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Review papers

Snow hydrology in Mediterranean mountain regions: A review

Abbas Fayad [a,b,*], Simon Gascoin [a], Ghaleb Faour [b], Juan Ignacio López-Moreno [c], Laurent Drapeau [a], Michel Le Page [a], Richard Escadafal [a]

[a] Centre d'Etudes Spatiales de la Biosphère (CESBIO), UPS/CNRS/IRD/CNES, Toulouse, France
[b] National Council for Scientific Research/Remote Sensing Center (CNRS/RSC), Beirut, Lebanon
[c] Pyrenean Institute of Ecology (CSIC), Department of Geoenvironmental Processes and Global Change, Zaragoza, Spain

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ABSTRACT

Water resources in Mediterranean regions are under increasing pressure due to climate change, economic development, and population growth. Many Mediterranean rivers have their headwaters in mountainous regions where hydrological processes are driven by snowpack dynamics and the specific variability of the Mediterranean climate. A good knowledge of the snow processes in the Mediterranean mountains is therefore a key element of water management strategies in such regions. The objective of this paper is to review the literature on snow hydrology in Mediterranean mountains to identify the existing knowledge, key research questions, and promising technologies. We collected 620 peer-reviewed papers, published between 1913 and 2016, that deal with the Mediterranean-like mountain regions in the western United States, the central Chilean Andes, and the Mediterranean basin. A large amount of studies in the western United States form a strong scientific basis for other Mediterranean mountain regions. We found that: (1) the persistence of snow cover is highly variable in space and time but mainly controlled by elevation and precipitation; (2) the snowmelt is driven by radiative fluxes, but the contribution of heat fluxes is stronger at the end of the snow season and during heat waves and rain-on-snow events; (3) the snow densification rates are higher in these regions when compared to other climate regions; and (4) the snow sublimation is an important component of snow ablation, especially in high-elevation regions. Among the pressing issues is the lack of continuous ground observation in high-elevation regions. However, a few years of snow depth (HS) and snow water equivalent (SWE) data can provide realistic information on snowpack variability. A better spatial characterization of snow cover can be achieved by combining ground observations with remotely sensed snow data. SWE reconstruction using satellite snow cover area and a melt model provides reasonable information that is suitable for hydrological applications. Further advances in our understanding of the snow processes in Mediterranean snow-dominated basins will be achieved by finer and more accurate representation of the climate forcing. While the theory on the snowpack energy and mass balance is now well established, the connections between the snow cover and the water resources involve complex interactions with the sub-surface processes, which demand future investigation.

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* Corresponding author.
E-mail address: abbas.fayad@gmail.com (A. Fayad).

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1. Introduction

Mountain regions are a major source of surface water and groundwater recharge in the world (Viviroli et al., 2007; Dettinger, 2014). The water balance in mountainous regions is defined by the interactions between the climate, cryospheric, and hydrological systems (de Jong et al., 2005; DeWalle and Rango, 2008). In mountainous regions that are under the influence of the Mediterranean climate (Bolle, 2003; Lionello et al., 2006), the wet-winters and hot and dry-summers climate, orographic enhanced precipitation, variability of temperature and the partitioning of rain and snow with elevation, and the high seasonal variability of the snow cover make the hydrologic processes in these mountainous regions significantly different from those found in other cryospheric regions and or dry or wet climates. Under the influence of the Mediterranean climate, an important fraction of the precipitation occurs during winter months (e.g., Demaria et al., 2013a; López-Moreno et al., 2013a; Valdés-Pineda et al., 2014), with the highest elevation areas receiving most of this winter precipitation as snow while the mid-elevation areas have a mixed precipitation regime (McCabe et al., 2007; Surfleet and Tullos, 2013; Guan et al., 2016). Winter precipitation is orographically enhanced along with elevation (Dettinger et al., 2004a,b; Behrangi et al., 2016; Derin et al., 2016). The snowmelt from the Mediterranean mountain occurs in the spring and summer when precipitation is otherwise scarce, and thus, this snowmelt is an essential water resource for many communities living in the surrounding low land regions (Morán-Tejeda et al., 2010; López-Moreno et al., 2008a, 2014).

The Mediterranean mountain regions include the countries around the Mediterranean Sea (e.g., Morocco, Spain, France, Italy, Bulgaria, Croatia, Greece, Turkey, and Lebanon), the western US (California), and the mid-latitude area of the central Chilean Andes. In almost all these regions, agriculture is an important source of income and employment, and snowmelt provides runoff during the crop-growing season when irrigation is the most needed. However, the sustainability of the water resources is threatened by the pressure of a growing population, increasing irrigation, and climate change (e.g., Barnett et al., 2008). While Mediterranean region have been considered as climate change ''hot spots'' since the first IPCC reports (Milly et al., 2005; Giorgi, 2006; Nohara et al., 2006; Nogués-Bravo et al., 2007; Giorgi and Lionello, 2008; Loarie et al., 2009; Kyselý et al., 2012; Kapnick and Delworth, 2013; Morán-Tejeda et al., 2014; Prudhomme et al., 2014; Harpold and Molotch, 2015; Vano et al., 2015; Kumar et al., 2016), there is also new evidence that the rate of atmospheric warming increases with elevation (Kotlarski et al., 2015; Pepin et al., 2015), which strengthens the concern about the climate change in Mediterranean mountain regions. The impact of atmospheric warming is expected to be strong in snow-dominated watersheds since snow accumulation and ablation are highly sensitive to air temperature (Beniston, 2003; Barnett et al., 2005; Howat and Tulaczyk, 2005; Brown and Mote, 2009; Cooper et al., 2016). The main consequence on warming is a shift in the hydrological regimes from a snow-dominated regime towards a rain-dominated regime (Berghuijs et al., 2014; Goulden and Bales, 2014). For example, in the western US, areas with elevations between 2000 and 2800 m are the most sensitive to global warming (Maurer et al., 2007). Regions in the western US where the average winter-wet-day minimum temperature increased by +3 °C are witnessing a reduction in the winter-total snowfall to precipitation ratio (Knowles et al., 2006). Most Northern-Hemisphere's snow-dependent regions are likely to experience increasing stress from low snow years within the next three decades (Diffenbaugh et al., 2012). Areas with an average winter temperature between −4 and −2 °C are expected to witness shifts towards earlier streamflow peaks (changes that exceed

45 days relative to those from 1961 to 1990) (Maurer et al., 2007). Similar results were reported in the Southern Alpine river basins (Zampieri et al., 2015). The Mediterranean climate is also characterized by a high inter-annual variability, although the underlying mechanisms depend upon the specific region. North and South American Mediterranean regions are under the influence of the climatic variability of the Pacific Ocean, while the Mediterranean climate in Europe and North Africa is relatively connected to the North-Atlantic climatic variability (López-Moreno et al., 2013a).

Research on the seasonal snow and snow hydrology in mountains is well established and several authors have already produced review articles or chapters on the following: (1) the physical properties of the snowpack (e.g., Armstrong and Burn, 2008; Kinar and Pomeroy, 2015; Sturm, 2015); (2) remote sensing of snow (Dozier and Painter, 2004; Seidel and Martinec, 2004; Dozier et al., 2009; Dietz et al., 2012; Frei et al., 2012; Deems et al., 2013; Lettenmaier et al., 2015; Sturm, 2015; Tedesco, 2015); (3) spatial distribution of the snow water equivalent, SWE (Dozier et al., 2016); (4) snow and mountain hydrology (e.g., Seidel and Martinec, 2004; de Jong et al., 2005; Bales et al., 2006; Armstrong and Burn, 2008; DeWalle and Rango 2008; Varhola et al., 2010; Hrachowitz et al., 2013; Bierkens, 2015; Sturm, 2015); (5) snow spatial representation in hydrologic and land-surface models (e.g., Clark et al., 2011); and the (6) projected climate impact on the cryospheric and hydrological systems in mountains (e.g., Beniston, 2003; de Jong et al., 2005; Huber et al., 2005; Vicuna and Dracup, 2007; Viviroli et al., 2007; Brown and Mote, 2009; Stewart, 2009; García-Ruiz et al., 2011; Diffenbaugh et al., 2012; Kapnick and Delworth, 2013; Beniston and Stoffel, 2014; Pepin et al., 2015; Sturm 2015; Wu et al., 2015; Meixner et al., 2016).

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

To our knowledge, no review to date has explicitly addressed the characterization of snow hydrologic processes related to snow in one of the major snow regions. Given the significance of the snowmelt as a water resource in Mediterranean regions, we considered that a review of the previous snow studies undertaken in Mediterranean mountain regions is needed. This review may be helpful, for example, in defining a new research program in this climate region, which is highly sensitive to global warming and where snowmelt is an important contributor to the hydrologic cycle.

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

We collected 620 peer-reviewed articles published between 1913 and 2016, which dealing with the snowpack and snow hydrology in Mediterranean regions. From this large number of papers, we adopted a hybrid quantitative (metadata analysis from the papers) and qualitative approach (literature review) to gain insight into the major issues, trends, and advances in this already large and growing research field. We present the geographic extent of the papers and the methodology to analyze them in Section 2. The key indicators obtained from the papers dataset are presented in Section 3. The second part of the paper is devoted to the review of the three key issues that emerge from this article database: Section 4 addresses the characterization of the climatic forcing in snow-dominated Mediterranean regions; Section 5 describes the main features of the snowpack obtained from ground measurements and remote sensing techniques; Section 6 focuses on the studies dedicated to the snowmelt modeling; and Section 7 draws conclusions and opportunities for future work.

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

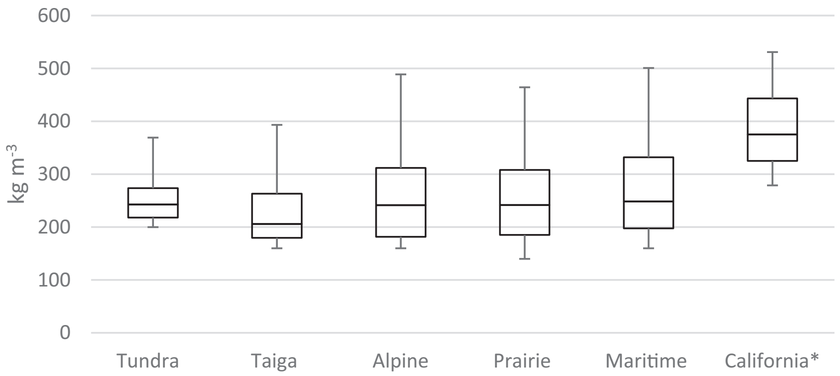

Fig. 1. Variation in the mean monthly snow density (Oct-June) (kg m^{-3}) adopted from Brown and Mote (2009) for the major climate regions. *California monthly snow density means (Jan-June) are based on long-term monthly data records (more than 20 years) retrieved from 46 snow courses and 26 SNOTEL stations (data are available online at wcc.nrcs.usda.gov/snow/). The average snow depth and standard deviation, not shown, were as follows: Tundra (43.8 cm, 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), and the average for California calculated from long term monthly snow courses and SNOTEL data was 146.1 cm (std dev = 97.5).

2. Methods

2.1. Geographic extent of the review

The Mediterranean climate is found on the western part of the continents between latitudes 30° and 45° (Bolle, 2003). The land regions around the Mediterranean Sea (southern Europe, Northern Africa and the Levantine region) form the largest area of this type of climate. The Mediterranean climate is also found in the western Coastal US (California, and western Oregon), and the central Chilean Andes (Fig. 2). Limited regions in southern Australia and southern Africa are also classified as Mediterranean (not shown). A combined Koppen (Kottek et al., 2006) and mountain classification scheme (Viviroli et al., 2007) was used to better distinguish the mountain regions associated with the Mediterranean climate (Fig. 2). The Koppen climate scheme defines five main groups and multi subtypes according to the long-time annual and monthly temperature means and precipitation totals. Of particular interest to this study are the Mediterranean (Csa, Csb) regions and the regions influenced by Mediterranean climate, such as the adjacent maritime zones (Cfb, Cfc) and the semi-arid regions (BSh, BSk). The Viviroli et al. (2007) scheme distinguishes a total of 15 relief patterns by combining elevation and a relief roughness indicator, and it was used to distinguish between mountainous and lowland areas.

2.2. Bibliographic sources

We used the website of the three major scientific publishers (Elsevier, Wiley, and Springer), Google Scholar, ReadCube, and open access journals websites to find articles from the early 20th century to the present, in which snow, hydrology, and mountain hydrology and climatology appeared in the title or abstract, or as a keyword. Only articles published in peer-reviewed journal with an impact factor greater than one and articles related to the Mediterranean regions presented above were considered. A second round of screening focused on reading the abstract and identifying articles where snow properties, snow hydrology, and mountain hydroclimatology are considered as part of the article's main objectives. As much as possible, we avoided papers where snow was addressed in a marginal context. Hundreds of articles were identified during the initial screening. A total of 620 articles, (published in 82 different journals) (Fig. 3a), were retained after the second screening. A table with the metadata for the articles is provided as Supplementary file (A1).

We identified a list of 35 different indicators that correspond to key research areas (Supplementary material A2). These were classified under three major groups (science, methods, and data) and subdivided into different categories. The first group focuses on science and it includes three categories: (1) meteorology and climatology in mountains (e.g., mountain climate, climate change and variability, climatology and meteorology, and hydrometeorology (Inc. hydroclimatology), (2) snow (e.g., snow hydrometeorology (Inc. climatology), snow properties, and snow hydrology) and (3) hydrology (e.g., mountain hydrology, hydrology in snow-dominated basins, and hydrogeology in mountains). The second group focuses on the following methods: (4) methods used to quantify the snow cover extent (e.g., remote sensing of snow); methods used to describe the spatial distribution of snowpack indicators (e.g., spatial statistics and trends in climate, snowpack, and hydrology); and methods used to simulate the main characteristics of snow accumulation, snow duration, and snowmelt processes (e.g., snow energy and mass balance simulation, hydrological modeling). The third group emphasizes the following: (5) data (i.e., length of data used, source and type of data (i.e., ground observations, projections, and reanalysis), and spatial scales (extent of the study area and elevation range). Each article was associated with a pair of longitude and latitude coordinates, which represent the approximate centroid of the study area highlighted in the paper, and each article was reported on a map that shows both the Koppen climate classes and the mountain regions, as defined by Viviroli et al. (2007) (Fig. 2).

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

3. Description of the articles database

3.1. Mountain ranges

Mountain regions covered in this review include the following (Fig. 3b): (1) the coastal regions of western United States (Bales et al., 2006) including the Oregon Cascade (Sproles et al., 2013) and California Sierra Nevada Mountains (Guan et al., 2013a;

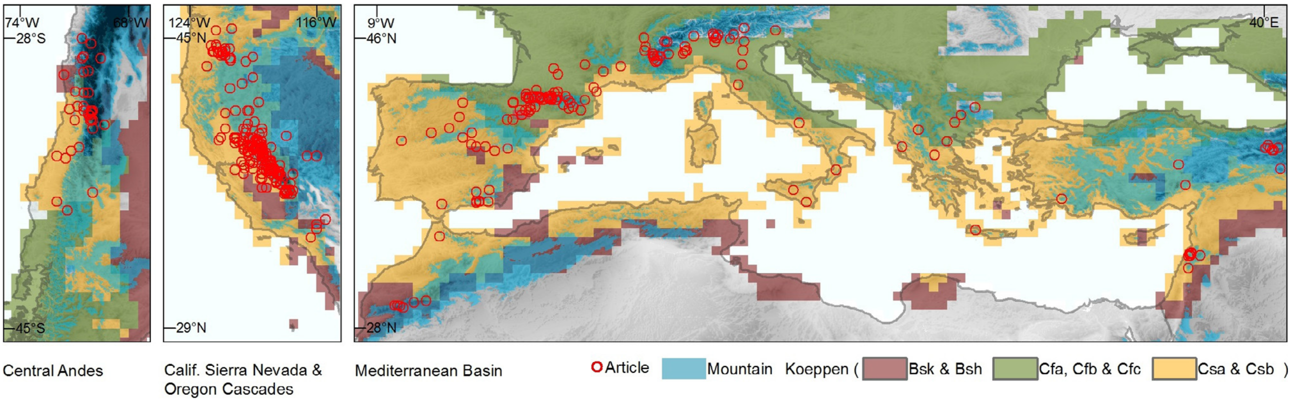

Fig. 2. Mediterranean mountain regions (a) Central Chile (b) western US and (c) Mediterranean Basin. Mountain regions were derived using the Viviroli et al. (2007) scheme based on the global multi-resolution terrain elevation data (GMTED2010) at 15-arc second resolution (Danielson and Gesch, 2011), and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

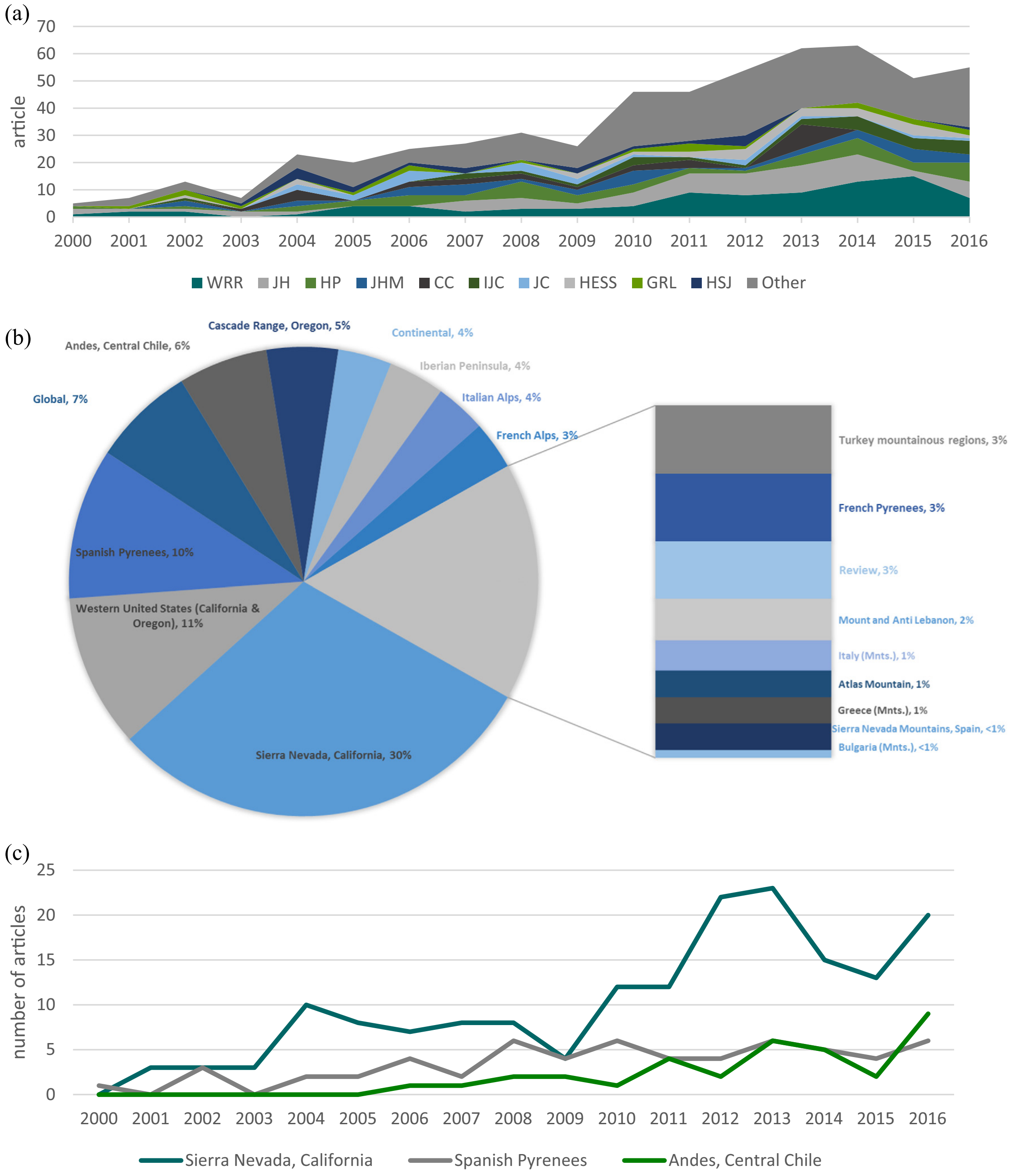

Fig. 3. Key bibliometric indicators were the following (from top to bottom): (a) cumulative yearly number of publications per journal (based on 561 articles published between 2000 and 2016); (b) Distribution of studies by major mountain regions shown; and (c) number of yearly published papers in California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

Molotch and Meromy, 2014); (2) the central Andes that cover two of Chile's major natural regions – Chile's central and southern zones (Favier et al., 2009; Cortés et al., 2011; Valdés-Pineda et al., 2014); the major mountain chains around the Mediterranean Sea (López-Moreno et al., 2011a), namely; (3) Spanish (López-Moreno et al., 2014), and French (Gascoin et al., 2015), Pyrenees; (4) Spanish Sierra Nevada Mountains (Pimentel et al., 2015); (5) French and Italian Maritime Alps (Dedieu et al., 2014) – which are under the influence of the Mediterranean climate (Durand et al., 2009); (6) Turkey and the Armenian Plateau (Tekeli, 2008); (7) Mount Lebanon and Anti Lebanon Ranges (Mhawej et al., 2014); and (8) Moroccan Atlas (Marchane et al., 2015). Little information was found on other Mediterranean Sea mountains (López-Moreno et al., 2011a), such as the Iberian Peninsula Mountains (Morán-Tejeda et al., 2014), Italian Apennines (Martelloni et al., 2013), Southern Calabrian mountains in Italy (Senatore et al., 2011), Julian Alps (Italy and Slovenia), Dinaric Alps (mostly over Croatia and Bosnia and Herzegovina), Bulgarian mountains (Brown and Petkova, 2007), Pindos (Greece), Rhodope (Greece), and Taurus (Turkey).

3.2. Bibliometric analysis

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

3.3. Thematic analysis

The papers cover multiple scales: (1) experimental sites and small catchments (Storck et al., 2002; Franz et al., 2010; López-Moreno et al., 2010, 2013b; Bales et al., 2011; Liu et al., 2013; Raleigh et al., 2013; Harpold et al., 2014; Girotto et al., 2014; Revuelto et al., 2016a; Marti et al., 2016); (2) snow-dominated basins (Lundquist et al., 2010; Powell et al., 2011; Rousselot et al., 2012; Smith et al., 2013; Welch et al., 2013; Cortés et al., 2014; Franz et al., 2014; Telesca et al., 2014; Marchane et al., 2015); (3) multiple basins, mountain ranges, and regional scales (Painter et al., 2009; López-Moreno et al., 2011a; Pavelsky et al., 2011; Guan et al., 2013b; Núñez et al., 2013; Slater et al., 2013; Stewart, 2013; Avanzi et al., 2014; Hüsler et al., 2014; Cornwell et al., 2016); and (4) continental scales and the global scale (e.g., Nohara et al., 2006; Pepin et al., 2015). The studies provide information on (1) mountain climatology and meteorology (Bonfils et al., 2008; Herrero and Polo, 2012; Pavelsky et al., 2012; Lute and Abatzoglou, 2014; Lundquist et al., 2015a; Guan et al., 2016); (2) long-term hydroclimatology and snowpack trends in mountains (López-Moreno and García-Ruiz, 2004; Hamlet et al., 2005; Mote et al., 2005; Stewart et al., 2005; Masiokas et al., 2006; McCabe et al., 2007; Pierce et al., 2008; Das et al., 2009); (3) meteorological forcing and topographic controls on snowfall and snowpack in mountains (Anderton et al., 2004; Guan et al., 2010; Rice et al., 2011; Musselman et al., 2012; Trujillo et al., 2012; Wayand et al., 2013; Ayala et al., 2014; Molotch and Meromy, 2014; Hinkelman et al., 2015; Lapo et al., 2015; López-Moreno et al., 2015; Harpold, 2016); (4) snowpack properties (Mizukami and Perica, 2008; Perrot et al., 2014; Trujillo and Molotch, 2014); (5) snow accumulation and ablation (Harpold et al., 2012; Meromy et al., 2013; Guan et al., 2013a; Avanzi et al., 2014; Sade et al., 2014); (6) snowmelt runoff (Tekeli et al., 2005a; Herrero et al., 2009; Şorman et al., 2009; Franz and Karsten, 2013; Liu et al., 2013; Jepsen et al., 2016a); and (7) different hydrological (Aguilar et al., 2010; Kourgialas et al., 2010; Lundquist and Loheide, 2011; Goulden et al., 2012; Schlaepfer et al., 2012; Harpold et al., 2015; Penna et al., 2015; Harpold, 2016); and (8) hydrogeological processes (Tague and Grant, 2009; Lowry et al., 2010) in snow-dominated mountain regions.

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

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

After 2000, the number of scientific publications increased exponentially each five years. Such a growth rate is higher than the doubling time for natural sciences, which is estimated at 8.7 years (Bornmann and Mutz, 2015). Fig. 5 summarizes the number of published papers (2000–2016) based on their key category. The main scientific area was the effect of meteorological and climatological variables on the snow hydrology that accounted for 29% of the studies (Fig. 5), of which about a half were dedicated to assessing climate change impacts on the hydrology and the snowpack. 25% and 7% of the studies were dedicated to hydrology and hydrogeology, respectively. The snowpack modeling accounted for 13% of the studies, and the snow remote sensing accounted for 8% (Fig. 5).

Table 1
Summary of key science topics identified in the literature; in addition, the table lists major variables, 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

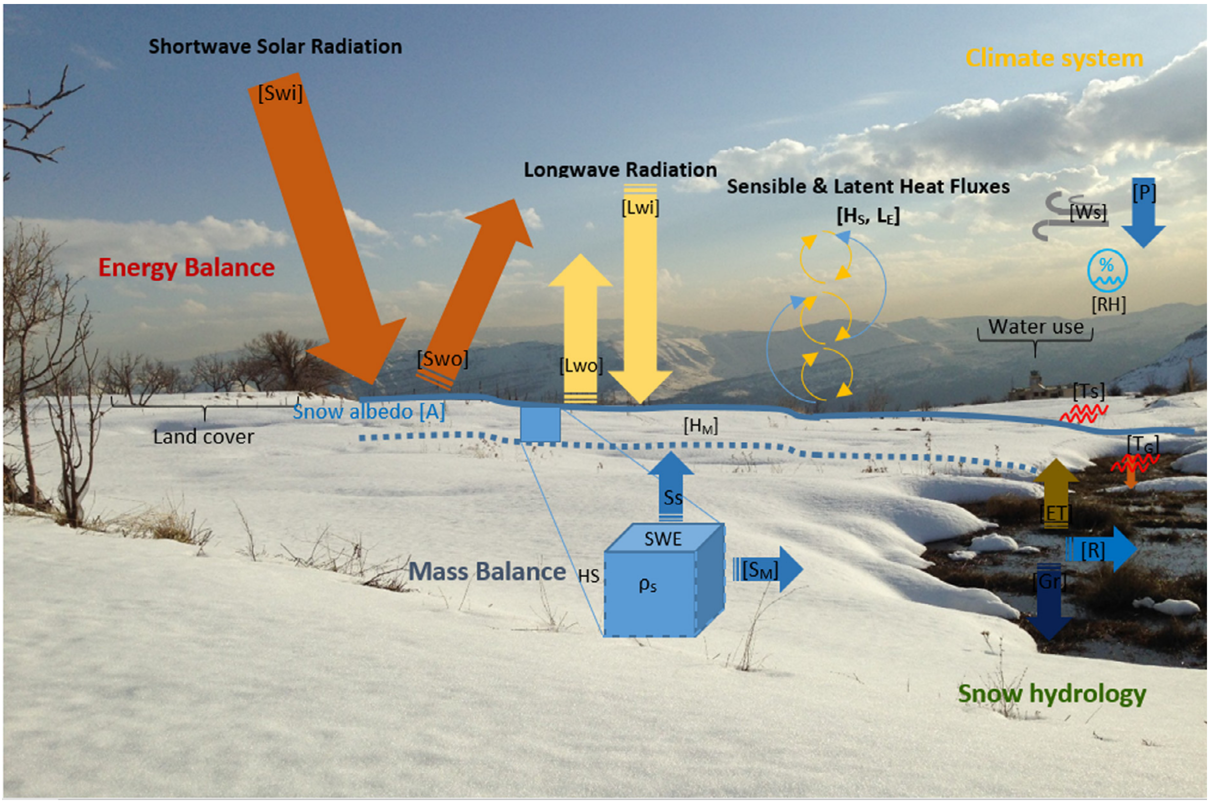

Fig. 4. Major climate forcing and snow processes in Mediterranean-like mountainous regions with emphasis on the specific objectives shown here for mountain hydrology and snowpack dynamics. Where SWi and SWo are incoming and outgoing shortwave radiation, respectively; Lwo and Lwi are the emitted and incoming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

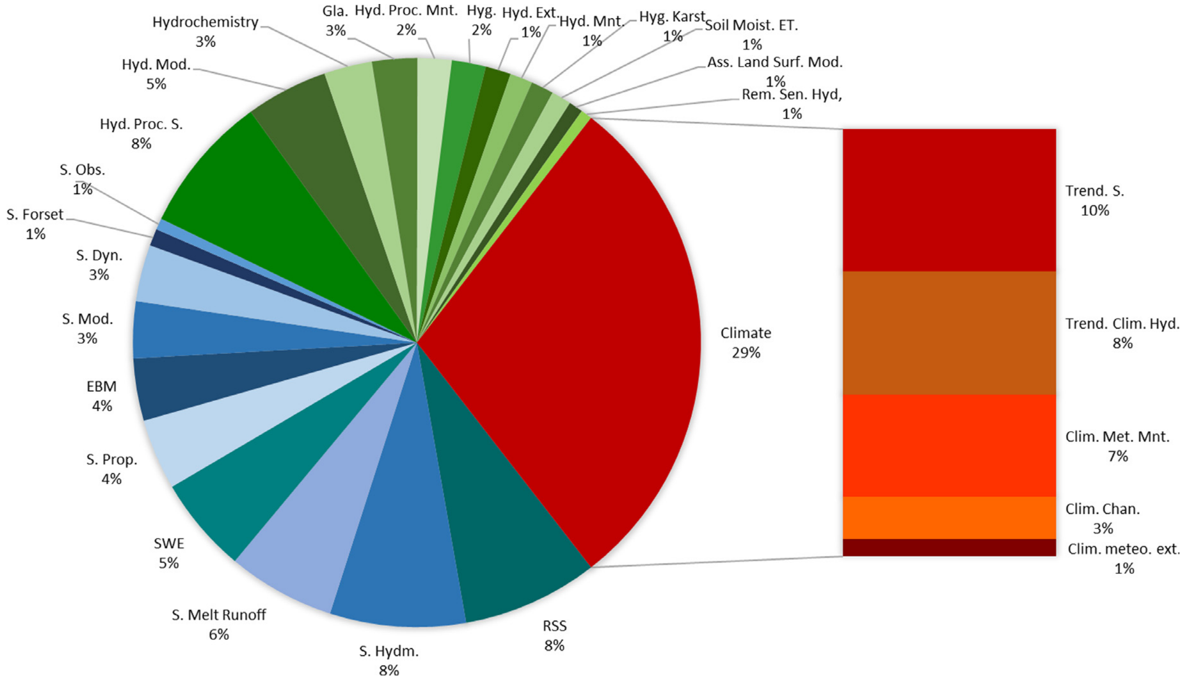

Fig. 5. Distribution of papers by science groups and key sub-categories with emphasis on climate forcing to the snowpack (29% of all studies, shown in red), snow studies (39%, blue), and snowmelt hydrology and hydrogeology (32%, green). S. is snow; Trend S. indicates a study that emphasizes on addressing climate change impacts on snow. RSS indicates a paper that focuses on remote sensing of snow. EBM indicates a study that describes and testes an energy balance model (see Appendix A2 for a detailed list of indicators). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

4. Climate forcing to the snowpack

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

4.1. Near-surface meteorological observations

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

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

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

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

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

4.2. Precipitation

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

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

Precipitation phase determination is often done as post-processing given that most gauges do not detect the phase. The precipitation phase is required to determine the water equivalent during the accumulation season, but also to properly correct precipitation undercatch, and for investigating rain-on-snow events which contribute to the snowpack ablation. Determining precipitation phase from ground observation can be achieved using: (1) thresholds for temperature (e.g., air, dewpoint, and wet bulb) (see Marks et al., 2013), (2) linear transition, range, and sigmoidal curve methods based on near-surface air temperature (e.g., Harpold et al., 2017), and (3) psychrometric energy balance method (Harder and Pomeroy, 2013). Despite the availability of these methods, one of the major limitation for the proper determination of precipitation phase from ground data is attributed to the lack of meteorological observations for stations in near locations to the precipitation gauges (Harpold et al., 2017).

Rain-on-snow events are not uncommon in Mediterranean mountains (Guan et al., 2016). These events help in warming the snowpack and add very high sensible heat to the snowpack through condensation, which accelerates melting and sometimes triggers catastrophic floods (McCabe et al., 2007; Surfleet and Tullos, 2013). In the western US, rain-on-snow-events appear to be partly driven by the El Niño–Southern Oscillation (ENSO), the

Pacific Decadal Oscillation (PDO) (McCabe et al., 2007; Lute and Abatzoglou, 2014) and atmospheric rivers (Trujillo and Molotch, 2014; Guan et al., 2016). To our knowledge, the impacts of rain-on-snow events were not specifically addressed in regions other than the western US. The analysis of rain-on-snow events remain challenging and warrant future investigation (Wayand et al., 2015).

Uncertainties associated with the spatial distribution of precipitation increases with elevation, where differences between datasets ranged between 5 to 60%, exceeding 200 mm yr-1 on average, were reported across the western US (Henn et al., 2017). Different methodologies were developed to compute the integrated precipitation in high-elevation watersheds (Valéry et al., 2010) and to generate gridded precipitation maps from daily ground observation (see Demaria et al. (2013b) and Lundquist et al. (2015a)) for a list of gridded precipitation products). The emergence of gridded precipitation products over the 2000 s has boosted the research in snow hydrology and facilitated the upscaling of point-scale studies. Precipitation grids are invaluable data for distributed hydrological modeling in both the operational and research context, e.g., to perform climate change impact studies at the scale of river basins (Mernild et al., 2016b). While the overall accuracy of gridded precipitation products has been deemed satisfactory, the biases increase with elevation (Mizukami et al., 2011; Lundquist et al., 2015a). Precipitation-gauge undercatch, a poor knowledge of wind patterns to correct the undercatch, and the lack of in situ input data are sources of errors in the gridded precipitation products (Dettinger, 2014; Lundquist et al., 2015b; Mizukami and Smith, 2012). In addition, temporal inconsistencies in multi-year gridded precipitation biases tend to increase the uncertainty in simulating hydrological responses in snow-dominated basins (Mizukami and Smith, 2012).

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

Over the past decade there had been an increase in the use of assimilation techniques and the downscaling of atmospheric model (e.g., Vionnet et al., 2016; Mernild et al., 2016a). These different techniques to estimate precipitation using a combination of ground observations, numerical weather prediction, and remote sensing observations are still not complete and the generated gridded data is at coarser and medium resolution at best (e.g., Quéno et al., 2016). There is more work needed to understand how atmospheric circulation (Jin et al., 2006; Lundquist et al., 2010) and the complex topography at the finer scales (López-Moreno et al., 2015) affects precipitation and snowfall and both topics are interesting field of research. An intercomparison between different gridded precipitation datasets (e.g., Lundquist et al., 2015a; Henn et al., 2017) across different mountain regions is needed. Reducing the bias in precipitation estimates along altitude and enhancing the spatial resolution of gridded precipitation could be the next breakthrough in mountain hydrology.

4.3. Air temperature

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

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

4.4. Radiation and heat fluxes

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

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

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

Our understanding of the energy exchange between the snowpack and the atmosphere in mountains is incomplete. The installation of more complete meteorological stations (including longwave/shortwave sensors and turbulent heat measurement systems) in mountains is needed in order to better characterize the different components of the energy balance. However, this requires solving the issue that eddy covariance systems are not considered reliable in complex terrain.

5. Snowpack

5.1. In situ observations

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

The main variable of interest for snow hydrologists is the SWE, which is obtained by multiplying the snow height by the snow density. The snow height is typically measured with a calibrated snow probe and it is easier to estimate than the snow density, which requires a more elaborate field-work (e.g., Bocchiola and Groppelli, 2010; Sturm et al., 2010; López-Moreno et al., 2011b). Field measurements are usually biased with observational errors (Lundquist et al., 2015b) and uncertainty about the representativeness of in-situ snow depth and density measurements (López-Moreno et al., 2011b, 2013b). Improving the in-situ accuracy of snow course measurements can be achieved by increasing the rate of data sampling along the snow course and minimizing human errors. Findings in the Spanish Pyrenees indicated that increasing the number of in-situ measurements (i.e., using at least five snow depth measurements at 5–10 meter intervals) could ensure a bias of less than 10% when estimating the average snow depth at plots of 100 m^2 (López-Moreno et al., 2011b). The snow density exhibits less variability than the snow depth (López-Moreno et al., 2013b), which implies the need for fewer snow density measurements along each course. Such findings support the US snow courses sampling guidelines, which indicates the need for 10 point measurements of HS, SWE, and density at 30 meter interval (over a 300 m transect) (Rice and Bales, 2010). The same applies for snow sampling approaches in other regions (e.g., Watson et al., 2006; Jost et al., 2007). However, collecting in-situ probe measurements at larger scales remains challenging. Steeps slopes and high-elevation areas (above 3000 m a.s.l) are unsafe and not easily accessible. Airborne and terrestrial Lidar now enable the measurement of HS with a centimetric accuracy at a much higher resolution than manual surveys (Section 5.2.4). However, these techniques remain costly and do not provide continuous observation of HS, such as AWS. A terrestrial time-lapse camera is a cost-effective device used to monitor the snow cover variability in both space and time, but its use is restricted to small spatial scales (less than 1 km^2) (Revuelto et al., 2014). As a result, it is difficult to capture the temporal variability of the HS and SWE by field sampling. On the other hand, continuous AWS measurements of snow depth and SWE remain site specific, and most of the time, they fail to capture the spatial variability of the snowpack due to the spatial heterogeneity of the climate and terrain with respect to the network density (Bales et al., 2006; Gottardi et al., 2012; Raleigh et al., 2016).

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

5.2. Remote sensing of seasonal snow cover

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

5.2.1. Optical remote sensing of the snow cover

The NASA MODIS Aqua/Terra daily snow products (collection 5 MOD10A1 and MYD10A1 (Hall et al., 2002)) are the most widely used. These products have provided the binary snow-covered area (SCA) and fractional SCA (fSCA), and the snow albedo at a 500 m resolution since 2000 for Terra and 2002 for Aqua. The SCA product allows the calculation of the snow cover duration (SCD), snow cover start date (SCS) and snow cover melt-out date (SCM). The SCA and fSCA allow the calculation of the snow coverage in a watershed. MODIS snow products were tested and applied in the Sierra Nevada California (Painter et al., 2009; Molotch and Meromy, 2014), Pyrenees (Gascoin et al., 2015), Southern Alps (Dedieu et al., 2014), Moroccan Atlas (Marchane et al., 2015), Armenian Plateau (Tekeli et al., 2006), and Mount Lebanon (Telesca et al., 2014).

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

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

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

Future improvement of snow cover representativeness from optical remote sensing could include better cloud removal and enhanced snow cover mapping in forested regions. Daily SCA from MODIS are hindered by their spatial resolution of 500 m which is too coarse to capture snow variability in heterogenous mountain slopes, in regions where snow is ephemeral, and at the end of the season when snow becomes patchy. The Sentinel-2 mission with its 20 m spatial resolution and 5 days revisit time is expected to provide better accuracy for mapping SCA in the heterogenous mountain regions.

5.2.2. Remote sensing of SWE

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

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

Despite these limitations of PMs, a number of studies demonstrated that PMs are able to capture the overall seasonal variations of snow accumulation, melt timing, and season length at the macro scale, and in contrast to imaging spectrometry, they are not affected by cloud cover (Foster et al., 2009; Vuyovich et al., 2014). Coupling ground-observed data SCA and PM sensed SWE is being investigated as an alternative for enhancing the SWE estimation in Mediterranean regions (e.g., Vuyovich et al., 2014; Şorman and Beser, 2013).

5.2.3. Snow albedo

The importance of snow albedo in Mediterranean regions has been attributed to the fact that most of the snowmelt is dominated by net radiation (Section 4.1). A decrease in snow albedo results in an increased amount of absorbed shortwave radiation and eventually, an enhancement in the snowmelt. Surface snow albedo changes in Mediterranean mountain regions are associated with snowpack thickness (Tekeli et al., 2006), snow grain size and surface wetness (Dozier et al., 2008, 2009), and snow impurities (mainly mineral dust and organic particles) (Lee and Liou, 2012). In California's Sierra Nevada, the reduction in the snow albedo during the melt season (March to April) is driven by the increase in surface temperature and the increase in the deposition of absorbing aerosols. Both temperature and aerosols contribute to the 61% decrease in snow albedo, and 26% of the albedo reduction was attributed to the increase in the aerosol optical depth (Lee and Liou, 2012). Snow albedo can be calculated by observing the incoming and reflected solar radiation at AWS. Given the lack of in-situ observations, many studies have used optical remote sensing techniques. The method to derive snow albedo from imaging spectrometry is well developed in literature (e.g., Dozier and Painter, 2004; Seidel and Martinec, 2004; Frei et al., 2012; Deems et al., 2013; Tedesco, 2015). In the Mediterranean context, most studies were conducted in Sierra Nevada, California using MOD10A1 or MODSCAG MODIS albedo products (Painter et al., 2003; Dozier et al., 2009; Lee and Liou, 2012). In the Armenian Plateau, the MOD10A1 albedo was found to be consistent with in situ measurements in terms of magnitude and temporal variability, with a small positive bias due to differences in the acquisition time (Tekeli et al., 2006). On the contrary, in the Spanish Sierra Nevada, the coarse-resolution albedo products from MODIS and SPOT underestimated the in-situ snow albedo due to the mixing effects of snow and snow-free patches in a MODIS pixel especially during the melting periods (e.g., Pimentel et al., 2016).

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

5.2.4. High resolution airborne and ground-based remote sensing

Over the past few years, a number of studies have used ground-based terrestrial laser scanners (TLS) and airborne LiDAR to measure the snow depth at high spatial resolution with decimetric accuracy (e.g., in California (Harpold et al., 2014; Kirchner et al., 2014; Zheng et al., 2016), and the Spanish Pyrenees (Revuelto et al., 2014; López-Moreno et al., 2015)). These technologies have enabled numerous fundamental advances in our knowledge of the snow depth distribution (see Section 5.4). They also hold potential for operational snow monitoring if their costs can be mitigated; otherwise, their application will remain restricted to relatively small areas, as noted in the scientific literature (<100 km^2). The NASA Airborne Snow Observatory (ASO) (Painter et al., 2016) is a notable exception since it is run over major water basins in the western US. ASO is composed of an imaging spectrometer and a Lidar altimeter to measure the snowpack reflectance and depth from an aircraft. The SWE maps are produced over 48 h using the snow reflectance as a proxy for snow density (Dozier et al., 2016). Recent alternatives were proposed to determine the snow depth at high resolution and at a lower cost: (1) an unmanned aircraft vehicle photogrammetric survey, and (2) high-resolution stereo satellite imagery (Marti et al., 2016).

5.3. Methods of HS and SWE regionalization

5.3.1. Regionalization

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

5.3.2. SWE reconstruction

Dozier et al. (2016) reviewed the methods to generate spatially distributed SWE as follows: (1) spatial interpolation from ground based networks only using statistical models, such as decision trees (Anderton et al., 2004); (2) constrained interpolation by remotely sensed SCA (Girotto et al., 2014); (3) SWE reconstruction using snow modeling (e.g., Raleigh and Lundquist, 2012; Guan et al., 2013b); and (4) reconstruction using data assimilation (Cortés et al., 2016) (see Section 6.1) and backmelt calculations (e.g., Raleigh and Lundquist, 2012), which may be combined with time-lapse photography (Revuelto et al., 2016a). The increase in the reliance of SWE reconstruction had been motivated by the assumption that knowledge of melt energy fluxes would be superior to knowledge of precipitation accumulation (Cline et al., 1998; Jepsen et al., 2012; Slater et al., 2013).

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

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

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

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

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

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

5.4. Snowpack spatial variability

5.4.1. Snow height spatial variability

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

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

Radiation: potential incoming solar radiation; Relative elevation (Inc. topographic position index (TPI) and combined TPI); Upwind slope: maximum upwind slope. Scale (micro 1–102 km^2; meso 102–104 km^2; macro > 104 km^2).
Sources: [1] Elder et al., 1998; [2] López-Moreno and Nogués-Bravo, 2005, 2006; [3] Anderton et al., 2004; [4] Zheng et al., 2016; [5–6] Revuelto et al., 2014, 2015; [7] Molotch et al., 2005; [8] López-Moreno et al., 2010; and [9] López-Moreno et al., 2015.

explaining snow distribution and depth, and the level of uncertainty in Mediterranean mountain regions.

For example, in Sierra Nevada California, Elder et al. (1998) obtained a model that could explain up to 70% of the observed variance in HS using the elevation, net radiation and slope as predictors. According to Molotch and Meromy (2014), snow cover persistence is driven by mountain controls where elevation (the most explanatory variable) and climate controls of precipitation and temperature determined most of the snow variability. Vegetation and slope ranked second in explaining part of the snow cover variability, whereas shortwave solar radiation and the terrain aspect were of tertiary importance. Similar findings were reported in the Spanish Pyrenees, which indicates that elevation and solar radiation explain a high percentage of the variance in HS (Anderton et al., 2004; López-Moreno and Nogués-Bravo, 2006).

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

Despite these encouraging results, to date, there is no accepted universal law to derive HS or SWE from a set of predictors that can be obtained anywhere. This is because the link between the terrain parameters and the snow distribution is not fully explained at the small scale (e.g., Molotch et al., 2005; López-Moreno et al., 2010, 2015; Revuelto et al., 2014; Zheng et al., 2016). This quest is hindered in particular by (1) the high inter-annual snow variability in Mediterranean regions, since most studies rely on 1–2 years of sporadic observations (e.g., Anderton et al., 2004; López-Moreno et al., 2010; Zheng et al., 2016), and (2) the increase in the scale dependency of the model results (e.g., the importance of elevation) as the grid cell size increases (López-Moreno et al., 2010).

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

5.4.2. Snowpack density

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

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

5.4.3. SWE

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

6. Snowmelt hydrology and hydrogeology

Once snowmelt occurs, the snowpack water is channeled through surface outflows and streams, and it undergoes evapotranspiration, subsurface flow and groundwater recharge via deep percolation (e.g., Knowles and Cayan, 2004; Franz et al., 2010; Lundquist and Loheide, 2011; Smith et al., 2013; Manning et al., 2012; Godsey et al., 2014). Given the spatio-temporal variability of the climatic conditions that were highlighted in the previous sections, the closure of the hydrologic budget in Mediterranean snow-dominated basins remains challenging (e.g., Ralph et al., 2016). In addition, several authors point to a limited understanding of surface and sub-surface hydrologic processes in mountains (Bales et al., 2006; Smith et al., 2013).

6.1. Snowmelt modeling

6.1.1. Snow melt models

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

Major sources of uncertainty in snow melt simulation arise from (1) the error in the input data (particularly precipitation), (2) reliance on DDM (due to limited information on incoming and reflected radiation and fluxes), which usually translates into the lack of accounting of snow sublimation, and (3) the model parameterization regarding rain/snow separation and turbulent fluxes (Franz et al., 2010; He et al., 2011; Raleigh and Lundquist, 2012; Slater et al., 2013; Avanzi et al., 2014). Snow model intercomparison studies in Mediterranean mountain regions (Franz et al., 2010; Slater et al., 2013) and elsewhere (Molotch and Margulis, 2008; Essery et al., 2013; Bavera et al., 2014) indicate that while very large differences can exist between models (different melt algorithms), proper simulation of snowmelt is highly associated with the proper parameterization of models (e.g., Smith et al., 2013) and the model's ability to solve SWE with high confidence (e.g., Franz et al., 2010). To the best of our knowledge the only snow-hydrological model comparison studies, which include Mediterranean catchments, are the studies of Franz et al. (2010) and Valéry et al. (2014a, 2014b). We believe that there is a need for testing and comparing different snow models and carrying out meaningful intercomparison exercises across different Mediterranean mountain regions. The reader is advised to look at model parameterizations and sensitivity (Clark et al., 2011; Garcia et al., 2013), the intercomparison in forested snow regions (e.g., Essery et al., 2009; Rutter et al., 2009), the influence of soil moisture response on snow distribution and melt (Bales et al., 2011; Kerkez et al., 2012; Harpold et al., 2015), single model SRM multi-site comparison (e.g., Martinec and Rango, 1986; Seidel and Martinec, 2004; DeWalle and Rango, 2008), ensemble model simulations (e.g., Franz et al., 2010; Essery et al., 2013), and the snow model intercomparison project (MIP) (e.g., DMIP (Smith et al., 2013) and SNOWMIP2 (Essery et al., 2009)).

6.1.2. Large-scale land surface models and assimilation techniques

The modeling of large-scale distributed cryospheric processes had been made possible through the application of the following: (1) finer scale land surface models with snow schemes (e.g., Boone et al., 2004; Livneh et al., 2010; Brun et al., 2013; Magand et al., 2014a,b; Singh et al., 2015); (2) physically based simulations using mesoscale WRF model (Caldwell et al., 2009; Pavelsky et al., 2011, 2012; Wayand et al., 2013; Liou et al., 2013; Franz et al., 2014; Oaida et al., 2015); (3) blending snow sensor observations and remote sensing data with snowmelt model simulations (e.g., Guan et al., 2013a; Rittger et al., 2016), and using data assimilation (e.g., Franz et al., 2014; Girotto et al., 2014) of ground and remote sensing data with Land Surface Model (Zaitchik and Rodell, 2009; Hancock et al., 2013) and Snow Data Assimilation System (SNODAS) (Guan et al., 2013a; Vuyovich et al., 2014); and (4) reanalysis of ground data (Gottardi et al., 2012; Avanzi et al., 2014), remote sensing data (Margulis et al., 2016), and land surface data (e.g., Durand et al., 2009; Vidal et al., 2010; Rousselot et al., 2012; Rutz et al., 2014).

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

6.2. Snowmelt contribution to runoff and groundwater

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

6.2.1. Snowmelt runoff

The simulation of the streamflow in snow-dominated Mediterranean regions was successfully achieved using lumped rainfall-runoff models with a snowmelt routine (e.g., Karpouzos et al., 2011), a distributed statistical model that combines remote sensing SCA and ground observation (e.g., Gómez-Landesa and Rango, 2002; Powell et al., 2011; Akyurek et al., 2011; Biggs and Whitaker, 2012), and a physically based distributed hydrologic model that balances both surface energy and water budgets and accounts for snowmelt using snowpack energy balance routines, such as the variable infiltration capacity (VIC) model (Maurer et al., 2007) and the Distributed Hydrology Soil Vegetation Model (DHSVM) (e.g., Wayand et al., 2013; Cristea et al., 2014). Apart from the modeling approach, the relationship between snowmelt and streamflow in Mediterranean snow-dominated regions has also been successfully addressed by the empirical analysis of streamflow data against observed SWE (Lundquist et al., 2004) and tracer tests (Liu et al., 2013).

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

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

6.2.2. Snowpack control on soil moisture and evapotranspiration

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

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

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

In Mediterranean regions, high-elevation areas are usually snowmelt-dominated whereas lower-regions are evapotranspira tion/infiltration-dominated (Lundquist and Cayan, 2002). Evapotranspiration tends to be low during the winter season through the beginning of the melt season due to the presence of the snow cover and at late summer and autumn due to soil dryness. During the melt season, the combined effect of increasing air temperatures and solar radiation tends to accelerate snowmelt, enhance water availability in soil, and increase surface temperature, which results in increased evapotranspiration (Leydecker and Melack, 2000). The inter-annual evapotranspiration is controlled by elevation and aspect, which define the amount of incoming solar radiation (Goulden et al., 2012; Lundquist and Loheide, 2011). Evapotranspiration in mid-altitude regions is usually water-limited, i.e., controlled by the precipitation (Christensen et al., 2008; Lundquist and Loheide, 2011), whereas in higher snow-dominated regions, it is relatively energy-limited, i.e., it responds more strongly to temperature variations (Christensen et al., 2008; Lundquist and

Loheide, 2011; Schlaepfer et al., 2012; Godsey et al., 2014; Jepsen et al., 2016a). Based on a number of papers reported in Jepsen et al. (2016a), the evapotranspiration in Sierra Nevada California under a warming climate, has an overall tendency to increase (medium confidence) in snow-dominated regions, and some regions are either susceptible to warming or expected to experience a slight decrease.

6.2.3. Groundwater recharge

Groundwater studies in Mediterranean mountain are most of the time presented at the basin scale and they provide little information on the link between snowpack dynamics and groundwater processes. Groundwater recharge in snow-dominated regions is dominated by the timing of the snowmelt (early or late spring) and the subsurface flow (Tague and Grant, 2009). In groundwater-dominated watersheds, the aquifer storage and the slow recession can help in sustaining discharge during the summer dry periods even under a negative yearly water balance (Jefferson et al., 2008). Despite its importance, the lack of extended studies has resulted in the availability of negligible information on the extent of snowpack control on groundwater resources in most Mediterranean mountains (e.g., Palmer et al., 2007; Lowry et al., 2010, 2011; Liu et al., 2013; Valdés-Pineda et al., 2014). The separation between rain-fed and snow-fed groundwater recharge is still incomplete due to a number of factors: (1) lack of groundwater wells and monitoring networks, (2) complex geology especially in karst regions (e.g., Hartmann et al., 2014; Tobin and Schwartz, 2016), and (3) the complexity of subsurface flows in mountain regions (e.g., Knowles and Cayan, 2004; Tague and Grant, 2009; Millares et al., 2009; Godsey et al., 2014). A comprehensive review on the different groundwater mechanisms and the importance of snow in groundwater recharge under projected warming scenarios over the western US can be found in the work of Meixner et al. (2016).

The link between snowmelt and groundwater spring discharge at the mesoscale in Mediterranean regions was addressed by using hydrochemical analysis. Studies on experimental snow-influenced micro- to mesoscale basins in Sierra Nevada California (Taylor et al., 2001; Friedman et al., 2002; Rademacher et al., 2005; Huth et al., 2004; Shaw et al., 2014), Oregon (Palmer et al., 2007), Serra da Estrela Mountain Portugal (Carreira et al., 2011), Sierra Nevada Spain (Fernández-Chacón et al., 2010), and the Southern Italian Alps (Penna et al., 2015) demonstrated the potentials for using stable isotopic analysis for hydrograph separation between snow-fed, rain-fed and groundwater-fed sources and to investigate flow paths (Bales et al., 2006), and the evolution of snowmelt (Taylor et al., 2001). Tracer tests were used to (1) separate between snowmelt runoff (including rain on snow) (Williams et al., 2001), subsurface flow and fall storm runoff (Liu et al., 2013; Perrot et al., 2014) and shallow evapotranspired groundwater from groundwater sources (Shaw et al., 2014), and (2) investigate meltwater-driven surface runoff and catchment transit time (e.g., McGuire and McDonnell, 2010). General chemical analyses also provided reliable information on the state of water residence time in springs (Rademacher et al., 2005). The karst aquifers are of particular relevance in the Mediterranean region since they represent a key source of freshwater supply for the people living in the Mediterranean basin (Doummar et al., 2014). The estimation of groundwater recharge from snowmelt in karst regions had been limited to mid and low latitude micro-scale snow-influenced mountainous regions with studies in southern Europe Spain (Andreo et al., 2004), Italy (Allocca et al., 2014), Greece (Novel et al., 2007), and the eastern Mediterranean regions of Mount Lebanon (Bakalowicz et al., 2007). A pioneering study in the mid-altitude mountain region in Crete showed promise for simulating the contribution of snowmelt to karst hydrosystems by coupling a karstic model and an energy balance snow model (Kourgialas et al., 2010).

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

7. Conclusion

The review of 620 papers published between 1913 and 2016 demonstrated that the science behind snowpack dynamics (energy and mass fluxes) and hydrological process in Mediterranean mountain regions is well developed. The number of studies that are dedicated to the snow in Mediterranean regions also reflects the societal importance of the topic in the context of climate change, economic development and population growth. The use of indicators helped in highlighting major snow hydrologic processes in Mediterranean mountains. In specific areas, such as in identifying major drivers for snowpack dynamics, it was difficult to draw definitive conclusions given the variety of approaches (e.g., different major drivers and methods). Our classification of Mediterranean mountains encompasses a large range of geologic and physiographic conditions. Despite the fact that the theory behind hydrologic processes in mountains is well established, drawing a common conclusion remains difficult beyond the case studies because the limited number of studies in this area of research area and the variety of approaches used (e.g., different models).

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

In Mediterranean mountain regions snowmelt are exposed to (1) periods of low precipitation or high temperature causing “snow drought” (Cooper et al., 2016), (2) heatwaves, (3) rain on snow events, and (4) and dust deposition on the snowpack. Increasing air temperatures will lead to a shift in precipitation regime with elevation (i.e., rain to snow and increase in rain-on-snow events). The dust deposition tends to enhance the snow melt by increasing the radiative exchange due to the decrease of snow albedo. Understanding snowmelt sensitivity to these climate variables is of primary importance to improving our knowledge on the hydrologic processes and water resources system responses in mountain regions and downstream areas.

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

Data assimilation portability to different regions is hindered by the reliance on larger data sets as input variables. In regions with limited ground-based observations, model outputs can be biased by an increased uncertainty. Similarly, the reliance on multiple other technologies (e.g., ground-based and remote sensing observations) makes the system highly dependent on the simultaneous availability of data from all systems (Guan et al., 2013a). The results using reanalysis of remote sensing data (Margulis et al., 2016) and physically based simulations run using the mesoscale WRF model (e.g., Caldwell et al., 2009; Wayand et al., 2013) seem to provide better results of SWE in regions with limited station data. One of the promising areas for research is the development of combined products, which include ground observations and remotely sensed data through data assimilation in snowpack models.

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

Advancing our understanding of hydrological processes in Mediterranean mountains is partly hindered by the sparse meteorological stations and hydrological gauging networks, and the large uncertainty in key variables, such as the stream flow in headwaters catchments (Avanzi et al., 2014; Lundquist et al., 2015b; Raleigh et al., 2016). In addition, there remain challenges in taking advantage of these advances in catchment hydrology because the response of the streamflow to the snowmelt is modulated by other hydrologic processes (ET, infiltration, groundwater flow). These processes are more strongly influenced by the subsurface properties (soil, geology), and hence, they are less easily constrained by current observational networks, remote sensing and modeling technologies. Closing on the water balance in Mediterranean mountain regions seems to be only feasible when these processes are solved simultaneously. Understanding of the connection between snowmelt, streamflow, evapotranspiration, and groundwater flow in snow-dominated regions is an open field for future research (e.g., Jefferson et al., 2008; Liu et al., 2013; Godsey et al., 2014; Jepsen et al., 2016a). Furthermore, there is a need to integrate human processes, such as reservoir management and irrigation, to investigate the vulnerability of the water resources under global change scenarios (e.g., Maurer et al., 2007; López-Moreno et al., 2008b; Viviroli et al., 2011; Anghileri et al., 2016).

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

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.jhydrol.2017.05.063.

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