow to the snowmelt is modulated by other hydrologic processes (ET,

1240 infiltration, groundwater flow). These processes are more strongly influenced by the
1241 subsurface properties (soil, geology), and hence, they are less easily constrained by current
1242 observational networks, remote sensing and modeling technologies. Closing on the water
1243 balance in Mediterranean mountain regions seems to be only feasible when these processes
1244 are solved simultaneously. Understanding of the connection between snowmelt, streamflow,
1245 evapotranspiration, and groundwater flow in snow-dominated regions is an open field for
1246 future research (e.g., Jefferson et al., 2008; Liu et al., 2013; Godsey et al., 2014; Jepsen et al.,
1247 2016a). Furthermore, there is a need to integrate human processes, such as reservoir
1248 management and irrigation, to investigate the vulnerability of the water resources under
1249 global change scenarios (e.g., Maurer et al., 2007; López-Moreno et al., 2008b; Viviroli et al.,
1250 2011; Anghileri et al., 2016).

1251 Snowpack response to climate variability and change remains one of the critical issues
1252 in Mediterranean mountains that motivated many of the reviewed studies (e.g., Guan et al.,
1253 2012, 2013b). Projected scenarios indicate a marked warming and increased dryness in
1254 Mediterranean regions, which will amplify the transition from a snow-dominated to a rain-
1255 dominated in mid elevation watersheds, and reduce the seasonal SWE and its persistence.
1256 These snow-related changes may have broad implications on evapotranspiration, groundwater
1257 recharge and runoff in many Mediterranean catchments. Mediterranean snow dominated
1258 basins are vulnerable to the increase in temperature and recurring dry periods. The
1259 sustainability of the water system, in the lowland regions, requires better understanding of the
1260 seasonal snow water storage and release as well as the quantification of uncertainties
1261 associated to the projected climate change, population growth, and land-use changes on the
1262 hydrologic responses of mountainous basins (e.g., Barnett et al., 2008; Morán-Tejeda et al.,
1263 2014). These challenges remain partially understood and warrant future research to anticipate
1264 their management in the coming decades.

1265 **8. Acknowledgments**

1266 This publication was made possible through support provided by the French National
1267 Research Institute for Sustainable Development (IRD). We thank the editor and two
1268 anonymous reviewers for their review comments and suggestions that have improved the
1269 presentation of this paper.

1270

1271 **9. References**

- 1272 Aguilar, C., Herrero, J., Polo, M.J., 2010. Topographic effects on solar radiation distribution in
1273 mountainous watersheds and their influence on reference evapotranspiration estimates at watershed
1274 scale. *Hydrology and Earth System Sciences* 14, 2479–2494.
- 1275 Akyurek, Z., Surer, S., Beser, Ö., 2011. Investigation of the snow cover dynamics in the Upper
1276 Euphrates Basin of Turkey using remotely sensed snow cover products and hydrometeorological
1277 data. *Hydrological Processes* 25, 3637–3648.
- 1278 Allocca, V., Manna, F., De Vita, P., 2014. Estimating annual groundwater recharge coefficient for
1279 karst aquifers of the southern Apennines (Italy). *Hydrology and Earth System Sciences* 18, 803–817.
- 1280 Anderton, S., White, S., Alvera, B., 2004. Evaluation of spatial variability in snow water equivalent
1281 for a high mountain catchment. *Hydrological Processes* 18, 435–453.
- 1282 Andreo, B., Liñán, C., Carrasco, F., Cisneros, C., Caballero, F., Mudry, J., 2004. Influence of rainfall
1283 quantity on the isotopic composition (^{18}O and ^2H) of water in mountainous areas. Application for
1284 groundwater research in the Yunquera-Nieves karst aquifers (S Spain). *Appl Geochem* 19, 561–574.
- 1285 Anghileri, D., Voisin, N., Castelletti, A., Pianosi, F., Nijssen, B., Lettenmaier, D., 2016. Value of
1286 long-term streamflow forecasts to reservoir operations for water supply in snow-dominated river
1287 catchments. *Water Resour Res* 52, 4209–4225.
- 1288 Argus, D., Fu, Y., Landerer, F., 2014. Seasonal variation in total water storage in California inferred
1289 from GPS observations of vertical land motion. *Geophys Res Lett* 41, 1971–1980.
- 1290 Armstrong, R.L. and Brun, E., (eds.) 2008. *Snow and Climate. Physical Processes, Surface Energy*
1291 *Exchange and Modeling*. Cambridge University Press. (ISBN-13: 9780521854542) 256 pp.
- 1292 Ashfaq, M., Ghosh, S., Kao, S., Bowling, L., Mote, P., Touma, D., Rauscher, S., Diffenbaugh, N.,
1293 2013. Near-term acceleration of hydroclimatic change in the western U.S. *Journal of Geophysical*
1294 *Research: Atmospheres* 118(19), 10,676–10,693.
- 1295 Avanzi, F., Michele, C., Ghezzi, A., Jommi, C., Pepe, M., 2014. A processing–modeling routine to
1296 use SNOTEL hourly data in snowpack dynamic models. *Advances in Water Resources* 73, 16–29.
- 1297 Ayala, A., McPhee, J., Vargas, X., 2014. Altitudinal gradients, midwinter melt, and wind effects on
1298 snow accumulation in semiarid midlatitude Andes under La Niña conditions. *Water Resources*
1299 *Research* 50, 3589–3594.

- 1300 Bair, E., Dozier, J., Davis, R., Colee, M., Claffey, K., 2015. CUES—a study site for measuring
1301 snowpack energy balance in the Sierra Nevada. *Frontiers in Earth Science*.
1302 <https://doi.org/10.3389/feart.2015.00058>
- 1303 Bakalowicz, M., Hakim, M., El-Hajj, A., 2007. Karst groundwater resources in the countries of
1304 eastern Mediterranean: the example of Lebanon. *Environmental Geology* 54, 597–604.
- 1305 Bales, R. C., Hopmans, J. W., O'Geen, A. T., Meadows, M., Hartsough, P. C., Kirchner, P., Hunsaker,
1306 C. T., Beaudette, D. 2011. Soil moisture response to snowmelt and rainfall in a Sierra Nevada mixed-
1307 conifer forest. *Vadose Zone Journal*, 10(3), 786-799.
- 1308 Bales, R., Molotch, N., Painter, T., Dettinger, M., Rice, R., Dozier, J., 2006. Mountain hydrology of
1309 the western United States. *Water Resources Research* 42 W08432, doi:10.1029/2005WR004387
- 1310 Balsamo, G., Albergel, C., Beljaars, A., Boussetta, S., Brun, E., Cloke, H., Dee, D., Dutra, E., Muñoz-
1311 Sabater, J., Pappenberger, F., de Rosnay, P., Stockdale, T., Vitart, F. 2015. ERA-Interim/Land: a
1312 global land surface reanalysis data set. *Hydrology and Earth System Sciences* 19, 389–407.
- 1313 Barnett, T., Adam, J., Lettenmaier, D., 2005. Potential impacts of a warming climate on water
1314 availability in snow-dominated regions. *Nature* 438, 303–309.
- 1315 Barnett, T., Pierce, D., Hidalgo, H., Bonfils, C., Santer, B., Das, T., Bala, G., Wood, A., Nozawa, T.,
1316 Mirin, A., Cayan, D., Dettinger, M., 2008. Human-Induced Changes in the Hydrology of the Western
1317 United States. *Science* 319, 1080–1083.
- 1318 Bavera, D., Bavay, M., Jonas, T., Lehning, M., Michele, D.C., 2014. A comparison between two
1319 statistical and a physically-based model in snow water equivalent mapping. *Advances in Water*
1320 *Resources* 63, 167–178
- 1321 Beaty, C.B., 1975. Sublimation or Melting: Observations from the White Mountains, California and
1322 Nevada, U.S.A. *Journal of Glaciology* 71, 275-286.
- 1323 Behrangi, A., Guan, B., Neiman, P., Schreier, M., Lambriksen, B., 2016. On the Quantification of
1324 Atmospheric Rivers Precipitation from Space: Composite Assessments and Case Studies over the
1325 Eastern North Pacific Ocean and the Western United States. *Journal of Hydrometeorology* 17, 369–
1326 382.
- 1327 Beniston, M., 2003. Climatic Change in Mountain Regions- A Review of Possible Impacts.pdf.
1328 *Climatic Change* 59, 5–31.
- 1329 Beniston, M., Stoffel, M., 2014. Assessing the impacts of climatic change on mountain water
1330 resources. *Science of The Total Environment* 493, 1129–1137.
- 1331 Berghuijs, W.R., Woods, R.A., Hrachowitz, M., 2014. A precipitation shift from snow towards rain
1332 leads to a decrease in streamflow. *Nature Climate Change* 4, 583–586.
- 1333 Bierkens, M., 2015. Global hydrology 2015: State, trends, and directions. *Water Resources Research*
1334 51, 4923–4947.
- 1335 Biggs, T., Whitaker, T., 2012. Critical elevation zones of snowmelt during peak discharges in a
1336 mountain river basin. *Journal of Hydrology* 438–439, 52–65.
- 1337 Bocchiola, D., Groppelli, B., 2010. Spatial estimation of snow water equivalent at different dates
1338 within the Adamello Park of Italy. *Cold Regions Science and Technology* 63, 97–109.
- 1339 Bocchiola, D., Rosso, R., 2007. The distribution of daily snow water equivalent in the central Italian
1340 Alps. *Advances in Water Resources* 30, 135–147.

- 1341 Bolle, H.J. (Ed.) 2003. Mediterranean Climate: Variability and Trends. Springer, New York. pp. 5–86.
1342 ISBN 978-3-642-55657-9.
- 1343 Bonfils, C., Santer, B., Pierce, D., Hidalgo, H., Bala, G., Das, T., Barnett, T., Cayan, D., Doutriaux,
1344 C., Wood, A., Mirin, A., Nozawa, T., 2008. Detection and Attribution of Temperature Changes in the
1345 Mountainous Western United States. *Journal of Climate* 21, 6404–6424.
- 1346 Boniface, K., Braun, J.J., McCreight, J.L., Nievinski, F.G., 2015. Comparison of Snow Data
1347 Assimilation System with GPS reflectometry snow depth in the Western United States. *Hydrological*
1348 *Processes* 29, 2425–2437.
- 1349 Boone, A., Habets, F., Noilhan, J., Clark, D., Dirmeyer, P., Fox, S., Gusev, Y., Haddeland, I., Koster,
1350 R., Lohmann, D., Mahanama, S., Mitchell, K., Nasonova, O., Niu, GY., Pitman, A., Polcher, J.,
1351 Shmakin, A.B., Tanaka, K., van den Hurk, B., Verant, S., Versegh, D., Viterbo, P., Yang, Z.L., 2004.
1352 The Rhône-aggregation land surface scheme intercomparison project: an overview. *J Clim* 17, 187–
1353 208.
- 1354 Bormann, K., Westra, S., Evans, J., McCabe, M., 2013. Spatial and temporal variability in seasonal
1355 snow density. *Journal of Hydrology* 484, 63–73.
- 1356 Bornmann, L., Mutz, R., 2015. Growth rates of modern science: A bibliometric analysis based on the
1357 number of publications and cited references. *Journal of the Association for Information Science and*
1358 *Technology* 66, 2215–2222.
- 1359 Boudhar, A., Boulet, G., Hanich, L., Sicart, J., Chehbouni, A., 2016. Energy fluxes and melt rate of a
1360 seasonal snow cover in the Moroccan High Atlas. *Hydrological Sciences Journal* 61(5), 931–943.
- 1361 Brown, R., Mote, P., 2009. The Response of Northern Hemisphere Snow Cover to a Changing
1362 Climate. *Journal of Climate* 22, 2124–2145.
- 1363 Brown, R., Petkova, N., 2007. Snow cover variability in Bulgarian mountainous regions, 1931–2000.
1364 *International Journal of Climatology* 27, 1215–1229.
- 1365 Brun, E., Vionnet, V., Boone, A., Decharme, B., Peings, Y., Valette, R., Karbou, F., Morin, S., 2013.
1366 Simulation of Northern Eurasian Local Snow Depth, Mass, and Density Using a Detailed Snowpack
1367 Model and Meteorological Reanalyses. *J Hydrometeorol* 14, 203–219.
- 1368 Buisan, S., Earle, M., Collado, J., Kochendorfer, J., Alastrué, J., Wolff, M., Smith, C. and López–
1369 Moreno, J., 2016. Assessment of the underestimation of snowfall accumulation by tipping bucket
1370 gauges used operationally by the Spanish national weather service. *Atmospheric Measurement*
1371 *Techniques Discussions* 0, 1–22, doi:10.5194/amt-2016-197.
- 1372 Buisan, S., Saz, M., López Moreno, J., 2014. Spatial and temporal variability of winter snow and
1373 precipitation days in the western and central Spanish Pyrenees. *International Journal of Climatology*
1374 35, 259–274.
- 1375 Burns, S., Molotch, N., Williams, M., Knowles, J., Seok, B., Monson, R., Turnipseed, A., Blanken, P.,
1376 2014. Snow Temperature Changes within a Seasonal Snowpack and Their Relationship to Turbulent
1377 Fluxes of Sensible and Latent Heat. *J. Hydrometeorol.* 15(1), 117–142.
- 1378 Caldwell, P., Chin, H.-N., Bader, D., Bala, G., 2009. Evaluation of a WRF dynamical downscaling
1379 simulation over California. *Climatic Change* 95, 499–521.
- 1380 Carreira, P., Marques, J., Marques, J., Chaminé, H., Fonseca, P., Santos, F., Moura, R., Carvalho, J.,
1381 2011. Defining the dynamics of groundwater in Serra da Estrela Mountain area, central Portugal: an
1382 isotopic and hydrogeochemical approach. *Hydrogeology Journal* 19, 117–131.

- 1383 Christensen, L., Tague, C., Baron, J., 2008. Spatial patterns of simulated transpiration response to
1384 climate variability in a snow dominated mountain ecosystem. *Hydrological Processes* 22, 3576–3588.
- 1385 Christy, J., 2012. Searching for Information in 133 Years of California Snowfall Observations. *J*
1386 *Hydrometeorol* 13, 895–912.
- 1387 Church, J.E. 1913. Recent studies of snow in the United States. *Quarterly Journal of the Royal*
1388 *Meteorological Society* 39, 43-52. DOI: 10.1002/qj.49704016905
- 1389 Clark, M., Hendriks, J., Slater, A., Kavetski, D., Anderson, B., Cullen, N., Kerr, T., Hreinsson, E.,
1390 Woods, R., 2011. Representing spatial variability of snow water equivalent in hydrologic and
1391 land-surface models: A review. *Water Resources Research* 47(7), W07539,
1392 doi:10.1029/2011WR010745.
- 1393 Cline, D., Bales, R., Dozier, J., 1998. Estimating the spatial distribution of snow in mountain basins
1394 using remote sensing and energy balance modeling. *Water Resources Research* 34, 1275–1285.
- 1395 Colli, M., Lanza, L., Rasmussen, R., Thériault, J.M., 2015. The collection efficiency of shielded and
1396 unshielded precipitation gauges. Part I: CFD airflow modeling. *J. Hydrometeorol.*, 17, 231–243,
1397 doi:10.1175/JHM-D-15-0010.1.
- 1398 Cooper, M., Nolin, A., Safeeq, M., 2016. Testing the recent snow drought as an analog for climate
1399 warming sensitivity of Cascades snowpacks. *Environmental Research Letters* 11, 084–009.
- 1400 Cornwell, E., Molotch, N., McPhee, J., 2016. Spatio-temporal variability of snow water equivalent in
1401 the extra-tropical Andes Cordillera from distributed energy balance modeling and remotely sensed
1402 snow cover. *Hydrology and Earth System Sciences* 20, 411–430.
- 1403 Cortés, G., Giroto, M., Margulis, S., 2014. Analysis of sub-pixel snow and ice extent over the
1404 extratropical Andes using spectral unmixing of historical Landsat imagery. *Remote Sens Environ* 141,
1405 64–78.
- 1406 Cortés, G., Giroto, M., Margulis, S., 2016. Snow process estimation over the extratropical Andes
1407 using a data assimilation framework integrating MERRA data and Landsat imagery. *Water Resour*
1408 *Res* 52, 2582–2600.
- 1409 Cortés, G., Vargas, X., McPhee, J., 2011. Climatic sensitivity of streamflow timing in the
1410 extratropical western Andes Cordillera. *Journal of Hydrology* 405, 93–109.
- 1411 Costa-Cabral, M., Roy, S., Maurer, E., Mills, W., Chen, L., 2013. Snowpack and runoff response to
1412 climate change in Owens Valley and Mono Lake watersheds. *Climatic Change* 116, 97–109.
- 1413 Cristea, N., Lundquist, J., Loheide, S., Lowry, C., Moore, C., 2014. Modelling how vegetation cover
1414 affects climate change impacts on streamflow timing and magnitude in the snowmelt-dominated
1415 upper Tuolumne Basin, Sierra Nevada. *Hydrological Processes* 28, 3896–3918.
- 1416 Daly, S.F., Davis, R., Ochs, E., Pangburn, T., 2000. An approach to spatially distributed snow
1417 modelling of the Sacramento and San Joaquin basins, California. *Hydrological Processes* 14, 3257–
1418 3271.
- 1419 Danielson, J.J., and Gesch, D.B., 2011. Global multi-resolution terrain elevation data 2010
1420 (GMTED2010): U.S. Geological Survey Open-File Report 2011–1073, 26 p.
- 1421 Das, T., Hidalgo, H.G., Pierce, D.W., Barnett, T.P., Dettinger, M.D., Cayan, D.R., Bonfils, C., Bala,
1422 G., Mirin, A., 2009. Structure and Detectability of Trends in Hydrological Measures over the Western
1423 United States. *Journal of Hydrometeorology* 10, 871–892.

- 1424 de Jong, C. (ed.), David N. Collins D.N., Ranzi, R. (eds.) 2005. *Climate and Hydrology of Mountain*
1425 *Areas*. Wiley. (ISBN: 978-0-470-85814-1) 338 pp.
- 1426 de Jong, C., Güreş, I., Rimmer, A., Shaban, A., Williams, M., 2012. *Mediterranean Mountain*
1427 *Environments* 87–113.
- 1428 Dedieu, J., Lessard-Fontaine, A., Ravazzani, G., Cremonese, E., Shalpykova, G., Beniston, M., 2014.
1429 *Shifting mountain snow patterns in a changing climate from remote sensing retrieval*. *Science of The*
1430 *Total Environment* 493, 1267–1279.
- 1431 Deems, J., Painter, T., Finnegan, D., 2013. *Lidar measurement of snow depth: a review*. *Journal of*
1432 *Glaciology* 59 (13), 467–479.
- 1433 Demaria, E., Maurer, E.P., Sheffield, J., Bustos, E., Poblete, D., Vicuña, S., Meza, F., 2013a. *Using a*
1434 *Gridded Global Dataset to Characterize Regional Hydroclimate in Central Chile*. *Journal of*
1435 *Hydrometeorology* 14, 251–265.
- 1436 Demaria, E., Maurer, E.P., Thrasher, B., Vicuña, S., Meza, F., 2013b. *Climate change impacts on an*
1437 *alpine watershed in Chile: Do new model projections change the story?* *Journal of Hydrology* 502,
1438 128–138.
- 1439 Derin, Y., Anagnostou, E., Berne, A., Borga, M., Boudevillain, B., Buytaert, W., Chang, C.-H.,
1440 Delrieu, G., Hong, Y., Hsu, Y., Lavado-Casimiro, W., Manz, B., Moges, S., Nikolopoulos, E., Sahlou,
1441 D., Salerno, F., Rodríguez-Sánchez, J.-P., Vergara, H., Yilmaz, K., 2016. *Multiregional Satellite*
1442 *Precipitation Products Evaluation over Complex Terrain*. *Journal of Hydrometeorology* 17, 1817–
1443 1836.
- 1444 Dettinger, M., 2014. *Climate change: Impacts in the third dimension*. *Nat Geosci* 7, 166–167.
- 1445 Dettinger, M., Redmond, K., Cayan, D., 2004. *Winter orographic precipitation ratios in the Sierra*
1446 *Nevada-Large-scale atmospheric circulations and hydrologic consequences*. *Journal of*
1447 *Hydrometeorology* 5, 1102–1116.
- 1448 Dettinger, M.D., Cayan, D.R., Meyer, M.K., Jeton, A.E., 2004. *Simulated hydrologic responses to*
1449 *climate variations and change in the Merced, Carson, and American River basins, Sierra Nevada,*
1450 *California, 1900–2099*. *Climatic Change* 62, 283–317.
- 1451 DeWalle, D R, Rango, A. 2008. *Principles of Snow Hydrology*. Cambridge Univ. Press. (ISBN-10:
1452 0511535678) 410 pp.
- 1453 Dietz, A., Kuenzer, C., Gessner, U., Dech, S., 2012. *Remote sensing of snow – a review of available*
1454 *methods*. *International Journal of Remote Sensing* 33, 4094–4134.
- 1455 Diffenbaugh, N., Scherer, M., Ashfaq, M., 2012. *Response of snow-dependent hydrologic extremes to*
1456 *continued global warming*. *Nat Clim Change* 3, 379–384.
- 1457 Doummar, J., Geyer, T., Baierl, M., Nödler, K., Licha, T., Sauter, M., 2014. *Carbamazepine*
1458 *breakthrough as indicator for specific vulnerability of karst springs: Application on the Jeita spring,*
1459 *Lebanon*. *Applied Geochemistry* 47, 150–156.
- 1460 Dozier, J., Bair, E., Davis, R., 2016. *Estimating the spatial distribution of snow water equivalent in*
1461 *the world’s mountains*. *Wiley Interdisciplinary Reviews: Water* 3, 461–474.
- 1462 Dozier, J., Green, R., Nolin, A., Painter, T., 2009. *Interpretation of snow properties from imaging*
1463 *spectrometry*. *Remote Sensing of Environment* 113, S25–S37.

- 1464 Dozier, J., Painter, T., 2004. Multispectral and hyperspectral remote sensing of alpine snow
1465 properties. *Annual Review of Earth and Planetary Sciences* 32, 465–494.
- 1466 Dozier, J., Painter, T., Rittger, K., Frew, J., 2008. Time–space continuity of daily maps of fractional
1467 snow cover and albedo from MODIS. *Advances in Water Resources* 31, 1515–1526.
- 1468 Durand, Y., Giraud, G., Laternser, M., Etchevers, P., Mérindol, L., Lesaffre, B., 2009. Reanalysis of
1469 47 Years of Climate in the French Alps (1958–2005): Climatology and Trends for Snow Cover.
1470 *Journal of Applied Meteorology and Climatology* 48, 2487–2512.
- 1471 Elder, K., Rosenthal, W., Davis, R., 1998. Estimating the spatial distribution of snow water
1472 equivalence in a montane watershed. *Hydrol Process* 12, 1793–1808.
- 1473 Essery, R., Morin, S., Lejeune, Y., Ménard, C., 2013. A comparison of 1701 snow models using
1474 observations from an alpine site. *Advances in Water Resources* 55, 131–148.
- 1475 Essery, R., Rutter, N., Pomeroy, J., Baxter, R., Stähli, M., Gustafsson, D., Barr, A., Bartlett, P., Elder,
1476 K., 2009. SNOWMIP2: An Evaluation of Forest Snow Process Simulations. *B Am Meteorol Soc* 90,
1477 1120–1135.
- 1478 Estévez, J., Gavilán, P., Giráldez, J.V., 2011. Guidelines on validation procedures for meteorological
1479 data from automatic weather stations. *Journal of Hydrology* 402, 144–154.
- 1480 Famiglietti, J.S., Lo, M., Ho, S.J., Bethune, J., Anderson, K.J., Syed, T.H., Swenson, S.C., de Linage,
1481 C.R., Rodell, M., 2011. Satellites measure recent rates of groundwater depletion in California’s
1482 Central Valley. *Geophysical Research Letters* 38(3), L03403. doi:10.1029/2010GL046442
- 1483 Favier, V., Falvey, M., Rabatel, A., Praderio, E., López, D., 2009. Interpreting discrepancies between
1484 discharge and precipitation in high altitude area of Chile’s Norte Chico region (26–32°S). *Water*
1485 *Resources Research* 45(2), W02424. DOI: 10.1029/2008WR006802
- 1486 Fayad, A., Gascoïn, S., Faour, G., Fanise, P., Drapeau, L., Somma, J., Fadel, A., Al Bitar, A.,
1487 Escadafal, R., 2017. Snow observations in Mount-Lebanon (2011–2016). *Earth Syst. Sci. Data*
1488 *Discuss.*, doi:10.5194/essd-2017-3.
- 1489 Fernández-Chacón, F., Benavente, J., Rubio-Campos, J.C., Kohfahl, C., Jiménez, J., Meyer, H.,
1490 Hubberten, H., Pekdeger, A., 2010. Isotopic composition ($\delta^{18}\text{O}$ and δD) of precipitation and
1491 groundwater in a semi-arid, mountainous area (Guadiana Menor basin, Southeast Spain).
1492 *Hydrological Processes* 24, 1343–1356.
- 1493 Filippa, G., Maggioni, M., Zanini, E., Freppaz, M., 2014. Analysis of continuous snow temperature
1494 profiles from automatic weather stations in Aosta Valley (NW Italy): Uncertainties and applications.
1495 *Cold Regions Science and Technology* 104–105, 5462.
- 1496 Foster, J.L., Hall, D.K., Kelly, R., Chiu, L., 2009. Seasonal snow extent and snow mass in South
1497 America using SMMR and SSM/I passive microwave data (1979–2006). *Remote Sensing of*
1498 *Environment* 113, 291–305.
- 1499 Franz, K., Butcher, P., Ajami, N., 2010. Addressing snow model uncertainty for hydrologic
1500 prediction. *Advances in Water Resources* 33, 820–832.
- 1501 Franz, K., Hogue, T., Barik, M., He, M., 2014. Assessment of SWE data assimilation for ensemble
1502 streamflow predictions. *Journal of Hydrology* 519, 2737–2746.
- 1503 Franz, K., Karsten, L., 2013. Calibration of a distributed snow model using MODIS snow covered
1504 area data. *Journal of Hydrology* 494, 160–175.

- 1505 Frei, A., Tedesco, M., Lee, S., Foster, J., Hall, D., Kelly, R., Robinson, D., 2012. A review of global
1506 satellite-derived snow products. *Advances in Space Research* 50, 1007–1029.
- 1507 Friedman, I., Smith, G., Johnson, C., Moscati, R., 2002. Stable isotope compositions of waters in the
1508 Great Basin, United States 2. Modern precipitation. *J Geophys Res Atmospheres* 107, ACL 15–1–
1509 ACL 15–22.
- 1510 Fu, Y., Argus, D., Landerer, F., 2015. GPS as an independent measurement to estimate terrestrial
1511 water storage variations in Washington and Oregon. *Journal of Geophysical Research: Solid Earth*
1512 120, 552–566.
- 1513 Gao, Y., Xie, H., Yao, T., Xue, C., 2010. Integrated assessment on multi-temporal and multi-sensor
1514 combinations for reducing cloud obscuration of MODIS snow cover products of the Pacific Northwest
1515 USA. *Remote Sensing of Environment* 114, 1662–1675.
- 1516 Garcia, E., Tague, C., Choate, J., 2013. Influence of spatial temperature estimation method in
1517 ecohydrologic modeling in the Western Oregon Cascades. *Water Resources Research* 49, 1611–1624.
- 1518 García-Ruiz, J., López-Moreno, I., Vicente-Serrano, S., Lasanta-Martínez, T., Beguería, S., 2011.
1519 Mediterranean water resources in a global change scenario. *Earth-Science Reviews* 105, 121–139.
- 1520 Gascoin, S., Hagolle, O., Huc, M., Jarlan, L., Dejoux, J.-F., Szczypta, C., Marti, R., Sánchez, R. 2015.
1521 A snow cover climatology for the Pyrenees from MODIS snow products. *Hydrol. Earth Syst. Sci.*, 19,
1522 2337–2351.
- 1523 Gascoin, S., Lhermitte, S., Kinnard, C., Bortels, K., Liston, G., 2013. Wind effects on snow cover in
1524 Pascua-Lama, Dry Andes of Chile. *Advances in Water Resources* 55, 25–39.
- 1525 Giorgi, F., 2006. Climate change hot spots. *Geophysical Research Letters* 33, L08707.
1526 doi:10.1029/2006GL025734.
- 1527 Giorgi, F., Lionello, P., 2008. Climate change projections for the Mediterranean region. *Global and*
1528 *Planetary Change* 63, 90–104.
- 1529 Giroto, M., Margulis, S., Durand, M., 2014. Probabilistic SWE reanalysis as a generalization of
1530 deterministic SWE reconstruction techniques. *Hydrological Processes* 28, 3875–3895.
- 1531 Godsey, S.E., Kirchner, J.W., Tague, C.L., 2014. Effects of changes in winter snowpacks on summer
1532 low flows: case studies in the Sierra Nevada, California, USA. *Hydrological Processes* 28, 5048–
1533 5064.
- 1534 Gómez-Landesa, E., Rango, A., 2002. Operational snowmelt runoff forecasting in the Spanish
1535 Pyrenees using the snowmelt runoff model. *Hydrological Processes* 16, 1583–1591.
- 1536 Gottardi, F., Obled, C., Gailhard, J., Paquet, E., 2012. Statistical reanalysis of precipitation fields
1537 based on ground network data and weather patterns: Application over French mountains. *Journal of*
1538 *Hydrology* 432-433, 154–167.
- 1539 Goulden, M., Bales, R., 2014. Mountain runoff vulnerability to increased evapotranspiration with
1540 vegetation expansion. *Proceedings of the National Academy of Sciences* 111, 14071–14075.
- 1541 Goulden, M.L., Anderson, R.G., Bales, R.C., Kelly, A.E., Meadows, M., Winston, G.C., 2012.
1542 Evapotranspiration along an elevation gradient in California's Sierra Nevada. *Journal of Geophysical*
1543 *Research: Biogeosciences* 117(G3), G03028. DOI: 10.1029/2012JG002027
- 1544 Grew, N., 1673. Some Observations Touching the Nature of Snow. *Phil. Trans.* 8, 5193–5196

- 1545 Guan, B., Molotch, N., Waliser, D., Fetzer, E., Neiman, P., 2010. Extreme snowfall events linked to
 1546 atmospheric rivers and surface air temperature via satellite measurements. *Geophysical Research*
 1547 *Letters* 37(20), L20401. DOI: 10.1029/2010GL044696
- 1548 Guan, B., Molotch, N., Waliser, D., Fetzer, E., Neiman, P., 2013a. The 2010/2011 snow season in
 1549 California's Sierra Nevada: Role of atmospheric rivers and modes of large-scale variability. *Water*
 1550 *Resources Research* 49, 6731–6743.
- 1551 Guan, B., Molotch, N., Waliser, D., Jepsen, S., Painter, T., Dozier, J., 2013b. Snow water equivalent
 1552 in the Sierra Nevada: Blending snow sensor observations with snowmelt model simulations. *Water*
 1553 *Resources Research* 49, 5029–5046.
- 1554 Guan, B., Waliser, D., Molotch, N., Fetzer, E., Neiman, P., 2012. Does the Madden–Julian Oscillation
 1555 Influence Wintertime Atmospheric Rivers and Snowpack in the Sierra Nevada? *Monthly Weather*
 1556 *Review* 140, 325–342.
- 1557 Guan, B., Waliser, D., Ralph, M., Fetzer, E., Neiman, P., 2016. Hydrometeorological characteristics
 1558 of rain-on-snow events associated with atmospheric rivers. *Geophysical Research Letters* 43, 2964–
 1559 2973.
- 1560 Hall, D., Riggs, G., Salomonson, V., DiGirolamo, N., Bayr, K., 2002. MODIS snow-cover products.
 1561 *Remote Sens Environ* 83, 181–194.
- 1562 Hamlet, A., Mote, P., Clark, M., Lettenmaier, D., 2005. Effects of Temperature and Precipitation
 1563 Variability on Snowpack Trends in the Western United States. *Journal of Climate* 18, 4545–4561.
- 1564 Hancock, S., Baxter, R., Evans, J., Huntley, B., 2013. Evaluating global snow water equivalent
 1565 products for testing land surface models. *Remote Sensing of Environment* 128, 107–117.
- 1566 Harder, P., and Pomeroy, J., 2013. Estimating precipitation phase using a phycrometric energy
 1567 balance method. *Hydrol. Processes* 27, 1901–1914.
- 1568 Harpold, A., 2016. Diverging sensitivity of soil water stress to changing snowmelt timing in the
 1569 Western U.S. *Advances in Water Resources* 92, 116–129.
- 1570 Harpold, A., Brooks, P., Rajagopal, S., Heidbuchel, I., Jardine, A., Stielstra, C., 2012. Changes in
 1571 snowpack accumulation and ablation in the intermountain west. *Water Resources Research* 48,
 1572 W11501. doi:10.1029/2012WR011949.
- 1573 Harpold, A., Guo, Q., Molotch, N., Brooks, P.D., Bales, R., Fernandez-Diaz, J.C., Musselman, K.N.,
 1574 Swetnam, T.L., Kirchner, P., Meadows, M.W., Flanagan, J., Lucas, R., 2014. LiDAR-derived
 1575 snowpack data sets from mixed conifer forests across the Western United States. *Water Resources*
 1576 *Research* 50, 2749–2755.
- 1577 Harpold, A., Molotch, N., 2015. Sensitivity of soil water availability to changing snowmelt timing in
 1578 the western U.S. *Geophysical Research Letters* 42, 8011–8020.
- 1579 Harpold, A., Molotch, N., Musselman, K., Bales, R., Kirchner, P., Litvak, M., Brooks, P., 2015. Soil
 1580 moisture response to snowmelt timing in mixed-conifer subalpine forests. *Hydrological Processes*
 1581 29, 2782–2798.
- 1582 Harpold, A.A., Kaplan, M.L., Klos, P.Z., Link, T., McNamara, J.P., Rajagopal, S., Schumer, R.,
 1583 Steele, C.M., 2017. Rain or snow: hydrologic processes, observations, prediction, and research needs.
 1584 *Hydrol. Earth Syst. Sci.* 21, 1–22, doi:10.5194/hess-21-1-2017.
- 1585 Hartmann, A., Goldscheider, N., Wagener, T., Lange, J., Weiler, M., 2014. Karst water resources in a
 1586 changing world: Review of hydrological modeling approaches. *Reviews of Geophysics* 52, 218–242.

- 1587 He, M., Hogue, T., Franz, K., Margulis, S., Vrugt, J., 2011. Characterizing parameter sensitivity and
1588 uncertainty for a snow model across hydroclimatic regimes. *Advances in Water Resources* 34, 114–
1589 127.
- 1590 Henn, B., Clark, M., Kavetski, D., Lundquist, J., 2015. Estimating mountain basin mean
1591 precipitation from streamflow using Bayesian inference. *Water Resources Research* 51, 8012–8033.
- 1592 Henn, B., Newman, A.J., Livneh, B., Daly, C., Lundquist, D., 2017. An assessment of differences in
1593 gridded precipitation datasets in complex terrain. *Journal of Hydrology*.
1594 <http://doi.org/10.1016/j.jhydrol.2017.03.008>
- 1595 Herrero, J., Polo, M.J., 2012. Parameterization of atmospheric longwave emissivity in a mountainous
1596 site for all sky conditions. *Hydrology and Earth System Sciences* 16, 3139–3147.
- 1597 Herrero, J., Polo, M.J., Moñino, A., Losada, M.A., 2009. An energy balance snowmelt model in a
1598 Mediterranean site. *Journal of Hydrology* 371, 98–107.
- 1599 Hinkelman, L., Lapo, K., Cristea, N., Lundquist, J., 2015. Using CERES SYN Surface Irradiance
1600 Data as Forcing for Snowmelt Simulation in Complex Terrain. *Journal of Hydrometeorology* 16,
1601 2133–2151.
- 1602 Horel, J., Dong, X., 2010. An Evaluation of the Distribution of Remote Automated Weather Stations
1603 (RAWS). *Journal of Applied Meteorology and Climatology* 49, 1563–1578.
- 1604 Howat, I., Tulaczyk, S., 2005. Climate sensitivity of spring snowpack in the Sierra Nevada. *Journal of*
1605 *Geophysical Research: Earth Surface*, 110(F4), F04021.
- 1606 Hrachowitz, M., Savenije, H.H.G., Blöschl, G., McDonnell, J.J., Sivapalan, M., Pomeroy, J.W.,
1607 Arheimer, B., Blume, T., Clark, M.P., Ehret, U., Fenicia, F., Freer, J.E., Gelfan, A., Gupta, H.V.,
1608 Hughes, D.A., Hut, R.W., Montanari, A., Pande, S., Tetzlaff, D., Troch, P.A., Uhlenbrook, S.,
1609 Wagener, T., Winsemius, H.C., Woods, R.A., Zehe, E., Cudennec, C., 2013. A decade of Predictions
1610 in Ungauged Basins (PUB)—a review. *Hydrological Sciences Journal* 58, 1198–1255.
- 1611 Huber, U.M., Uli M., Bugmann, H., Harald K.M., Reasoner, M., Mel A., (Eds.) 2005. *Global Change*
1612 *and Mountain Regions. An Overview of Current Knowledge*. Springer. (ISBN 978-1-4020-3508-1)
1613 652 pp.
- 1614 Hüsler, F., Jonas, T., Riffler, M., Musial, J., Wunderle, 2014. A satellite-based snow cover climatology
1615 (1985–2011) for the European Alps derived from AVHRR data. *The Cryosphere* 8, 73–90.
- 1616 Huth, A.K., Leydecker, A., Sickman, J.Q., Bales, R., 2004. A two-component hydrograph separation
1617 for three high-elevation catchments in the Sierra Nevada, California. *Hydrological Processes* 18,
1618 1721–1733.
- 1619 Jefferson, A., Nolin, A., Lewis, S., Tague, C., 2008. Hydrogeologic controls on streamflow sensitivity
1620 to climate variation. *Hydrological Processes* 22, 4371–4385.
- 1621 Jepsen, S., Harmon, T., Shi, Y., 2016b. Watershed model calibration to the base flow recession curve
1622 with and without evapotranspiration effects. *Water Resour Res* 52, 2919–2933.
- 1623 Jepsen, S., Molotch, N., Williams, M., Rittger, K., Sickman, J., 2012. Interannual variability of
1624 snowmelt in the Sierra Nevada and Rocky Mountains, United States: Examples from two alpine
1625 watersheds. *Water Resources Research* 48(2), W02529.
- 1626 Jepsen, S.M., Harmon, T.C., Meadows, M.W., Hunsaker, C.T., 2016a. Hydrogeologic influence on
1627 changes in snowmelt runoff with climate warming: Numerical experiments on a mid-elevation
1628 catchment in the Sierra Nevada, USA. *J Hydrol* 533, 332–342.

- 1629 Jin, J., Miller, N., Sorooshian, S., Gao, X., 2006. Relationship between atmospheric circulation and
1630 snowpack in the western USA. *Hydrological Processes* 20, 753–767.
- 1631 Jost, G., Weiler, M., Gluns, D., Alila, Y., 2007. The influence of forest and topography on snow
1632 accumulation and melt at the watershed-scale. *Journal of Hydrology* 347, 101–115.
- 1633 Kapnick, S., Delworth, T., 2013. Controls of Global Snow under a Changed Climate. *Journal of*
1634 *Climate* 26, 5537–5562.
- 1635 Kapnick, S., Hall, A., 2010. Observed Climate–Snowpack Relationships in California and their
1636 Implications for the Future. *Journal of Climate* 23, 3446–3456.
- 1637 Karpouzou, D.K., Baltas, E.A., Kavalieratou, S., Babajimopoulos, C., 2011. A hydrological
1638 investigation using a lumped water balance model: the Aison River Basin case (Greece). *Water and*
1639 *Environment Journal* 25, 297–307.
- 1640 Kenawy, A., Lopez-Moreno, J. I., McCabe, M., Vicente-Serrano, S., 2015. Evaluation of the TMPA-
1641 3B42 precipitation product using a high-density rain gauge network over complex terrain in
1642 northeastern Iberia. *Global and Planetary Change* 133, 188–200.
- 1643 Kerkez, B., Glaser, S., Bales, R., Meadows, M., 2012. Design and performance of a wireless sensor
1644 network for catchment-scale snow and soil moisture measurements. *Water Resources Research* 48,
1645 W09515.
- 1646 Kim, J., Kang, H.-S., 2007. The Impact of the Sierra Nevada on Low-Level Winds and Water Vapor
1647 Transport. *Journal of Hydrometeorology* 8, 790–804.
- 1648 Kinar, N., Pomeroy, J., 2015. Measurement of the physical properties of the snowpack. *Reviews of*
1649 *Geophysics* 53, 481-544. doi:10.1002/2015RG000481.
- 1650 Kirchner, P., Bales, R., Molotch, N., Flanagan, J., Guo, Q., 2014. LiDAR measurement of seasonal
1651 snow accumulation along an elevation gradient in the southern Sierra Nevada, California. *Hydrol*
1652 *Earth Syst Sc* 18, 4261–4275.
- 1653 Knowles, K., Dettinger, M.D., Cayan, D.R., 2006. Trends in Snowfall versus Rainfall in the Western
1654 United States. *Journal of Climate* 19, 4545-4559.
- 1655 Knowles, N., Cayan, D.R., 2004. Elevational dependence of projected hydrologic changes in the San
1656 Francisco estuary and watershed. *Climatic Change* 62(1), 319-336.
- 1657 Koeniger, P., Toll, M., Himmelsbach, T., 2016. Stable isotopes of precipitation and spring waters
1658 reveal an altitude effect in the Anti-Lebanon Mountains, Syria. *Hydrol Process* 30, 2851–2860.
- 1659 Kostadinov, T., Lookingbill, T., 2015. Snow cover variability in a forest ecotone of the Oregon
1660 Cascades via MODIS Terra products. *Remote Sensing of Environment* 164, 155-169.
- 1661 Kotlarski, S., Lüthi, D., Schär, C., 2015. The elevation dependency of 21st century European climate
1662 change: an RCM ensemble perspective. *International Journal of Climatology* 35, 3902–3920.
- 1663 Kottek, M., Grieser, J., Beck, C., Rudolf, B., Rubel, F., 2006. World Map of the Köppen-Geiger
1664 climate classification updated. *Meteorologische Zeitschrift* 15, 259–263.
- 1665 Kourgialas, N., Karatzas, G., Nikolaidis, N., 2010. An integrated framework for the hydrologic
1666 simulation of a complex geomorphological river basin. *Journal of Hydrology* 381, 308–321.
- 1667 Kumar, S., Zwiers, F., Dirmeyer, P., Lawrence, D., Shrestha, R., Werner, A., 2016. Terrestrial
1668 contribution to the heterogeneity in hydrological changes under global warming. *Water Resources*
1669 *Research* 52, 3127–3142.

- 1670 Kyselý, J., Beguería, S., Beranová, R., Gaál, L., López-Moreno, J., 2012. Different patterns of climate
1671 change scenarios for short-term and multi-day precipitation extremes in the Mediterranean. *Global*
1672 *and Planetary Change* 98-99, 63–72.
- 1673 Lapo, K., Hinkelman, L., Raleigh, M., Lundquist, J., 2015. Impact of errors in the downwelling
1674 irradiances on simulations of snow water equivalent, snow surface temperature, and the snow energy
1675 balance. *Water Resources Research* 51(3), 1649–1670.
- 1676 Latron, J., Gallart, F., 2008. Runoff generation processes in a small Mediterranean research catchment
1677 (Vallcebre, Eastern Pyrenees). *Journal of Hydrology* 358, 206–220.
- 1678 Lee, W.-L., Liou, 2012. Effect of absorbing aerosols on snow albedo reduction in the Sierra Nevada.
1679 *Atmospheric Environment* 55, 425–430.
- 1680 Lettenmaier, D., Alsdorf, D., Dozier, J., Huffman, G., Pan, M., Wood, E., 2015. Inroads of remote
1681 sensing into hydrologic science during the WRR era. *Water Resources Research* 51, 7309–7342.
- 1682 Leydecker, A., Melack, J., 2000. Estimating evaporation in seasonally snow-covered catchments in
1683 the Sierra Nevada, California. *Journal of Hydrology* 236, 121–138.
- 1684 Li, D., Durand, M., Margulis, S., 2012. Potential for hydrologic characterization of deep mountain
1685 snowpack via passive microwave remote sensing in the Kern River basin, Sierra Nevada, USA.
1686 *Remote Sensing of Environment* 125, 34–48.
- 1687 Lionello, P., Malanotte-Rizzoli, P., Boscolo, R., Alpert, P., Artale, V., Li, L., Luterbacher, J., May,
1688 W., Trigo, R., Tsimplis, M., Ulbrich, U., Xoplaki, E. (2006). Lionello, P., Malanotte-Rizzoli, P.,
1689 Boscolo, R. (Eds.). *The Mediterranean climate: an overview of the main characteristics and issues.*
1690 *Developments in Earth and Environmental Sciences*.pp. 1-421. ISBN: 978-0-444-52170-5.
- 1691 Liou, K., Gu, Y., Leung, L., Lee, W., Fovell, R., 2013. A WRF simulation of the impact of 3-D
1692 radiative transfer on surface hydrology over the Rocky Mountains and Sierra Nevada. *Atmospheric*
1693 *Chemistry and Physics* 13, 11709–11721.
- 1694 Liston, G. E., 1995: Local advection of momentum, heat, and moisture during the melt of patchy
1695 snow covers. *J. Appl. Meteor.* 34, 1705–1715.
- 1696 Liston, G., Pielke, R., Greene, E., 1999. Improving first-order snow-related deficiencies in a
1697 regional climate model. *Journal of Geophysical Research: Atmospheres* (1984–2012) 104, 19559–
1698 19567.
- 1699 Liu, F., Hunsaker, C., Bales, R., 2013. Controls of streamflow generation in small catchments across
1700 the snow–rain transition in the Southern Sierra Nevada, California. *Hydrological Processes* 27, 1959–
1701 1972.
- 1702 Livneh, B., Xia, Y., Mitchell, K., Ek, M., Lettenmaier, D., 2010. Noah LSM Snow Model Diagnostics
1703 and Enhancements. *J Hydrometeorol* 11, 721–738.
- 1704 Loarie, S., Duffy, P., Hamilton, H., Asner, G., Field, C., Ackerly, D., 2009. The velocity of climate
1705 change. *Nature* 462, 1052–1055.
- 1706 López-Moreno, J.I., 2005. Recent variations of snowpack depth in the Central Spanish Pyrenees.
1707 *Arctic Antarctic and Alpine Research* 37, 253–260.
- 1708 López-Moreno, J.I., Beniston, M., García-Ruiz, J.M., 2008a. Environmental change and water
1709 management in the Pyrenees: Facts and future perspectives for Mediterranean mountains. *Global and*
1710 *Planetary Change* 61, 300–312.

- 1711 López-Moreno, J.I., Fassnacht, S.R., Beguería, S., Latron, J., 2011b. Variability of snow depth at the
1712 plot scale: implications for mean depth estimation and sampling strategies. *The Cryosphere* 5, 617–
1713 629.
- 1714 López-Moreno, J.I., Fassnacht, S.R., Heath, J.T., Musselman, K.N., Revuelto, J., Latron, J., Morán-
1715 Tejada, E., Jonas, T., 2013a. Small scale spatial variability of snow density and depth over complex
1716 alpine terrain: Implications for estimating snow water equivalent. *Advances in Water Resources* 55,
1717 40–52.
- 1718 López-Moreno, J.I., García-Ruiz, J., 2004. Influence of snow accumulation and snowmelt on
1719 streamflow in the central Spanish Pyrenees / Influence de l'accumulation et de la fonte de la neige sur
1720 les écoulements dans les Pyrénées centrales espagnoles. *Hydrological Sciences Journal* 49.
- 1721 López-Moreno, J.I., Goyette, S., Beniston, M., Alvera, B., 2008b. Sensitivity of the snow energy
1722 balance to climatic changes: prediction of snowpack in the Pyrenees in the 21st century. *Climate*
1723 *Research* 36, 203–217.
- 1724 López-Moreno, J.I., Latron, J., 2008. Influence of canopy density on snow distribution in a temperate
1725 mountain range. *Hydrological Processes* 22, 117–126.
- 1726 López-Moreno, J.I., Latron, J., Lehmann, A., 2010. Effects of sample and grid size on the accuracy
1727 and stability of regression based snow interpolation methods. *Hydrological Processes* 24, 1914–1928.
- 1728 López-Moreno, J.I., Nogués-Bravo, D., 2005. A generalized additive model for the spatial
1729 distribution of snowpack in the Spanish Pyrenees. *Hydrological Processes* 19, 3167–3176.
- 1730 López-Moreno, J.I., Nogués-Bravo, D., 2006. Interpolating local snow depth data: an evaluation of
1731 methods. *Hydrological Processes* 20, 2217–2232.
- 1732 López-Moreno, J.I., Pomeroy, J., Revuelto, J., Vicente-Serrano, S., 2012. Response of snow
1733 processes to climate change: spatial variability in a small basin in the Spanish Pyrenees. *Hydrological*
1734 *Processes* 27, 2637–2650.
- 1735 López-Moreno, J.I., Revuelto, J., Fassnacht, S., Azorín-Molina, C., Vicente-Serrano, S.,
1736 Morán-Tejada, E., Sexstone, G., 2015. Snowpack variability across various spatio-temporal
1737 resolutions. *Hydrological Processes* 29, 1213–1224.
- 1738 López-Moreno, J.I., Vicente-Serrano, S.M., Morán-Tejada, E., Lorenzo-Lacruz, J., Kenawy, A.,
1739 Beniston, M., 2011a. Effects of the North Atlantic Oscillation (NAO) on combined temperature and
1740 precipitation winter modes in the Mediterranean mountains: observed relationships and projections for
1741 the 21st century. *Global and Planetary Change* 77 (1-2), 62–76
- 1742 López-Moreno, J.I., Vicente-Serrano, S.M., Zabalza, J., Beguería, S., Lorenzo-Lacruz, J., Azorin-
1743 Molina, C., Morán-Tejada, E., 2013b. Hydrological response to climate variability at different time
1744 scales: A study in the Ebro basin. *Journal of Hydrology* 477, 175–188.
- 1745 López-Moreno, J.I., Zabalza, J., Vicente-Serrano, S.M., Revuelto, J., Gilaberte, M., Azorin-Molina,
1746 C., Morán-Tejada, E., García-Ruiz, J.M., Tague, C., 2014. Impact of climate and land use change on
1747 water availability and reservoir management: Scenarios in the Upper Aragón River, Spanish Pyrenees.
1748 *Science of The Total Environment* 493, 1222–1231.
- 1749 Lowry, C., Deems, J., Steven, L., Lundquist, J., 2010. Linking snowmelt-derived fluxes and
1750 groundwater flow in a high elevation meadow system, Sierra Nevada Mountains, California.
1751 *Hydrological Processes* 24, 2821–2833.

- 1752 Lowry, C., Loheide, S., Moore, C., Lundquist, J., 2011. Groundwater controls on vegetation
1753 composition and patterning in mountain meadows. *Water Resources Research* 47, W00J11.
- 1754 Luce, C., Lopez-Burgos, V., Holden, Z., 2014. Sensitivity of snowpack storage to precipitation and
1755 temperature using spatial and temporal analog models. *Water Resour Res* 50, 9447–9462.
- 1756 Lundquist, J., Cayan, D., 2002. Seasonal and spatial patterns in diurnal cycles in streamflow in the
1757 western United States. *J Hydrometeorol* 3, 591–603.
- 1758 Lundquist, J., Dettinger, M., Cayan, D., 2005. Snow-fed streamflow timing at different basin scales:
1759 Case study of the Tuolumne River above Hetch Hetchy, Yosemite, California. *Water Resources*
1760 *Research* 41(7), W07005.
- 1761 Lundquist, J., Dickerson-Lange, S., Lutz, J., Cristea, N., 2013. Lower forest density enhances snow
1762 retention in regions with warmer winters: A global framework developed from plot-scale
1763 observations and modeling. *Water Resour Res* 49, 6356–6370.
- 1764 Lundquist, J., Flint, A., 2006. Onset of snowmelt and streamflow in 2004 in the western United
1765 States: How shading may affect spring streamflow timing in a warmer world. *J Hydrometeorol* 7,
1766 1199–1217.
- 1767 Lundquist, J., Hughes, M., Henn, B., Gutmann, E., Livneh, B., Dozier, J., Neiman, P., 2015a. High-
1768 Elevation Precipitation Patterns: Using Snow Measurements to Assess Daily Gridded Datasets across
1769 the Sierra Nevada, California. *J Hydrometeorol* 16, 1773–1792.
- 1770 Lundquist, J., Loheide, S., 2011. How evaporative water losses vary between wet and dry water years
1771 as a function of elevation in the Sierra Nevada, California, and critical factors for modeling. *Water*
1772 *Resources Research* 47, W00H09.
- 1773 Lundquist, J., Minder, J., Neiman, P., Sukovich, E., 2010. Relationships between Barrier Jet Heights,
1774 Orographic Precipitation Gradients, and Streamflow in the Northern Sierra Nevada. *Journal of*
1775 *Hydrometeorology* 11, 1141–1156.
- 1776 Lundquist, J., Wayand, N., Massmann, A., Clark, M., Lott, F., Cristea, N., 2015b. Diagnosis of
1777 insidious data disasters. *Water Resources Research* 51, 3815–3827.
- 1778 Lundquist, J.D., Cayan, D.R., Dettinger, M.D., 2004. Spring Onset in the Sierra Nevada: When Is
1779 Snowmelt Independent of Elevation? *Journal of Hydrometeorology* 5, 327–342.
- 1780 Lute, A., Abatzoglou, J., 2014. Role of extreme snowfall events in interannual variability of snowfall
1781 accumulation in the western United States. *Water Resources Research* 50, 2874–2888.
- 1782 Magand, C., Ducharne, A., Le Moine, N., Gascoïn, S., 2014. Introducing Hysteresis in Snow
1783 Depletion Curves to Improve the Water Budget of a Land Surface Model in an Alpine Catchment.
1784 *Journal of Hydrometeorology* 15, 631–649.
- 1785 Luce, C., Tarboton, D., 2004. The application of depletion curves for parameterization of subgrid
1786 variability of snow. *Hydrol. Process.* 18, 1409–1422.
- 1787 Magand, C., Ducharne, A., Moine, N., Gascoïn, S., 2014. Introducing Hysteresis in Snow Depletion
1788 Curves to Improve the Water Budget of a Land Surface Model in an Alpine Catchment. *Journal of*
1789 *Hydrometeorology* 15, 631–649.
- 1790 Manning, A., Clark, J., Diaz, S., Rademacher, L., Earman, S., Plummer, N., 2012. Evolution of
1791 groundwater age in a mountain watershed over a period of thirteen years. *Journal of Hydrology* 460-
1792 461, 13–28.

- 1793 Marchane, A., Jarlan, L., Hanich, L., Boudhar, A., Gascoïn, S., Tavernier, A., Filali, N., le Page, M.,
 1794 Hagolle, O., Berjamy, B., 2015. Assessment of daily MODIS snow cover products to monitor snow
 1795 cover dynamics over the Moroccan Atlas mountain range. *Remote Sensing of Environment* 160, 72–
 1796 86.
- 1797 Margulis, S., Cortés, G., Giroto, M., Durand, M., 2016. A Landsat-Era Sierra Nevada Snow
 1798 Reanalysis (1985–2015). *J Hydrometeorol* 17, 1203–1221.
- 1799 Marks, D., Dozier, J., 1992. Climate and energy exchange at the snow surface in the Alpine Region of
 1800 the Sierra Nevada: 2. Snow cover energy balance. *Water Resources Research* 28, 3043–3054.
- 1801 Marks, D., Dozier, J., Davis, R., 1992. Climate and energy exchange at the snow surface in the Alpine
 1802 Region of the Sierra Nevada: 1. Meteorological measurements and monitoring. *Water Resources*
 1803 *Research* 28, 3029–3042.
- 1804 Marks, D., Winstral, A., Reba, M., Pomeroy, J., and Kumar, M., 2013. An evaluation of methods for
 1805 determining during-storm precipitation phase and the rain/snow transition elevation at the surface in a
 1806 mountain basin. *Adv. Water Resour.*, 55, 98–110.
- 1807 Martelloni, G., Segoni, S., Lagomarsino, D., Fanti, R., Catani, F., 2013. Snow accumulation/melting
 1808 model (SAMM) for integrated use in regional scale landslide early warning systems. *Hydrology and*
 1809 *Earth System Sciences* 17, 1229–1240.
- 1810 Marti, R., Gascoïn, S., Berthier, E., de Pinel, M., Houet, T., Laffly, D., 2016. Mapping snow depth in
 1811 open alpine terrain from stereo satellite imagery. *The Cryosphere Discussions* 1–36.
- 1812 Martinec, J., Rango, A., 1986. Parameter values for snowmelt runoff modelling. *Journal of Hydrology*
 1813 84, 197–219.
- 1814 Martinec, J.M., 1975. Snowmelt runoff model for stream flow forecasts. *Nordic Hydrology*, 6 (3)
 1815 145–154.
- 1816 Masiokas, M., Villalba, R., Luckman, B., Quesne, C., Aravena, J., 2006. Snowpack Variations in the
 1817 Central Andes of Argentina and Chile, 1951–2005: Large-Scale Atmospheric Influences and
 1818 Implications for Water Resources in the Region. *Journal of Climate* 19, 6334–6352.
- 1819 Maurer, E., Brekke, L., Pruitt, T., 2010. Contrasting Lumped and Distributed Hydrology Models for
 1820 Estimating Climate Change Impacts on California Watersheds I. *JAWRA Journal of the American*
 1821 *Water Resources Association* 46, 1024–1035.
- 1822 Maurer, E.P., Stewart, I.T., Bonfils, C., Duffy, P., Cayan, D., 2007. Detection, attribution, and
 1823 sensitivity of trends toward earlier streamflow in the Sierra Nevada. *Journal of Geophysical Research:*
 1824 *Atmospheres* (1984–2012) 112.
- 1825 Mazurkiewicz, A., Callery, D., McDonnell, J., 2008. Assessing the controls of the snow energy
 1826 balance and water available for runoff in a rain-on-snow environment. *Journal of Hydrology* 354(1-4),
 1827 1-14.
- 1828 McCabe, G., Hay, L., Clark, M., 2007. Rain-on-Snow Events in the Western United States. *Bulletin*
 1829 *of the American Meteorological Society* 88, 319–328.
- 1830 McGuire, K., McDonnell, J. 2010. Hydrological connectivity of hillslopes and streams: Characteristic
 1831 time scales and nonlinearities. *Water Resources Research* 46, W10543, doi:10.1029/2010WR009341.
- 1832 Meixner, T., Manning, A., Stonestrom, D., Allen, D., Ajami, H., Blasch, K., Brookfield, A., Castro,
 1833 C., Clark, J., Gochis, D., Flint, A., Neff, K., Niraula, R., Rodell, M., Scanlon, B., Singha, K.,

- 1834 Walvoord, M., 2016. Implications of projected climate change for groundwater recharge in the
1835 western United States. *Journal of Hydrology* 534, 124–138.
- 1836 Mernild, S., Liston, G., Hiemstra, C., Malmros, J., Yde, J., McPhee, J., 2016a. The Andes Cordillera.
1837 Part I: snow distribution, properties, and trends (1979–2014). *International Journal of Climatology*
1838 37(4), 1680–1698.
- 1839 Mernild, S., Liston, G., Hiemstra, C., Yde, J., McPhee, J., Malmros, J., 2016b. The Andes Cordillera.
1840 Part II: Rio Olivares Basin snow conditions (1979–2014), central Chile. *International Journal of*
1841 *Climatology* 37(4), 1699–1715.
- 1842 Meromy, L., Molotch, N., Link, T., Fassnacht, S., Rice, R., 2013. Subgrid variability of snow water
1843 equivalent at operational snow stations in the western USA. *Hydrological Processes* 27, 2383–2400.
- 1844 Mhawej, M., Faour, G., Fayad, A., Shaban, A., 2014. Towards an enhanced method to map snow
1845 cover areas and derive snow-water equivalent in Lebanon. *Journal of Hydrology* 513, 274–282.
- 1846 Millares, A., Polo, M.J., Losada, M.A., 2009. The hydrological response of baseflow in fractured
1847 mountain areas. *Hydrology and Earth System Sciences* 13, 1261–1271.
- 1848 Milly, P., Dunne, K., Vecchia, A., 2005. Global pattern of trends in streamflow and water availability
1849 in a changing climate. *Nature* 438, 347–50.
- 1850 Mizukami, N., Perica, S., 2008. Spatiotemporal Characteristics of Snowpack Density in the
1851 Mountainous Regions of the Western United States. *Journal of Hydrometeorology* 9, 1416–1426.
- 1852 Mizukami, N., Perica, S., Hatch, D., 2011. Regional approach for mapping climatological snow water
1853 equivalent over the mountainous regions of the western United States. *Journal of Hydrology* 400, 72–
1854 82.
- 1855 Mizukami, N., Smith, M., 2012. Analysis of inconsistencies in multi-year gridded quantitative
1856 precipitation estimate over complex terrain and its impact on hydrologic modeling. *Journal of*
1857 *Hydrology* 428–429, 129–141.
- 1858 Molotch, N., Bales, R., 2006. Comparison of ground-based and airborne snow surface albedo
1859 parameterizations in an alpine watershed: Impact on snowpack mass balance. *Water Resources*
1860 *Research* 42(5), W05410.
- 1861 Molotch, N., Colee, M., Bales, R., Dozier, J., 2005. Estimating the spatial distribution of snow water
1862 equivalent in an alpine basin using binary regression tree models: the impact of digital elevation data
1863 and independent variable selection. *Hydrological Processes* 19, 1459–1479.
- 1864 Molotch, N., Margulis, S., 2008. Estimating the distribution of snow water equivalent using remotely
1865 sensed snow cover data and a spatially distributed snowmelt model: A multi-resolution, multi-sensor
1866 comparison. *Advances in Water Resources* 31, 1503–1514.
- 1867 Molotch, N., Meromy, L., 2014. Physiographic and climatic controls on snow cover persistence in the
1868 Sierra Nevada Mountains. *Hydrological Processes* 28, 4573–4586.
- 1869 Morán-Tejeda, E., Ceballos-Barbancho, A., Llorente-Pinto, J., 2010. Hydrological response of
1870 Mediterranean headwaters to climate oscillations and land-cover changes: The mountains of Duero
1871 River basin (Central Spain). *Global and Planetary Change* 72, 39–49.
- 1872 Morán-Tejeda, E., Lorenzo-Lacruz, J., López-Moreno, J., Rahman, K., Beniston, M., 2014.
1873 Streamflow timing of mountain rivers in Spain: Recent changes and future projections. *Journal of*
1874 *Hydrology* 517, 1114–1127.

- 1875 Mote, P., 2003. Trends in snow water equivalent in the Pacific Northwest and their climatic causes.
1876 *Geophysical Research Letters* 30.
- 1877 Mote, P., 2006. Climate-driven variability and trends in mountain snowpack in Western North
1878 America. *Journal of Climate* 19, 6209–6220.
- 1879 Mote, P., Hamlet, A., Clark, M., Lettenmaier, D., 2005. Declining mountain snowpack in western
1880 North America. *Bulletin of the American Meteorological Society* 86, 39–49.
- 1881 Musselman, K., Molotch, N., Margulis, S., Kirchner, P., Bales, R., 2012. Influence of canopy
1882 structure and direct beam solar irradiance on snowmelt rates in a mixed conifer forest. *Agricultural
1883 and Forest Meteorology* 161, 46–56.
- 1884 Neiman, P., Ralph, M., Moore, B., Zamora, R., 2014. The Regional Influence of an Intense Sierra
1885 Barrier Jet and Landfalling Atmospheric River on Orographic Precipitation in Northern California: A
1886 Case Study. *Journal of Hydrometeorology* 15, 1419–1439.
- 1887 Nogués-Bravo, D., Araújo, M., Errea, M., Martínez-Rica, J., 2007. Exposure of global mountain
1888 systems to climate warming during the 21st Century. *Global Environmental Change* 17, 420–428.
- 1889 Nohara, D., Kitoh, A., Hosaka, M., Oki, T., 2006. Impact of Climate Change on River Discharge
1890 Projected by Multimodel Ensemble. *Journal of Hydrometeorology* 7, 1076–1089.
- 1891 Novel, J.P., Dimadi, A., Zervopoulou, A., Bakalowicz, M., 2007. The Aggitis karst system, Eastern
1892 Macedonia, Greece: Hydrologic functioning and development of the karst structure. *Journal of
1893 Hydrology* 334, 477–492.
- 1894 Null, S., Viers, J., Mount, J., 2010. Hydrologic Response and Watershed Sensitivity to Climate
1895 Warming in California's Sierra Nevada. *PLoS One* 5 (4), e9932.
- 1896 Núñez, J., Rivera, D., Oyarzún, R., Arumí, J.L., 2013. Influence of Pacific Ocean multidecadal
1897 variability on the distributional properties of hydrological variables in north-central Chile. *Journal of
1898 Hydrology* 501, 227–240.
- 1899 Oaida, C., Xue, Y., Flanner, M., Skiles, M., Sales, F., Painter, T., 2015. Improving snow albedo
1900 processes in WRF/SSiB regional climate model to assess impact of dust and black carbon in snow on
1901 surface energy balance and hydrology over western U.S. *Journal of Geophysical Research:
1902 Atmospheres* 120, 3228–3248.
- 1903 Ouellette, K., Linage, C., Famiglietti, J., 2013. Estimating snow water equivalent from GPS vertical
1904 site position observations in the western United States. *Water Resources Research* 49, 2508–2518.
- 1905 Pagán, B., Ashfaq, M., Rastogi, D., Kendall, D., Kao, S.-C., Naz, B., Mei, R., Pal, J., 2016. Extreme
1906 hydrological changes in the southwestern US drive reductions in water supply to Southern California
1907 by mid century. *Environmental Research Letters* 11, 094026.
- 1908 Painter, T., Berisford, D., Boardman, J., Bormann, K., Deems, J., Gehrke, F., Hedrick, A., Joyce, M.,
1909 Laidlaw, R., Marks, D., Mattmann, C., McGurk, B., Ramirez, P., Richardson, M., Skiles, S., Seidel,
1910 F., Winstral, A., 2016. The Airborne Snow Observatory: Fusion of scanning lidar, imaging
1911 spectrometer, and physically-based modeling for mapping snow water equivalent and snow albedo.
1912 *Remote Sens Environ* 184, 139–152.
- 1913 Painter, T., Dozier, J., Roberts, D., Davis, R., Green, R., 2003. Retrieval of subpixel snow-covered
1914 area and grain size from imaging spectrometer data. *Remote Sensing of Environment* 85, 64–77.

- 1915 Painter, T., Rittger, K., McKenzie, C., Slaughter, P., Davis, R., Dozier, J., 2009. Retrieval of subpixel
 1916 snow covered area, grain size, and albedo from MODIS. *Remote Sensing of Environment* 113, 868–
 1917 879.
- 1918 Palmer, C., Gannett, M., Hinkle, S., 2007. Isotopic characterization of three groundwater recharge
 1919 sources and inferences for selected aquifers in the upper Klamath Basin of Oregon and California,
 1920 USA. *Journal of Hydrology* 336, 17–29.
- 1921 Pan, X., Yang, D., Li, Y., Barr, A., Helgason, W., Hayashi, M., Marsh, P., Pomeroy, J., and Janowicz,
 1922 R. J., 2016. Bias corrections of precipitation measurements across experimental sites in different
 1923 ecoclimatic regions of western Canada. *The Cryosphere*, 10, 2347-2360, doi:10.5194/tc-10-2347-
 1924 2016.
- 1925 Pavelsky, T., Kapnick, S., Hall, A., 2011. Accumulation and melt dynamics of snowpack from a
 1926 multiresolution regional climate model in the central Sierra Nevada, California. *Journal of*
 1927 *Geophysical Research: Atmospheres* (1984–2012) 116.
- 1928 Pavelsky, T., Sobolowski, S., Kapnick, S., Barnes, J., 2012. Changes in orographic precipitation
 1929 patterns caused by a shift from snow to rain. *Geophysical Research Letters* 39.
- 1930 Penna, D., van Meerveld, H.J., Oliviero, O., Zuecco, G., Assendelft, R.S., Dalla Fontana, G., Borga,
 1931 M., 2015. Seasonal changes in runoff generation in a small forested mountain catchment.
 1932 *Hydrological Processes* 29, 2027–2042.
- 1933 Pepin, N., Bradley, R.S, Diaz, H.F., Baraer, M., Caceres, E., Forsythe, N., Fowler, H., Greenwood,
 1934 G., Hashmi, M., Liu, X., Miller, J., Ning, L., Ohmura, A., Palazzi, E., Rangwala, I., Schöner, W.,
 1935 Severskiy, I., Shahgedanova, M., Wang, M., Williamson, S., Yang, D., 2015. Elevation-dependent
 1936 warming in mountain regions of the world. *Nature Climate Change* 5, 424–430.
- 1937 Perrot, D., Molotch, N., Williams, M., Jepsen, S., Sickman, J., 2014. Relationships between stream
 1938 nitrate concentration and spatially distributed snowmelt in high elevation catchments of the western
 1939 U.S. *Water Resources Research* 50, 8694–8713.
- 1940 Pierce, D., Barnett, T., Hidalgo, H., Das, T., Bonfils, C., Santer, B., Bala, G., Dettinger, M., Cayan,
 1941 D., Mirin, A., Wood, A., Nozawa, T., 2008. Attribution of Declining Western U.S. Snowpack to
 1942 Human Effects. *Journal of Climate* 21, 6425–6444.
- 1943 Pimentel, R., Aguilar, C., Herrero, J., Pérez-Palazón, M., Polo, M., 2016. Comparison between Snow
 1944 Albedo Obtained from Landsat TM, ETM+ Imagery and the SPOT VEGETATION Albedo Product
 1945 in a Mediterranean Mountainous Site. *Hydrology* 3(1), 10; doi:10.3390/hydrology3010010.
- 1946 Pimentel, R., Herrero, J., Zeng, Y., Su, Z., Polo, M., 2015. Study of Snow Dynamics at Subgrid Scale
 1947 in Semiarid Environments Combining Terrestrial Photography and Data Assimilation Techniques.
 1948 *Journal of Hydrometeorology* 16, 563–578.
- 1949 Powell, C., Blesius, L., Davis, J., Schuetzenmeister, F., 2011. Using MODIS snow cover and
 1950 precipitation data to model water runoff for the Mokelumne River Basin in the Sierra Nevada,
 1951 California (2000–2009). *Global and Planetary Change* 77, 77–84.
- 1952 Prudhomme, C., Giuntoli, I., Robinson, E., Clark, D., Arnell, N., Dankers, R., Fekete, B., Franssen,
 1953 W., Gerten, D., Gosling, S., Hagemann, S., Hannah, D., Kim, H., Masaki, Y., Satoh, Y., Stacke, T.,
 1954 Wada, Y., Wisser, D., 2014. Hydrological droughts in the 21st century, hotspots and uncertainties
 1955 from a global multimodel ensemble experiment. *Proceedings of the National Academy of Sciences*
 1956 111, 3262–3267.

- 1957 Quéno, L., Vionnet, V., Dombrowski-Etchevers, I., Lafaysse, M., Dumont, M., Karbou, F., 2016.
 1958 Snowpack modelling in the Pyrenees driven by kilometric-resolution meteorological forecasts.
 1959 Cryosphere 10, 1571–1589.
- 1960 Rademacher, L., Clark, J., Clow, D., Hudson, B., 2005. Old groundwater influence on stream
 1961 hydrochemistry and catchment response times in a small Sierra Nevada catchment: Sagehen Creek,
 1962 California. *Water Resources Research* 41(2), W02004.
- 1963 Raleigh, M., Livneh, B., Lapo, K., Lundquist, J., 2016. How Does Availability of Meteorological
 1964 Forcing Data Impact Physically Based Snowpack Simulations?. *Journal of Hydrometeorology* 17, 99–
 1965 120.
- 1966 Raleigh, M., Lundquist, J., 2012. Comparing and combining SWE estimates from the SNOW-17
 1967 model using PRISM and SWE reconstruction. *Water Resources Research* 48(1), W01506.
- 1968 Raleigh, M., Rittger, K., Moore, C., Henn, B., Lutz, J., Lundquist, J., 2013. Ground-based testing of
 1969 MODIS fractional snow cover in subalpine meadows and forests of the Sierra Nevada. *Remote
 1970 Sensing of Environment* 128, 44–57.
- 1971 Ralph, F., Prather, K., Cayan, D., Spackman, J.R., DeMott, P., Dettinger, M., Fairall, C., Leung, R.,
 1972 Rosenfeld, D., Rutledge, S., Waliser, D., White, A., Cordeira, J., Martin, A., Helly, J., Intrieri, J.,
 1973 2016. CalWater Field Studies Designed to Quantify the Roles of Atmospheric Rivers and Aerosols in
 1974 Modulating U.S. West Coast Precipitation in a Changing Climate. *B Am Meteorol Soc* 97, 1209–
 1975 1228.
- 1976 Rasmussen, R., Baker, B., Kochendorfer, J., Meyers, T., Landolt, S., Fischer, A. P., Black, J.,
 1977 Theriault, J. M., Kucera, P., Gochis, D., Smith, C., Nitu, R., Hall, M., Ikeda, K., Gutmann, E., 2012.
 1978 How well are we measuring snow: The NOAA/FAA/NCAR winter precipitation test bed. *B. Am.
 1979 Meteorol. Soc.*, 93, 811-829, 2012.
- 1980 Revuelto, J., Jonas, T., López-Moreno, J.I., 2016a. Backward snow depth reconstruction at high
 1981 spatial resolution based on time-lapse photography. *Hydrol Process* 30, 2976–2990.
- 1982 Revuelto, J., López-Moreno, J.I., Azorin-Molina, C., Vicente-Serrano, S.M., 2014. Topographic
 1983 control of snowpack distribution in a small catchment in the central Spanish Pyrenees: intra- and
 1984 inter-annual persistence. *The Cryosphere* 8, 1989–2006.
- 1985 Revuelto, J., López-Moreno, J.I., Azorin-Molina, C., Vicente-Serrano, S.M., 2015. Canopy
 1986 influence on snow depth distribution in a pine stand determined from terrestrial laser data. *Water
 1987 Resources Research* 51, 3476–3489.
- 1988 Revuelto, J., Vionnet, V., López-Moreno, J.I., Lafaysse, M., Morin, S., 2016b. Combining snowpack
 1989 modeling and terrestrial laser scanner observations improves the simulation of small scale snow
 1990 dynamics. *J Hydrol* 533, 291–307.
- 1991 Rice, R., Bales, R., 2010. Embedded sensor network design for snow cover measurements around
 1992 snow pillow and snow course sites in the Sierra Nevada of California. *Water Resources Research*
 1993 46(3), W03537.
- 1994 Rice, R., Bales, R., Painter, T., Dozier, J., 2011. Snow water equivalent along elevation gradients in
 1995 the Merced and Tuolumne River basins of the Sierra Nevada. *Water Resources Research* 47(8),
 1996 W08515.
- 1997 Rittger, K., Bair, E., Kahl, A., Dozier, J., 2016. Spatial estimates of snow water equivalent from
 1998 reconstruction. *Advances in Water Resources* 94, 345–363.

- 1999 Rittger, K., Painter, T., Dozier, J., 2013. Assessment of methods for mapping snow cover from
2000 MODIS. *Advances in Water Resources* 51, 367–380.
- 2001 Rousselot, M., Durand, Y., Giraud, G., Mérindol, L., Dombrowski-Etchevers, I., Déqué, M.,
2002 Castebrunet, H., 2012. Statistical adaptation of ALADIN RCM outputs over the French Alps –
2003 application to future climate and snow cover. *The Cryosphere* 6, 785–805.
- 2004 Rutter, N., Essery, R., Pomeroy, J., Altimir, N., Andreadis, K., Baker, I., Barr, A., Bartlett, P., Boone,
2005 A., Deng, H., Douville, H., Dutra, E., Elder, K., Ellis, C., Feng, X., Gelfan, A., Goodbody, A., Gusev,
2006 Y., Gustafsson, D., Hellström, R., Hirabayashi, Y., Hirota, T., Jonas, T., Koren, V., Kuragina, A.,
2007 Lettenmaier, D., Li, W.-P., Luce, C., Martin, E., Nasonova, O., Pumpanen, J., Pyles, D., Samuelsson,
2008 P., Sandells, M., Schädler, G., Shmakin, A., Smirnova, T., Stähli, M., Stöckli, R., Strasser, U., Su, H.,
2009 Suzuki, K., Takata, K., Tanaka, K., Thompson, E., Vesala, T., Viterbo, P., Wiltshire, A., Xia, K., Xue,
2010 Y., Yamazaki, T., 2009. Evaluation of forest snow processes models (SnowMIP2). *Journal of*
2011 *Geophysical Research* 114(D6), D06111.
- 2012 Rutz, J., Steenburgh, J., Ralph, M., 2014. Climatological Characteristics of Atmospheric Rivers and
2013 Their Inland Penetration over the Western United States. *Monthly Weather Review* 142, 905–921.
- 2014 Sade, R., Rimmer, A., Litaor, I., Shamir, E., Furman, A., 2014. Snow surface energy and mass
2015 balance in a warm temperate climate mountain. *Journal of Hydrology* 519, 848–862.
- 2016 Scanlon, B., Longuevergne, L., Long, D., 2012. Ground referencing GRACE satellite estimates of
2017 groundwater storage changes in the California Central Valley, USA. *Water Resour Res* 48(4),
2018 W04520.
- 2019 Schlaepfer, D., Lauenroth, W., Bradford, J., 2012. Consequences of declining snow accumulation for
2020 water balance of mid-latitude dry regions. *Global Change Biology* 18, 1988–1997.
- 2021 Schulz, O., Jong, C. de, 2004. Snowmelt and sublimation: field experiments and modelling in the
2022 High Atlas Mountains of Morocco. *Hydrology and Earth System Sciences* 8, 1076–1089.
- 2023 Seidel, K. and Martinec, J., 2004. *Remote Sensing in Snow Hydrology. Runoff Modelling, Effect of*
2024 *Climate Change.* (ISBN: 978-3-540-40880-2) 150 pp.
- 2025 Senatore, A., Mendicino, G., Smiatek, G., Kunstmann, H., 2011. Regional climate change projections
2026 and hydrological impact analysis for a Mediterranean basin in Southern Italy. *Journal of Hydrology*
2027 399, 70–92.
- 2028 Şensoy, A., Şorman, A., Tekeli, A., Şorman, Ü., Garen, D., 2006. Point-scale energy and mass
2029 balance snowpack simulations in the upper Karasu basin, Turkey. *Hydrological Processes* 20, 899–
2030 922.
- 2031 Şensoy, A., Uysal, G., 2012. The Value of Snow Depletion Forecasting Methods Towards
2032 Operational Snowmelt Runoff Estimation Using MODIS and Numerical Weather Prediction Data.
2033 *Water Resources Management* 26, 3415–3440.
- 2034 Sevruk, B., J.-A. Hertig, and R. Spiess, 1991. The effect of precipitation gauge orifice rim on the wind
2035 field deformation as investigated in a wind tunnel. *Atmos. Environ.*, 25A, 1173–1179.
- 2036 Shamir, E., Georgakakos, K., 2006. Distributed snow accumulation and ablation modeling in the
2037 American River basin. *Advances in Water Resources* 29, 558–570.
- 2038 Shaw, G., Conklin, M., Nimz, G., Liu, F., 2014. Groundwater and surface water flow to the Merced
2039 River, Yosemite Valley, California: 36Cl and Cl⁻ evidence. *Water Resources Research* 50, 1943–
2040 1959.

- 2041 Singh, R.S., Reager, J.T., Miller, N.L., Famiglietti, J.S., 2015. Toward hyper-resolution
 2042 land-surface modeling: The effects of fine-scale topography and soil texture on CLM4.0
 2043 simulations over the Southwestern U.S. *Water Resources Research* 51, 2648–2667.
- 2044 Slater, A.G., Barrett, A.P., Clark, M.P., Lundquist, J.D., Raleigh, M.S., 2013. Uncertainty in seasonal
 2045 snow reconstruction: Relative impacts of model forcing and image availability. *Advances in Water*
 2046 *Resources* 55, 165–177.
- 2047 Smith, C., Kontu, A., Laffin, R. and Pomeroy, J., 2016. An assessment of two automated snow water
 2048 equivalent instruments during the WMO Solid Precipitation Intercomparison Experiment. *The*
 2049 *Cryosphere Discuss*, 0, 1–31, doi:10.5194/tc-2016-57, 2016.
- 2050 Smith, M., Koren, V., Zhang, Z., Moreda, F., Cui, Z., Cosgrove, B., Mizukami, N., Kitzmiller, D.,
 2051 Ding, F., Reed, S., Anderson, E., Schaake, J., Zhang, Y., Andréassian, V., Perrin, C., Coron, L.,
 2052 Valéry, A., Khakbaz, B., Sorooshian, S., Behrangi, A., Imam, B., Hsu, K.-L., Todini, E., Coccia, G.,
 2053 Mazzetti, C., Andres, E., Francés, F., Orozco, I., Hartman, R., Henkel, A., Fickenscher, P., Staggs, S.,
 2054 2013. The distributed model intercomparison project – Phase 2: Experiment design and summary
 2055 results of the western basin experiments. *Journal of Hydrology* 507, 300–329.
- 2056 Şorman, A., Beser, O. 2013. Determination of snow water equivalent over the eastern part of Turkey
 2057 using passive microwave data. *Hydrol. Process.* 27, 1945–1958
- 2058 Şorman, A., Şensoy, Tekeli, Şorman, Ü., Akyürek, 2009. Modelling and forecasting snowmelt runoff
 2059 process using the HBV model in the eastern part of Turkey. *Hydrological Processes* 23, 1031–1040.
- 2060 Sorman, U., Beser, O., 2013. Determination of snow water equivalent over the eastern part of Turkey
 2061 using passive microwave data. *Hydrological Processes* 27, 1945–1958.
- 2062 Sproles, E., Kerr, T., Nelson, C., Aspe, D., 2016. Developing a Snowmelt Forecast Model in the
 2063 Absence of Field Data. *Water Resources Management* 30, 2581–2590.
- 2064 Sproles, E.A., Nolin, A.W., Rittger, K., Painter, T., 2013. Climate change impacts on maritime
 2065 mountain snowpack in the Oregon Cascades. *Hydrology and Earth System Sciences* 17, 2581–2597.
- 2066 Stewart, I., 2009. Changes in snowpack and snowmelt runoff for key mountain regions. *Hydrological*
 2067 *Processes* 23, 78–94.
- 2068 Stewart, I., 2013. Connecting physical watershed characteristics to climate sensitivity for California
 2069 mountain streams. *Climatic Change* 116, 133–148.
- 2070 Stewart, I., Cayan, D., Dettinger, M., 2005. Changes toward earlier streamflow timing across western
 2071 North America. *Journal of Climate* 18, 1136–1155.
- 2072 Storck, P., Lettenmaier, D., Bolton, S., 2002. Measurement of snow interception and canopy effects
 2073 on snow accumulation and melt in a mountainous maritime climate, Oregon, United States. *Water*
 2074 *Resources Research* 38, 5–1–5–16.
- 2075 Sturm, M., 2015. White water: Fifty years of snow research in WRR and the outlook for the future.
 2076 *Water Resources Research* 51, 4948–4965.
- 2077 Sturm, M., Holmgren, J., Liston, G.E., 1995. A Seasonal Snow Cover Classification System for Local
 2078 to Global Applications. *J. Climate*, 8, 1261–1283.
- 2079 Sturm, M., Taras, B., Liston, G., Derksen, C., Jonas, T., Lea, J., 2010. Estimating Snow Water
 2080 Equivalent Using Snow Depth Data and Climate Classes. *Journal of Hydrometeorology* 11, 1380–
 2081 1394.

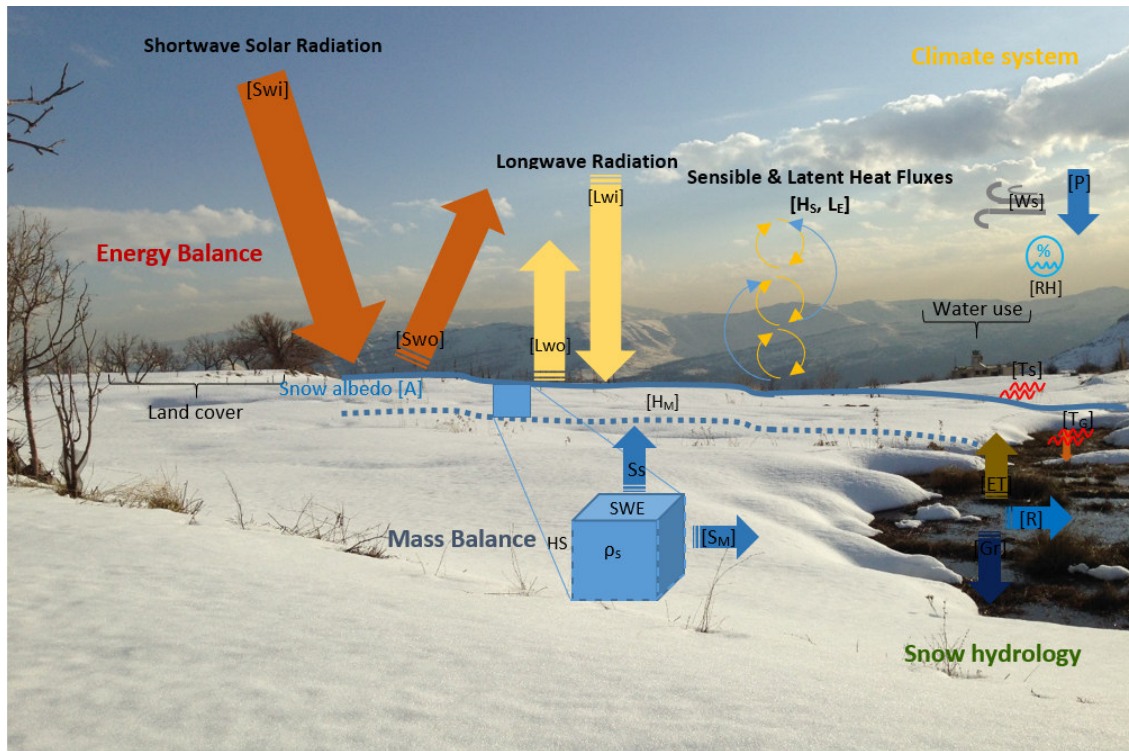
- 2082 Surfleet, C., Tullos, D., 2013. Variability in effect of climate change on rain-on-snow peak flow
2083 events in a temperate climate. *Journal of Hydrology* 479, 24–34.
- 2084 Svoma, B., 2011. Winter Climatic Controls on Spring Snowpack Density in the Western United
2085 States. *Arct Antarct Alp Res* 46, 118–126.
- 2086 Szczypta, C., Gascoin, S., Houet, T., Hagolle, O., Dejoux, J.F., Vigneau, C., Fanise, P., 2015. Impact
2087 of climate and land cover changes on snow cover in a small Pyrenean catchment. *Journal of*
2088 *Hydrology* 521, 84–99.
- 2089 Tague, C., Grant, G., 2009. Groundwater dynamics mediate low flow response to global warming in
2090 snow-dominated alpine regions. *Water Resources Research* 45(7), W07421.
- 2091 Tague, C., Peng, H., 2013. The sensitivity of forest water use to the timing of precipitation and
2092 snowmelt recharge in the California Sierra: Implications for a warming climate. *Journal of*
2093 *Geophysical Research: Biogeosciences* 118, 875–887.
- 2094 Tanaka, S., Zhu, T., Lund, J., Howitt, R., Jenkins, M., Pulido, M., Tauber, M., Ritzema, R., Ferreira,
2095 I., 2006. Climate Warming and Water Management Adaptation for California. *Climatic Change* 76,
2096 361–387.
- 2097 Taylor, S., Feng, X., Kirchner, J., Osterhuber, R., Klaue, B., Renshaw, C., 2001. Isotopic evolution of
2098 a seasonal snowpack and its melt. *Water Resources Research* 37, 759–769.
- 2099 Tedesco M (ed.) 2015. *Remote Sensing of the Cryosphere*. Wiley. (ISBN: 978-1-118-36885-5) 432
2100 pp.
- 2101 Tekeli, A., Şensoy, A., Şorman, A., Akyürek, Z., Şorman, Ü., 2006. Accuracy assessment of MODIS
2102 daily snow albedo retrievals with in situ measurements in Karasu basin, Turkey. *Hydrological*
2103 *Processes* 20, 705–721.
- 2104 Tekeli, E., 2008. Early findings in comparison of AMSR-E/Aqua L3 global snow water equivalent
2105 EASE grids data with in situ observations for Eastern Turkey. *Hydrological Processes* 22, 2737–
2106 2747.
- 2107 Tekeli, E., Akyürek, Z., Şensoy, A., Şorman, A., Şorman, Ü., 2005b. Modelling the temporal
2108 variation in snow-covered area derived from satellite images for simulating/forecasting of snowmelt
2109 runoff in Turkey/Modélisation de la variation temporelle de la surface enneigée à partir d'images
2110 satellitaires pour la simulation/prévision de l'écoulement de fonte nivale en Turquie. *Hydrological*
2111 *Sciences Journal* 50(4), 669–682.
- 2112 Tekeli, E., Akyürek, Z., Şorman, A., Şensoy, A., Şorman, Ü., 2005a. Using MODIS snow cover maps
2113 in modeling snowmelt runoff process in the eastern part of Turkey. *Remote Sensing of Environment*
2114 97, 216–230.
- 2115 Telesca, L., Shaban, A., Gascoin, S., Darwich, T., Drapeau, L., Hage, M., Faour, G., 2014.
2116 Characterization of the time dynamics of monthly satellite snow cover data on Mountain Chains in
2117 Lebanon. *Journal of Hydrology* 519, 3214–3222.
- 2118 Thériault, J., Rasmussen, R., Ikeda, K., Landolt, S., 2012. Dependence of snow gauge collection
2119 efficiency on snowflake characteristics. *J. Appl. Meteor. Climatol.*, 51, 745–762, doi:10.1175/JAMC-
2120 D-11-0116.1.
- 2121 Thirel, G., Notarnicola, C., Kalas, M., Zebisch, M., Schellenberger, T., Tetzlaff, A., Duguay, M.,
2122 Mölg, N., Burek, P., de Roo, A., 2012. Assessing the quality of a real-time Snow Cover Area product
2123 for hydrological applications. *Remote Sens Environ* 127, 271–287.

- 2124 Tobin, B., Schwartz, B., 2016. Using periodic hydrologic and geochemical sampling with limited
2125 continuous monitoring to characterize remote karst aquifers in the Kaweah River Basin, California,
2126 USA. *Hydrol Process* 30, 3361–3372.
- 2127 Trujillo, E., Molotch, N., 2014. Snowpack regimes of the Western United States. *Water Resources*
2128 *Research* 50, 5611–5623.
- 2129 Trujillo, E., Molotch, N., Goulden, M., Kelly, A., Bales, R., 2012. Elevation-dependent influence of
2130 snow accumulation on forest greening. *Nature Geoscience* 5, 705–709.
- 2131 Valdés-Pineda, R., Pizarro, R., García-Chevesich, P., Valdés, J., Olivares, C., Vera, M., Balocchi, F.,
2132 Pérez, F., Vallejos, C., Fuentes, R., Abarza, A., Helwig, B., 2014. Water governance in Chile:
2133 Availability, management and climate change. *Journal of Hydrology* 519, 2538–2567.
- 2134 Valéry, A., Andréassian, V. and Perrin, C., 2010. Regionalization of precipitation and air temperature
2135 over high-altitude catchments - learning from outliers. *Hydrological Sciences Journal*, 55(6): 928-940.
- 2136 Valéry, A., V. Andréassian and C. Perrin. 2014a. As simple as possible but not simpler: what is useful
2137 in a temperature-based snow-accounting routine? Part 1 - Comparison of six snow accounting routines
2138 on 380 catchments. *Journal of Hydrology*, 517: 1166-1175.
- 2139 Valéry, A., V. Andréassian and C. Perrin. 2014b. As simple as possible but not simpler: what is useful
2140 in a temperature-based snow-accounting routine? Part 2 - Sensitivity analysis of the Cemaneige snow
2141 accounting routine on 380 catchments. *Journal of Hydrology*, 517: 1176-1187.
- 2142 Vano, J., Nijssen, B., Lettenmaier, D., 2015. Seasonal hydrologic responses to climate change in the
2143 Pacific Northwest. *Water Resources Research* 51, 1959–1976.
- 2144 Varhola, A., Wawerla, J., Weiler, M., Coops, N., Bewley, D., Alila, Y., 2010. A New Low-Cost,
2145 Stand-Alone Sensor System for Snow Monitoring. *Journal of Atmospheric and Oceanic Technology*
2146 27, 1973–1978.
- 2147 Vicuna, S., Dracup, J.A., 2007. The evolution of climate change impact studies on hydrology and
2148 water resources in California. *Climatic Change* 82, 327–350.
- 2149 Vicuña, S., Garreaud, R., McPhee, J., 2011. Climate change impacts on the hydrology of a snowmelt
2150 driven basin in semiarid Chile. *Climatic Change* 105, 469–488.
- 2151 Vidal, J., Martin, E., Franchistéguy, L., Baillon, M., Soubeyroux, J., 2010. A 50-year
2152 high-resolution atmospheric reanalysis over France with the Safran system. *International Journal of*
2153 *Climatology* 30, 1627–1644.
- 2154 Vionnet, V., Dombrowski-Etchevers, I., Lafaysse, M., Quéno, L., Seity, Y., and Bazile, E., 2016.
2155 Numerical weather forecasts at kilometer scale in the French Alps : evaluation and applications for
2156 snowpack modelling. *J. Hydrometeor.*, doi:http://dx.doi.org/10.1175/JHM-D-15-0241.1
- 2157 Viviroli, D., Archer, D.R., Buytaert, W., Fowler, H.J., Greenwood, G.B., Hamlet, A.F., Huang, Y.,
2158 Koboltschnig, G., Litaor, I., López-Moreno, J.I., Lorentz, S., Schädler, B., Schreier, H., Schwaiger,
2159 K., Vuille, M., Woods, R., 2011. Climate change and mountain water resources: overview and
2160 recommendations for research, management and policy. *Hydrology and Earth System Sciences* 15,
2161 471–504.
- 2162 Viviroli, D., Dürr, H., Messerli, B., Meybeck, M., Weingartner, R., 2007. Mountains of the world,
2163 water towers for humanity: Typology, mapping, and global significance. *Water Resources Research*
2164 43(7), W07447.

- 2165 Vuyovich, C., Jacobs, J., Daly, S., 2014. Comparison of passive microwave and modeled estimates of
2166 total watershed SWE in the continental United States. *Water Resources Research* 50, 9088–9102.
- 2167 Watson, F., Anderson, T., Newman, W., Alexander, S., Garrott, R., 2006. Optimal sampling schemes
2168 for estimating mean snow water equivalents in stratified heterogeneous landscapes. *Journal of*
2169 *Hydrology* 328, 432–452.
- 2170 Wayand, N., Hamlet, A., Hughes, M., Feld, S., Lundquist, J., 2013. Intercomparison of
2171 Meteorological Forcing Data from Empirical and Mesoscale Model Sources in the North Fork
2172 American River Basin in Northern Sierra Nevada, California. *Journal of Hydrometeorology* 14, 677–
2173 699.
- 2174 Wayand, N., Lundquist, J., Clark, M., 2015. Modeling the influence of hypsometry, vegetation, and
2175 storm energy on snowmelt contributions to basins during rain-on-snow floods. *Water Resources*
2176 *Research* 51, 8551–8569.
- 2177 Welch, S., Kerkez, B., Bales, R., Glaser, S., Rittger, K., Rice, R., 2013. Sensor placement strategies
2178 for snow water equivalent (SWE) estimation in the American River basin. *Water Resources Research*
2179 49, 891–903.
- 2180 Williams, M., Leydecker, A., Brown, A., Melack, J., 2001. Processes regulating the solute
2181 concentrations of snowmelt runoff in two subalpine catchments of the Sierra Nevada, California.
2182 *Water Resources Research* 37, 1993–2008.
- 2183 Woeikof, A., 1885. On the influence of accumulations of snow on climate. *Quarterly Journal of the*
2184 *Royal Meteorological Society*, 299–309.
- 2185 Wrzesien, M., Pavelsky, T., Kapnick, S., Durand, M., Painter, T., 2015. Evaluation of snow cover
2186 fraction for regional climate simulations in the Sierra Nevada. *International Journal of Climatology*
2187 35(9), 2472–2484.
- 2188 Wu, W., Lan, C., Lo, M., Reager, J., Famiglietti, J., 2015. Increases in the annual range of soil water
2189 storage at northern middle and high latitudes under global warming. *Geophysical Research Letters* 42,
2190 3903–3910.
- 2191 Zaitchik, B., Rodell, M., 2009. Forward-Looking Assimilation of MODIS-Derived Snow-Covered
2192 Area into a Land Surface Model. *Journal of Hydrometeorology* 10, 130–148.
- 2193 Zampieri, M., Scoccimarro, E., Gualdi, S., Navarra, A., 2015. Observed shift towards earlier spring
2194 discharge in the main Alpine rivers. *Science of The Total Environment* 503-504, 222–232.
- 2195 Zheng, Z., Kirchner, P., Bales, R., 2016. Topographic and vegetation effects on snow accumulation in
2196 the southern Sierra Nevada: a statistical summary from lidar data. *Cryosphere* 10, 257–269.
- 2197

- 2198
- snow distribution and densification rates are marked by high intra-annual variability
- 2199
- snow cover persistence is mainly controlled by precipitation and elevation
- 2200
- snowmelt is driven by radiative fluxes
- 2201
- heat flux contribution to snowmelt increases during heat waves and rain-on-snow events
- 2202
- snow sublimation is an important component of snow ablation in high-elevation regions
- 2203

ACCEPTED MANUSCRIPT



2204

ACCEPTED MANUSCRIPT