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Review papers

Snow hydrology in Mediterranean mountain regions: A review

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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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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