Evaposublimation from the snow in the Mediterranean mountains of Sierra Nevada (Spain)

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Abstract. In this study we quantify the evaposublimation and the energy balance of the seasonal snowpack in the Mediterranean semiarid region of Sierra Nevada, Spain (37° N). In these kinds of regions, the incidence of this return of water to the atmosphere is particularly significant important to the hydrology and water availability. The analysis of the evaposublimation from snow allows us to deduct the losses of water expected in the short and medium term, and is critical for the efficient planning of this basic and scarce resource. To achieve this, we performed 15 test 10 field campaigns from 2009 to 2015, during which detailed measurements of mass fluxes of a controlled volume of snow were recorded using a modified version of an evaporation pan with lysimeter. Meteorological data at the site of the snow control volume was extensively monitored during the tests. With these data, a point energy balance snowmelt model was validated for the area. This model, fed with the complete meteorological dataset available at the Refugio Poqueira Station (2500 m -a.s.l.), let us estimate that evaposublimation losses for this site can range from 24 to 33% of total annual ablation. This ratio is changeable very variable throughout the year and between years, depending on the particular combination and timing of the meteorological inputs, generally unforeseeable occurrence of snowfall and mild weather events, which is generally quite erratic in this semiarid region. Evaposublimation proceeds at maximum rates of up to 0.49 mm h^{-1}, an order of magnitude less than maximum melt rates. However, evaposublimation occurs during 60% of the time that snow lies, while snowmelt only takes up 10% of this time. Hence, both processes remain close in magnitude on the annual scale.

1 Introduction

Seasonal snow can occur in temperate areas at increasing altitudes as the latitudedescends with decreasing latitude. In these mountainous regions, snow becomes the primary source of water during the year (Shaban et al., 2004) and rules its availability and timing. Snow plays a vital role as a source of water supply for human consumption, irrigation, and survival of species and habitats during the dry season. Any debate and management decision regarding water use and sustainability in these drought–prone areas must be based on the accurate knowledge of the snowpack dynamics. In this context, the partitioning of ablation into melting and evaporation/sublimation determines the water return to the atmosphere and the replenishment of surface and groundwater. This is particularly relevant in a scenario of global warming that implies a potential snow regression in these areas because of impacts on the energy and mass flux regimes (Pérez-Palazón et al., 2015).

Significant research has been carried out on snow dynamics (Garstka, 1964; Mellor, 1964; Colbeck, 1982; Morris, 1989), especially on the description of the energy balance that drives the different mass fluxes of ablation that affect the snowpack (Anderson, 1968; Kuusisto, 1986; Jordan, 1991; Marks and Dozier, 1992; Tarboton and Luce, 1996). Generalization for mountainous areas is particularly difficult as energy balance changes with elevation, aspect and vegetation cover since these factors modify the local temperature, wind exposure, and shadowing of solar and longwave radiation. Besides, in Mediterranean regions these meteorological variables are subject to the characteristic irregular weather patterns. As a consequence of this variability, annual snowmelt timing can shift from a single typical main springtime melting cycle to several mid–winter partial or complete melting cycles.

The snow dynamics in semiarid environments is so dependent on the energy state of the snowpack, that accurate modelling usually requires physical approaches that calculate the energy balance (Schulz and de Jong, 2004). Many of the problems usually found when validating the models and quantifying the actual evaporation taking place are due to the difficulty of taking measurements under rough winter conditions typical of high mountain areas. To begin with, automatic ground sensors are difficult to maintain operational long enough to obtain ~~significant~~ continuous data series over a period of years. In addition, the spatial variability of the snowpack makes it difficult to produce a realistic estimate of the snow processes, which change substantially over small distances, according to aspect and elevation. Satellite images are a good source of ~~distributed~~ spatial data, but they mostly provide direct information only about the presence or absence of snow (Hall et al., 2002). Research is currently being carried out into the estimation of other snow variables, like snow water equivalent, from satellite sources, and in most cases it requires the joint use of remote sensing and energy balance modelling (Cline et al., 1998; Molotch and Margulis, 2008).

One of the mass balance fluxes ~~of snow~~ in the snowpack is the water vapour exchange between the snow surface and the atmosphere~~, and~~ . It is directly linked to the latent heat ~~balance. Evaporation and sublimation of water from the snow surface occur alternately depending on the phase it is in~~flux and it is governed by the complex turbulent phenomena occurring in the boundary layer. The evaposublimation process requires a high amount of energy available at the snowpack to complete the phase transition (e.g., Strasser et al., 2008). The evaposublimation rate ~~depends on~~ can be calculated as a function of the vapour pressure gradient between the surface of the snow and the air, ~~which is mainly~~ and it is decisively influenced by the local wind intensity ~~, and hence, by the complex turbulent phenomena occurring in the boundary layer~~and turbulence. This makes both its measurement and its simulation one of the most complicated elements of all the fluxes involved in the energy balance in the snowpack. Numerous studies have focused on measuring and estimating evaposublimation losses from snowpacks in forested (Schmidt et al., 1998; Molotch et al., 2007) and unforested areas (Pomeroy and Essery, 1999; Fassnacht, 2004). ~~Evaposublimation rates are substantially enhanced in the latter (West, 1962).~~ Mountainous areas provide particularly good conditions for evaposublimation due to their inherently lower vapour pressure and higher wind speed (Gray and Prowse, 1993). In this kind of topography, it is not uncommon to experience periods with strong wind and low humidity (Herrero et al., 2009) that trigger high evaposublimation rates. Schulz and de Jong (2004) remark that high solar radiation and rising air temperatures, usual in semiarid environments, support evaposublimation as long as the snowpack remains cold and snowmelt does not dominate in the ablation process.

Given the conditions described for semiarid mountainous areas, the spatial and temporal variation of the evaposublimation rates from the snow may be considerable. Under this constraint, it is difficult to give a meaningful average value. Leydecker and Melack (2000) calculated that the average annual evaporation from the snowpack was 36% of the annual precipitation in Sierra Nevada, California (37°N and 3000 m . a.s.l.), while its magnitude varied from 12 to 156 mm between years (Leydecker and Melack, 1999). Froyland (2013) estimated the amount of evaposublimation in the semiarid San Francisco Peaks of the Colorado plateau (35°N and 2100 m . a.s.l.) in a range of between 17% and 43% of the annual snowfall. A similar result was obtained by Herrero et al. (2009) in Sierra Nevada, Spain (37°N and 2500 m . a.s.l.), where an annual evaposublimation of between 21% and 42% was calculated for two consecutive years using a physical snow model. This change in the evaposublimation rates from the snow raises doubts about its actual effect on the overall basin hydrology. Only the dating of snow accumulation is accepted as a critical factor for establishing the annual evaposublimation rate and the runoff efficiency of high elevation snowpacks (Avery et al., 1992).

Evaposublimation from the snowpack can be measured at single points on the ground using different methodologies. 1) Snow water equivalent sensors (Johnson and Marks, 2004) and snowmelt lysimeters with snowpillows (Tekeli et al., 2005) are used in conjunction with the methodology developed for studying evapotranspiration on agricultural lands. Snow lysimeters are a suitable field method for estimating the permeability of a snowpack (Datt et al., 2010). The main problem of these devices is is that the snow conditions above these automatic devices may differ from those in the natural snow because of the disturbance of the snow–ground interface (Dingman, 2002) or the appearance of snow bridging. Besides, there is a poor correspondence between the meltwater produced at the snow surface and the water arriving at the base of the snowpack on a unit–area basis(Kattelmann, 2000). This is due to several factors such us snow bridging, sensitivity of the sensors to changes in humidity and temperature, and their need for constant maintenance because of the adverse meteorology. Besides, unenclosed snowmelt lysimeters allow lateral flow of water into and out of the column of snow overlying the collector. In , which is a problem when we want to test snow energy balance models (Kattelmann, 2000). Moreover, in semiarid mountain areas, the snow pillow measurements are adversely influenced by the typically shallow snow cover and the frequently high wind speed (Schulz and de Jong, 2004). 2) A second approach is based on eddy covariance (EC) systems (Baldocchi et al., 1988) for direct measurement of the vertical turbulent fluxes of sensible and latent heat from the snowpack. This technology has been employed to calculate sublimation over snow in terrains of varying complexity (Pomeroy and Essery, 1999; Molotch et al., 2007; Marks et al., 2008), most of them in forested areas and over short periods of time. EC systems allow for the most direct measurement of latent heat flux and provide valuable high–resolution (typically 10 Hz) time data series. However, the instruments required for taking these measurements are complex, fragile, and require large, clear, low–angle areas to function optimally (Froyland, 2013). Experiments EC instrumentation is quickly evolving during the last years, and successful applications under a wide variety of environments can already be found (e.g., Reverter et al., 2010; Eugster and Merbold, 2015; Knowles et al., 2015), as it is no longer as complex and fragile as it used to be (Hock, 2005). EC provides very accurate point measurements, even though the translation of these point data to a surface area still represents a challenge nowadays (Eugster and Merbold, 2015). However, experiments using EC systems are still expensive and time consuming, as the data obtained demand complex and rigorous analysis with corrections and post–processing to ensure measurement accuracy (Reba et al., 2009). 3) A final approach is based on the evaporation pan method (Doty and Johnston, 1969; Föhn, 1973; Lemmelä and Kuusisto, 1974; Avery et al., 1992; Radionov et al., 1997; Hachikubo, 2001). This traditional technology is a simple, inexpensive, and portable means of measurement based on the monitoring of a sample of snow collected *in situ* into a container that does not appreciably alter the natural snow conditions. It can be considered as a small–scale snowmelt lysimeter that works for short periods of time during which the device is not left unattended. This methodology has been commonly used in alpine environments (Kaser, 1982; Suzuki et al., 1999; Jackson and Prowse, 2009; Froyland, 2013) where rough meteorological conditions prevent the use of the more precise but delicate instrumentation. The main disadvantage of this method is that it provides us with discrete results that have to be obtained manually, and, with respect to EC, that it needs some adequate measures or estimates of the parameters used for calculating the turbulent exchange of latent and sensible heat.

The objective of this work is to assess the significance and time variability of the evaposublimation losses from the snowpack in the Mediterranean semiarid mountains of Sierra Nevada (Spain). Model performance and reliability is tested against direct measurements of evaposublimation and melting carried out using a portable version of an evaporation pan with lysimeter in ~~15~~ 10 field campaigns throughout this region under different weather conditions from 2009 to 2015. Insights into the processes governing evaposublimation are obtained by using an energy balance snow model (Herrero et al., 2009) fed by a detailed meteorological dataset (2008–2015) from the Refugio Poqueira weather station (2500 m ~~.~~a.s.l.), and calibrated using the recorded ablation data.

2 Study area

Sierra Nevada is a linear mountain range, 90 km long and 20 km wide, parallel to the Mediterranean coastline of southern Spain and situated at an approximate latitude of 37°N. The highest peak stands at 3479 m ~~.~~a.s.l. at a distance of approximately 40 km from the sea (Fig. 1). This “island” of high mountain climate and snow surrounded by Mediterranean semiarid conditions is relatively recent in geological terms, having been formed during the Alpine Orogeny, that brought out ancient materials of the Triassic period. Sierra Nevada’s more than twenty peaks over 3000 m ~~.~~a.s.l. are aligned along a west–east axis that divides the area into a north–continental and a south–Mediterranean climatic zone. These zones exhibit strong differences associated with their topographic gradients, coastal exposure to the south, and the prevailing winds from the west. The northern face hosts a major ski resort, the southernmost of Western Europe, which relies upon artificially created snow to maintain a continuous snowpack during the whole ski season, typically from late November to April/May.

Physical characteristics and location have favoured a rich flora and fauna, and have led to Sierra Nevada’s classification as a biodiversity hotspot, with official recognition as a UNESCO Biosphere Reserve (1986), National Park (1999), LTER (Long–Term Ecological Research) site (2008), and Nature 2000 site (2012). Snow occurrence and persistence are the main drivers of the hydrological dynamics of Sierra Nevada. By buffering the generation of runoff and maintaining soil moisture, these dynamics prolong water flow in rivers well past the wet season, and ultimately determine habitat distribution.

During the winter season, a continuous snowpack is likely to persist above 2500–3000 m a.s.l., though often interrupted by periods of intense melting. Even during the summer, areas of patchy snow can be found above 3000 m a.s.l. in wind–protected spots, especially on the north face, even though their maintenance between years is subject to the intensity and timing of the snowfall events. Precipitation varies greatly in space, with elevation, longitude and face (north/south), and between years. The mean annual precipitation on the west side of the Sierra, facing the prevailing direction of incoming storms, is 550 mm at 1000 m a.s.l. and 750 mm at 2000 m a.s.l. On the opposite side, on the east and the north–east, there is an important rain shadow effect that diminishes this mean annual precipitation down to 300 mm at 1000 m a.s.l. and 465 mm at 2000 m a.s.l. The mean gradient of precipitation with elevation along the entire Sierra is about 150 mm km^{-1} above 1300 m a.s.l. Snowfalls occur mainly from November to April at altitudes above 2000 m a.s.l. At the Refugio Poqueira weather station (2500 m a.s.l; Fig. 1), the average precipitation is 889 mm per year, 59% of which occurs as snow. The variability between years makes the precipitation oscillate greatly between 1426 mm for a wet year and 520 mm for a dry one. The fraction of solid precipitation also varies between 88% and 46%, with a general tendency to be higher with lower annual precipitation values. The difference in total snowfall varies from 910 mm in a wet year to 335 mm in a dry year. The amount of rain on accumulated snow (rain–on–snow events) averages 117 mm per year, ranging from 7 to 223 mm depending on the particular circumstances of each year. The wind speed is high, with an average of 3.4 m s^{-1} at this station.

To study the evaposublimation dynamics, ~~15~~ 10 field surveys were carried out on both the northern and southern faces of Sierra Nevada, always on sites without snow–vegetation interactions. The southern tests were performed at the Refugio Poqueira, a monitoring site which has been operational since 2004. It is equipped with an alter–shielded rain gauge to improve snow catch in windy conditions (Alter, 1937), and sensors monitoring the main variables of impact on the energy balance of the snow: temperature, relative humidity, short and longwave radiation (since 2008), wind speed, and pressure. Since 2009, a digital camera has registered the daily spatial variation of the snow cover fraction and depth over a 30x30 m area at this site (Pimentel et al., 2015). Snow surveys are carried out throughout the winter season, with systematic measurements of the physical properties of the snowpack.

Tests on the north side were conducted above the town of Pradollano (Fig. 1), at different locations with elevation ranging between 2400 and 2600 m a.s.l., since no permanent monitoring sites were available on this face. Portable weather stations were used during the surveys to monitor the weather variables listed above. Although the weather conditions are not very different from those in the south in terms of precipitation and cloudiness, the north–facing slopes receive lower effective surface radiation than south–facing ones. This favours the existence of shady areas, especially in winter, which in turn affect temperature and soil moisture. Snow remains colder and stays on the surface for longer. Vegetation and ecosystems are also affected by this shadow effect (Dionisio et al., 2012).

3 Methodology

The energy and mass balance snow model designed by Herrero et al. (2009) was used to analyse the ablation processes at the study area from the field data collected during different surveys performed on the snowpack from 2009 to 2015. During these field surveys, the actual evaposublimation and melt rates were measured under different atmospheric conditions and at different stages of the snow season. The evaposublimation regime was assessed from the model simulation for the complete study period 2008?–2015 2008–2015 using 5–min weather data series available from the Refugio Poqueira monitoring site.

3.1 Snow model

The energy and mass balance equations in Herrero et al. (2009) are applied over a 1–layer vertical column in the snowpack to simulate the evolution of the snow water equivalent (SWE), the snow depth, and both the snowmelt and evaposublimation fluxes. The model is driven by time series of the following meteorological data: precipitation, air temperature, relative humidity, wind speed, solar radiation and incoming longwave radiation. Its physical structure follows the approach of models like those presented by Tarboton and Luce (1996) or Koivusalo and Kokkonen (2002). This kind of energy balance models with a simplified snowpack structure have provided a reliable performance and short runtime, while making use of a limited number of parameters to provide an appropriate representation of the processes that govern the snow dynamics (Magnusson et al., 2015). In this model, two calibration parameters are selected (Herrero et al., 2009), the snow roughness and the sensible heat–transfer coefficient under windless conditions.

The basic equations of the balance, as well as the definition of the different mass and energy terms, and some improvements on the original model regarding snowfall partition, albedo and longwave radiation, are included in Appendix A, while further details of the numerical resolution of the algorithm and its application to Sierra Nevada can be found in Herrero et al. (2009). Some improvements on the original model regarding snowfall partition, albedo and longwave radiation are described below.

Precipitation is directly measured by the weather station in every case. It is partitioned into rain or snow using the wet bulb temperature, T_w. This is taken as the temperature for the rain, which is considered frozen if $T_w <= 0$°C. T_w can be estimated from the temperature of the air, T_a, the relative humidity of the air, W_a, and the atmospheric pressure, P_a, using Normand's Rule (e.g., Stull, 2000).

The shortwave albedo of the snow , α, is a property of the snowpack surface that changes with time, usually decreasing as the snow grain size increases. Albedo plays an important role in the energy balance of the snow, especially during the melting periods. This influence is even greater in semiarid mountainous areas because of the high solar radiation rates, small zenith angles and a very dry and clean atmosphere (Aguilar et al., 2010; Abermann et al., 2014). In this model , if no measurements are available, α is parametrised as a function of the snow surface age between a maximum value of 0.8 for recent snow and a minimum of 0.4 for old snow. The ageing process is predicted with a linear decay with time (Baker et al., 1990; Pimentel et al., 2013) slower for cold snow (0.006 day^{-1}) than for melting snow (0.018 day^{-1}). New snowfall refreshes α at a rate of 0.05 mm^{-1} of new SWE.

The equivalent atmospheric emissivity, ε_a, is used to calculate the incoming longwave radiation, L_{down}, from the temperature of the atmosphere. The model can work with direct measurements of L_{down} where available, or estimate ε_a from the near–surface temperature, relative humidity and clearness index (related to solar radiation and cloudiness) using the empirical expression of Herrero and Polo (2012) .

~~Finally, the snow model~~ The snow model includes two main parameters, explained in Appendix A, that are usually subject to calibration ~~under semiarid/Mediterranean conditions~~ when no reliable and/or extensive measurements are available for them: the ~~aerodynamic~~ roughness length of the snow z_0, a parameter with influence on both the bulk latent–heat and sensible–heat transfer coefficients, ~~K_{UE}~~ K_{LE} (Eq. A5) and K_H (Eq. A6), respectively, and the sensible–heat transfer coefficient in windless conditions, K_{H0} (Eq. A4).

Although the concept of ~~aerodynamic~~ roughness length is well defined from a theoretical viewpoint, it is difficult to establish its real value under field conditions~~(Calanca, 2001)~~. Anderson (1976) measured values of z_0 for seasonal snow cover that vary from 0.1 to 38 mm, while Dingman (2002) proposed reducing this interval to values between 0.5 and 5 mm. King et al. (2008) show measurements for z_0 that lay in the interval from 0.2 to 4 mm for seasonal snow cover, even though these values can increase up to 20 mm on metamorphosed snow with undulating surfaces. This corresponds to a range of two degrees of magnitude for a parameter that has an important effect on the result of the mass and energy balance in Eq. (A1) and Eq. (A2) (Hock, 2005; Brun et al., 2008). Its simulation is complicated and problematic since, as well as evolving over time for the same surface during its metamorphosis (Plüss and Mazzoni, 1994) and being related to wind speed (Andreas, 2011), it lacks a well–defined physical meaning (Hock, 2005). For simplicity, in many modelling applications z_0 is regarded as constant throughout the simulation (Tarboton and Luce, 1996; Essery et al., 1999), and no discrimination is made between z_0 ~~and~~ as the roughness length for momentum and the roughness lengths for water vapour pressure and ~~the roughness length~~ for temperature (e.g. Braithwaite, 1995; King et al., 2008), even though they may differ in several orders of magnitude (Calanca, 2001). This was the approach followed by Herrero et al. (2009) in the previous studies of the snow made in this study area and it is maintained in this research.

Regarding K_{H0}, a parameter also related to the turbulent heat fluxes, Tarboton and Luce (1996), Cline (1997) and Dingman (2002) ignore it in their formulas, while Jordan et al. (1999) and Koivusalo and Kokkonen (2002) stress its importance, and assign to it an even greater value than that predicted by the theory in accordance with the measurements obtained. In Herrero et al. (2009), this parameter turned out to be essential to simulate the processes correctly, and so it is consistently incorporated in the modelling.

In this study, the stability correction factors for non–adiabatic temperature gradients (in Eq. (A3) and Eq. (A4)) were not included, as their contribution to improving the accuracy of the results has proven inconclusive to date (e.g. Braithwaite, 1995; Tarboton and Luce, 1996; Hock, 2005; Herrero et al., 2009). Therefore, the model considers neutral buoyancy, at adiabatic lapse rate, which is consistent with the idea that on a mountainous hillside with ~~significant~~ steep slopes, stable atmosphere states do not develop in the way they do in valley areas. In the former, the boundary layer is more prone to mixing due to katabatic downhill flowing winds that are generated even under calm clear–sky conditions (Barry, 1992). According to Braithwaite (1995), uncertainty in z_0 may cause larger errors than neglecting stability. K_{H0} and z_0 have been maintained as calibration parameters, this time estimated from direct measurements of evaposublimation and snowmelt instead of from snow depth and density values, as was done in Herrero et al. (2009).

3.2 Snow field surveys

Ten different daily field campaigns were carried out during the period 2009–2015 throughout Sierra Nevada, both on the south and north faces, to measure ablation from the snow, that is, the changes in the weight of a snowpack due to evaposublimation, deposition/condensation and melting. Each campaign lasted from 3 to 18 hours, and they were divided into 15 single meteorological states during which stationary or quasi–stationary meteorological conditions prevailed. They were conducted under different meteorological and topographical conditions, in different seasons, and with different types of snow, in order to achieve a representation of the states of the snowpack.

Evaposublimation (and deposition/condensation) and melting from the snowpack were measured using a modified version of the evaporation pan method with lysimeter. This method, also known as gravimetric, involves measuring the changes in mass of a finite volume of snow. Snow evaporation pans have been used for over forty years by, for example, Doty and Johnston (1969), Föhn (1973), Lemmelä and Kuusisto (1974), Bengtsson (1980). It must be noted that, under precipitation or windy conditions, which can blow the snow into or out of the pan, there may be a variation in the mass measured in the control volume that will not be directly distinguishable from evaposublimation unless it is measured separately.

The experimental device used in this study was developed following Avery et al. (1992) with some particular adjustments. It consists of two–tiered trays of white HDPE, the upper one being filled with undisturbed snow exposed to evaposublimation and deposition/condensation on its surface. The lower tray collects and protects from further evaporation the water that melts and percolates through the snow sample and through several holes drilled in the base of the upper pan in a regular grid. Both pans can be weighed jointly and separately, so evaposublimation or deposition/condensation and melting can be measured at the same time. This snow "ablameter" device has an exposed surface of 1260 (29.1×43.3) cm^2 and a depth of approximately 8 cm. Kaser (1982) and Valeo et al. (2005) used a similar device with only one pan, made of acrylic glass and aluminium respectively, both with small surface areas of 400 and 260 cm^2 but they encountered some limitations due to this reduced size and the accumulation of meltwater in the pan. Froyland et al. (2010) also used just one transparent container made of acrylic glass with an exposure area of 700 cm^2, with which they could not measure the melting snow. The device used here is closer to the quasi–lysimeters used by Radionov et al. (1997) or Jackson and Prowse (2009), who placed two stacked trays to measure meltwater. Avery et al. (1992) also developed a similar design that they called "sublimimeter", made of insulation foam and Teflon–coated steel, able to hold a snow volume of 35×35×10 cm^3.

The size of the trays selected for these experiments is as large as possible within the constraints of handling and weight. In this way, the snow contained is less affected by the small scale eddies in the wind field caused by the discontinuity in the surface of the snow, which may play a ~~significant~~ appreciable role in the sublimation rate (Earman et al., 2006). The change of mass and the weight of meltwater in the lysimeter were measured with a hand weighing scale Kern HDB (5K5) with a ~~precision~~ accuracy of 5 g, which for the 1260 cm^2 of the pan, gives us a resolution of 0.04 mm of SWE. During the snowmelt period, the setting–up and loading of the pans with snow is done early in the morning, when the snow structure is more stable. The snow probe is previously cut and then loaded into the pan by a sliding movement to keep the snow surface and structure as undisturbed as possible. In order to facilitate this operation, one of the short sides of the top tray can be removed. The pans are positioned with the top surface of the loaded snow flush with the original snow surface surrounding the pan, but safely separated from it to avoid mass exchange. In order not to disturb the snow properties, measurements are separated as much as possible in time (2–5 h). Measurement accuracy is preferred over its timing, keeping in mind that the understanding of the processes requires the same time resolution as the process itself, which in the case of evaporation may be hourly or higher (Lundberg, 1993). Each test lasts no more than 24 hours. On warm days with plenty of snowmelt, the test ends when the structure and surface of the snow samples begin to be unrepresentative of the surrounding snow.

Additionally, some snow properties required by the model were also measured during each field test. Albedo was measured using a hand pyranometer, Solar Power ISM400 (400–1100 nm~~$\pm 5\%$~~), and snow density was estimated by gravimetric determinations of 1/3 litre core samples obtained in situ. Finally, the snow temperature was regularly measured during each test to establish the initial energy state of the snow and to check the correct performance of the snow model during the associated simulations.

3.3 Meteorological data during field surveys

During each snow ablation field test, extensive monitoring of the meteorological variables required by the model was performed by a complete weather station. The tests on the southern face of Sierra Nevada were carried out in ~~the surroundings of~~ an area within a radius of 20 m from the permanent weather station at the Refugio Poqueira monitoring site, at 2500 m ~~-~~a.s.l. On the northern face, the field tests were located at different points throughout the area above the town of Pradollano, at altitudes ranging from 2400 to 2600 m ~~-~~a.s.l., where a portable weather station was installed close to the ablameter device. In both cases, following the indications of Lundberg (1993), the ablameter was located upwind of the station to guarantee negligible disturbances of the meteorological conditions at the test point. Tabs. 1 and 2 show the main characteristics of the sensors installed in each weather station. At Refugio Poqueira, temperature, T_a, and relative humidity, RH_a, were measured at 2.5 m above the snow surface, and wind speed at 3.0 m. At the portable weather stations, these heights change to 0.6 and 0.8 m respectively. The air vapour pressure was ~~determined by the standard psychrometric method~~calculated from T_a and RH_a using the empirical relation in Dingman (2002). Finally, solar radiation was measured using ~~a standard pyranometer~~ silicon photovoltaic pyranometers in both cases, while downward longwave radiation could only be measured at the permanent station of Refugio Poqueira, but not for the portable station at Pradollano. Both stations were managed by Campbell Scientific dataloggers with a 1–sec frequency of measurement and 1 to 5–min averaging record of the outputs.

4 Results

The main purpose of the field surveys was two–fold: first, to measure the actual evapotranspiration rates in Sierra Nevada under different meteorological and snow conditions, and second, to provide meltwater and vapour rate data to validate the snow model performance. With the calibrated and validated model, a continuous point simulation at this site was performed to quantify the actual importance of evaposublimation in the snow ablation at different time scales, and its influence on the annual water balance.

4.1 Measurements of melt and evaposublimation

Table 3 summarises the main meteorological and snow mass fluxes measured for each of the 15 ~~stationary periods identified during the field tests~~data sets obtained during the 10 field campaigns. The number of the field in the first column identifies the measurement ~~test, 10 in total~~campaign. Two of them (tests 8 and 10) are divided into 3 and 4 stationary periods each, because of the observed change of the meteorological forcing conditions (solar radiation, air or snow temperature, and even wind speed), mainly due to the transition from daytime to night time. The date and duration of each ~~test~~ data set is also recorded. The meteorological conditions over ~~the~~ each test period are summarised as the average wind speed, relative humidity, temperature and shortwave radiation state (sunny “S”, partially cloudy “C”, overcast “O” or night “N”). The total melt and evaposublimation amounts measured with the ablameter are expressed in ~~$mm\ h^{-1}$~~$mm\ h^{-1}$. Finally, information about albedo α, and topography (slope, aspect, and face of Sierra Nevada, north or south) of the exact monitoring position is also shown.

~~At first, the evaposublimation measurement, though less intense, is more reliable than the melting measurement , as the latter~~ The melting measurement relies on the correct drainage from the upper tray, ~~that~~ which may sometimes be incomplete. We paid special attention to avoid the refreezing of meltwater in the drain holes, which was not observed in any of the performed tests. Three observations, one related to M in test 9, and two other related to E in tests 5 and 7, had to be rejected because they presented measurement errors due to accidents during the experimental work.

The first thing that stands out is that, as expected, melt is a discontinuous phenomenon that occurs with increasing intensity as temperature rises, but mainly during daytime. Moreover, temperature was found to be a necessary but not sufficient ~~driver~~ cause for melting. As can be observed, there are some night tests with mean air temperatures of ~~$5°C$~~ 5°Cwith no melt at all, since without the positive heat input ~~from~~ caused by the dissipation of shortwave radiation, the sensible heat exchange cannot compensate for the cooling effect caused by longwave radiation and sublimation. Only one from a total of five night tests resulted in measuring melt (test 9), and the snowpack required a mean air temperature above ~~9°C~~ 9°Cfor this to occur.

On the contrary, evaposublimation is a ~~quasi–constant phenomenon, almost always found,~~ continuous phenomenon, albeit at low rates. Only in two of the tests (8a and 10b) was there a complete absence of measured vapour flux, that is, there was no change of weight in the trays. The first of them (test 8a) is a night time test over recent cold snow, at very low air temperature (~~−9.3°C~~-9.3°C) and with light wind (2.4 m s^{-1}). These meteorological conditions are very similar to those encountered in the consecutive test 8b, which is the only one with a measured net deposition/condensation (gain of mass in the trays) and with an intense rate (0.036 mm h^{-1} during 5.3 hours of test). Under the meteorological conditions in test 8a, carried out from 18:35 to 04:00, the expected behaviour is an initial sublimation while the snow cools from its "warmed" initial state to its night balanced state. Once the snow reaches its equilibrium temperature, the following deposition/condensation is the only mechanism to compensate longwave losses, which balanced in the end the initial loss of mass in the trays, as measured. The other test without noticeable E is 10b, carried out on a sunny day with high air temperature (~~9°C~~9°C) and very low wind speed (0.5 m s^{-1}), the lowest measured speed. These data may indicate that there is a threshold of wind that can inhibit the vapour fluxes; otherwise, these fluxes are always present. Even though their maximum rates were one order of magnitude under those for melting, accumulation of evaposublimation throughout the year may result in ~~a significant~~ an substantial total amount in the annual mass budget. Vapour loss rates above 0.04 mm h^{-1} were measured equally on days under intense melting (test 2) and on cold wet days (test 3). Maximum evaposublimation rates of 0.11 mm h^{-1} were measured under favourable weather conditions for evaposublimation (cold days with low relative humidity and gentle wind speeds around 5.0 m s^{-1}).

4.2 Measurements vs. model estimates – test periods

Table 4 shows the results obtained when the energy balance snow model is applied over the test periods. The differences between measured and simulated melting/evaposublimation rates are also presented for each test as statistics for the error of the simulation. E_{sim} only refers to the positive outgoing flux. When E is simulated with a negative sign, it is taken as deposition/condensation C_{sim}. The last column shows z_0, which was calibrated estimated for each test in agreement with the actual conditions observed on the surface of the snowby minimizing the sum of the mean errors of E and M. The comparison of measured and simulated values of E , and M , and the fraction of E from the total ablation $E+M$ are plotted in Fig. 3. The goodness of the calibration is determined by using the mean error ME, the mean absolute error MAE and the root mean square error $RMSE$. The agreement between model and observations for both E and M is very high, except for one outlier, which is circled. $RMSE$ for E is 0.008 mm h^{-1} (6.7% 6.7% of the maximum E measured), while for M it is 0.009 mm h^{-1} (0.6% 0.6% of the maximum M). As for E fraction, most values concentrate on 1 (E without melting) perfectly matched by model simulations. Some inaccuracy is found in mixed states with simultaneous E and M, with a final $RMSE$ of 0.013 and a ME of 0.04 (0.4%).

The selected values for z_0 (Table 4) mostly range from 1.0 to 0.3 mm. These values are lower than the calibrated value in Herrero et al. (2009), 2.5 mm. Test 3 is the only one with a lower value, 0.1 mm, and it corresponds to conditions that promoted the formation of a thin layer of ice on top of the snow, so its surface appeared particularly smooth. In general, z_0 under 0.5 mm is only measured estimated on the north face of Sierra Nevada in tests performed in January or February. In this area at that time, snow is more likely to form surface ice layers with a noticeable influence on z_0. The average value of z_0 for all these field campaigns is 0.61 mm. The second calibration parameter of the model, K_{H0}, was found to perform correctly adequately throughout all the cases if taken constant and equal to 1 W m^{-2} K^{-1} which is in agreement with other studies (Jordan, 1991; Jordan et al., 1999), and lower than the previously obtained value of 6 W m^{-2} K^{-1} in Herrero et al. (2009). The inclusion of a decaying albedo instead of a constant value, together with the more accurate value of the longwave term in the energy balance equation, are some of the reasons behind these differences, together with the use of water fluxes as optimisation objectives instead of snow depth values. In the next section we test the model performance for snow depth under these calibrated values.

The five night time tests are particularly significantmeaningful, as the absence of shortwave radiation (K flux in Eq. (A2)) during the test period allows us to better adjust the calibration parameters in the energy balance. Also, the two measurement periods that extend throughout several continuous tests (8a–8b–8c and 10a–10b–10c–10d) show good agreement between measurements and simulations while maintaining the same calibrated parameters. This is a good indication of the validity of this calibration and the resilience of the model under different meteorological states.

Night test 8a, with 0 mm of measured E, is simulated by the model as a mixed state with an initial loss and a subsequent gain of vapour, reaching a balance by the end of the test. This is consistent with the hypothesis made in the previous section, even though the balance point is reached simulating a deposition/condensation rate much lower than that measured in the following hours, during test 8b. This test 8b stands out as an outlier because a high deposition/condensation rate (negative E) of -0.036 mm h^{-1} is measured (circled in Fig. 3a) from 07:20 to 12:40, but it is simulated as only -0.004 mm h^{-1} during the night interval. According to the model, this deposition/condensation occurs from 04:00 to dawn, with a low air temperature (~~$-7.7°C$~~-7.7°C), not too high relative humidity (~~55%~~55%), and light wind (1.9 m s^{-1}), over very cold snow (~~$-17.5°C$~~-17.5°C). Once the sun rises, the model predicts sublimation as the snow temperature increases to balance with the air temperature. ~~Unless proved otherwise, these results cannot be considered as~~ This difference in the deposition/condensation rate is not likely to be due to a measurement error but ~~a true deviation between measurements and modelling , even though the behaviour of the model on the whole seems consistent with that expected~~to a modelling issue. The model succeeded in reproducing the sequence of deposition/condensation and sublimation but missed the deposition/condensation rate by an order of magnitude. Further work is needed to test this deviation by the model and identify its sources.

To estimate the sensitivity of the model to changes in z_0 within the ranges found in the field, we repeated the prior simulations considering a constant z_0 value equal to its average calibrated value. The results are plotted in Fig. 4. The error made when simulating with ~~$z_0 = 0.61$~~ z_0=0.61 mm increases slightly in E (ME increases from ~~0.002~~ 0.002 to 0.003 mm h^{-1} and $RMSE$ from ~~0.008~~ 0.008 to 0.012 mm h^{-1}). The increase in the errors in M (ME from 0.003 to 0.051 mm h^{-1} and $RMSE$ from ~~0.009~~ 0.009 to 0.164 mm h^{-1}) is concentrated in one particular test that moves away from the 1:1 line, though errors still remain ~~low~~ small as ME is only 3.4% of the maximum measured M. ~~The instantaneous E fraction from total ablation is barely affected by the change in z_0.~~ It appears that the range of variation in measurements of z_0 is low enough not to affect the results ~~significantly~~substantially.

4.3 Annual simulation

On the basis of the above results, the energy balance model was used to simulate snow ablation processes at the Refugio Poqueira site from 2008/09 to 2014/15. Meteorological data from the Refugio Poqueira weather station were used to drive the simulation. The parameters for this simulation were selected from the results of the validation achieved during the test periods. Thus, K_{H0} and z_0 are supposed fixed and equal to 1 W m^{-2} K^{-1} and 0.61 mm respectively.

The validation of the snow model was assessed in terms of the snow depth observed at the Refugio Poqueira station. Fig. 5.a) shows how the model ~~smoothly~~ reproduced the main patterns in the intra– and inter–annual cycles in the snowpack. The correct simulation of accumulation and melting over time and the good match of the timing of the different intra–annual melting cycles means that the model is computing adequately not only the snow depth and SWE time series, but also the cumulative energy balance of the snowpack (López-Moreno et al., 2013). Figs. 5.b) and 5.c) show the observed and simulated annual maximum accumulation and duration of the snowpack respectively. In both cases the simulated values fit well with the observations regardless of the wet/dry character of the year and the number of snowmelt cycles encountered. For the period 2009/10–2012/13, the maximum snowpack depths measured ranged from 627 to 1400 mm, while the number of cycles with total disappearance of the snow varied between 3 and 7. In general, autumn and spring precipitation events fall as snow but melt within a few days. However, there are drier or warmer years when complete melt is reached even during the winter. Snowpack duration ranged from 85 to 138 days. In the simulation, the Mean Error ME and the Root Mean Square Error $RMSE$ were -81 and 235 mm for daily snow depth, 63 and 136 mm for annual maximum depth, and 2.8 and 10.5 days for annual snowpack duration.

Fig. 6 shows the course of simulated cumulative snowfall, SWE, evaposublimation and snowmelt for each one of the seven hydrological years under study. The average annual ratio of total evaposublimation versus total ablation is 30.6%, oscillating from a minimum of 24.2% in 2010/11 to a maximum of 32.8% in 2014/15. The year with the highest total vapour loss is 2009/10, with 204 mm, while the year with the lowest loss is 2011/12 with 94 mm. Despite this low value, the percentage of evaposublimated snowfall is high for this year, 29.4%. In general, years with low total snowfall result in a higher percentage of evaposublimation and a higher number of melting cycles. The model also estimates a mean annual deposition/condensation of 0.9% of the total snowfall (4.8 $mm\,yr^{-1}$).

Evaposublimation occurs steadily whenever there is accumulated snow, with less intensity towards the spring with the general rise in temperatures. Conversely, snowmelt shows a more intermittent behaviour, taking place only during the periods of warmer weather during the winter and with dominating intensity during the spring. This persistence of vapour losses is illustrated in Fig. 8, where the probability density function (pdf) for 5–min values of E and M are plotted. The maximum rates for M are approximately one order of magnitude higher than the rates for E, although M is 0 or very close to 0 for almost 90% of the time with snow cover, compared to the 40% associated with zero values of E.

Fig. 7 represents the ratio of the evaposublimation versus total ablation in each month of the year, averaged over the entire simulated period. The graph highlights the seasonal variations of the percentage of evaposublimation on an annual basis. In the months of December, January, and February, evaposublimation accounts on average for 47–51% of all the ablation that takes place. Snowmelt is present in these winter months, but with a moderate intensity (Fig. 9). During the following months, the evaposublimation ratio decreases sharply as snowmelt dominates, decreasing to approximately 22% in March, 12% in April and 4% in May. Monthly M always dominates when compared to E (Fig. 9), increasingly during the spring months. However, the standard deviation of M is always higher than that of E, and it has the same order of magnitude as the mean itself, which means that zero melt can be expected in every month but January, March and April. In contrast, monthly E is less variable and shows lower standard deviations.

The cumulative annual energy fluxes in W m^{-2} for the period 2008/09–2014/15, together with their mean and standard deviation proportion, are shown in Fig. 10. Warming fluxes H and K are on the positive side of the *x* axis while cooling fluxes U_R, ~~U_E~~LE, and L appear on the negative side. Their average fractions of the energy balance are 60% for turbulent sensible exchange (H) and 40% for shortwave radiation (K) as positive (warming) fluxes; -54% for longwave radiation (L), -32% for turbulent latent exchange (~~U_E~~LE), and -14% for advective heat associated with precipitation (U_P) as negative (cooling) fluxes. The standard deviations are small, compared to those from the mass fluxes, L being the most variable flux with 7%. Even though L dominates on average over ~~U_E~~ LE as a negative flux, there is one particular year (2010/11) in which both fluxes are equal. The ratio between H and K also changes moderately between years.

5 Discussion

The turbulent heat transfer terms are probably the most uncertain contribution to solving the energy budget over the snow. ~~The validity of the application of boundary layer theory to determine the turbulent fluxes over the snow, especially on complex mountainous terrains, is not clear~~ Flux–profile and bulk transfer approaches have been shown to be problematic over sloping terrain to determine turbulent fluxes (Hock, 2005). In general, snow in mountainous areas must always be considered as a non–uniform surface, either because of the presence of patchy snow, obstacles such as rocks or shrubs that stand out of the snow surface on shallow snowpacks, or topographic gradients themselves. Besides the usual wind exposure of higher elevations, gravity winds usually develop even during calm days, promoting turbulent transfer under every meteorological condition (Feick et al., 2007). These turbulent terms include the calibration parameters used in the energy balance modelling, one referring to the sensible heat exchange (K_{H0}) and the other to both the sensible and latent heat exchange (z_0). The determination of both parameters, together with the consideration of stability effects, are the major challenges of the physically–based snow models. These calibration parameters appear to be very site–dependent, according to the wide spectrum of variation described in the literature. In this work, these coefficients have been calibrated for Sierra Nevada (Spain) at approximately 2500 m ~~.~~a.s.l. using detailed measurements of mass fluxes E and M, with a final result of 1 W m^{-2} K^{-1} for K_{H0} and 0.61 mm for z_0 as a seasonal average value. Despite the large uncertainty that still exists regarding the roughness length of the different types of snow surfaces (Martin and Lejeune, 1998), the measurements for this study area suggest a range of z_0 from 0.1 mm, for very smooth icy surfaces, to 1.0 mm on metamorphosed snow that shows surface forms as snow cups.

The final value of the evaposublimation rate calculated from the snow surface is directly related to the latent heat flux, so the uncertainty associated with this turbulent phenomenon is carried forward to the estimation of E. The measurements confirm that~~the~~, for the study sites in Sierra Nevada, the evaposublimation rate is small in magnitude (up to 0.11 mm h^{-1}) compared to snowmelt (up to 4.2 mm h^{-1}) but it is very continuous over time and acts under virtually all weather conditions. Only in one (10b) of the 15 measured meteorological states did evaposublimation or deposition/condensation appear to be inhibited: on a very warm windless ~~day~~period, with major snow melting. The simulations performed with the snow model confirm the continuity of vapour loss throughout the year and between years, with a mean rate of 1.2 mm d^{-1} (equivalent to 0.054 mm h^{-1}) and maximum rates of 7.2 mm d^{-1} and 0.49 mm h^{-1}. As for melting, the simulated mean rate was 2.7 mm d^{-1} (equivalent to 0.12 mm h^{-1}), while the maximum rates were 39.6 mm d^{-1} and 4.8 mm h^{-1}. Maximum evaposublimation rates are reached during very windy periods, with maintained speed values above 8 m s^{-1} and temperature close to 0°C. The relative humidity does not halt the process as long as it remains below 80%, a value that indicates its supporting role to the wind effects.

Our evaposublimation rates are somewhat higher than those measured by Kaser (1982), who found maximum sublimation rates of 2 mm d^{-1} in the ~~Alpine~~ Alps during the summer at 3000 m ~~.~~a.s.l., some way balanced with a correspondingly high deposition/condensation overnight. However, in a high latitude area like Canada, Valeo et al. (2005) recorded maximum values of sublimation equal to 6.3 mm in 8 hours (0.8 mm h^{-1} on average) in Alberta (51°N), while Jackson and Prowse (2009) simulated mean vapour loss of 0.4 mm d^{-1} in open sites at Okanagan Basin (49°N) with SNTHERM (Jordan, 1991). The latter also simulated maximum melting rates of 40.5 mm d^{-1}, similar to the values found in this study. Even at this latitude, events of warm and dry air masses can occur during winter (the Chinook, popularly translated as “snow–eater”, is an example of foehn winds), which occasionally enhance sublimation losses from the snow up to these values. In warmer areas, conditions to record high sublimation losses are easier to find. Avery et al. (1992) measured a maximum evaposublimation loss of 8.5 mm d^{-1} under clear, dry and windy conditions on the Colorado Plateau of Arizona at 35°N and 2100 m ~~-~~a.s.l. In any case, modelled or simulated, it is reported than this rate is highly variable depending on the local conditions of the wind regime (Feick et al., 2007), on the meteorology and, therefore, on the time of the year when the snowpack accumulates.

During our field measurements, one of the tests in Refugio Poqueira showed a strong deposition/condensation rate of 0.036 mm h^{-1} that could not be simulated with the model. The simulation of hoar growth in complex terrain is a difficult task since it demands ~~high resolution~~ data of the ~~wind regime, including thermally and topographically induced winds (Feick et al., 2007)~~local wind regime with a spatial resolution under 10 m (Feick et al., 2007), which was not accomplished for the tests in Poqueira, located 10 to 20 m away from the station. Further measurements and study are necessary to establish whether this deposition/condensation rate is a common phenomenon in the area, where problems with hoar and ice over structures (for example, at ski resorts) are often reported.

Total annual evaposublimation is estimated as 24–33% of the total ablation of the snow, which represents a ~~significant~~ substantial fraction. This result confirms the previous estimations made by Herrero et al. (2009), reached without direct measurement of this water flux, and highlights the advantage of using physical models in approaching these processes. The difference in the annual evaposublimation between different climatic zones is related to the availability of those meteorological states that favour evaposublimation. In Sierra Nevada, evaposublimation is present almost continuously to a greater or lesser extent, so its contribution becomes important on an annual basis. The worst–case scenario for high evaposublimation rates takes place when the snow pack accumulates early in the season (Avery et al., 1992). The importance and variability of evaposublimation in Sierra Nevada agrees with other studies in warm and semiarid mountainous regions around the world, such as California (20% (Marks and Dozier, 1992), 36% (Leydecker and Melack, 2000)), Colorado (15% (Hood et al., 1999), 17–43% (Froyland, 2013)), Canada (40% (Gray and Prowse, 1993)), the Andean Altiplano (30–90% (Vuille, 1996)), the Atlas mountains (44% (Schulz and de Jong, 2004), 7–20% (Boudhar et al., 2016)), and Israel (46–82% (Sade et al., 2014)), although its exact proportion depends greatly on the exact location of the sampling point and its altitude. At the Refugio Poqueira study site (2500 m ~~-~~a.s.l., 37~~°~~°N), and in most of Sierra Nevada in general, year–to–year climate variability in precipitation and temperature interact non–linearly to allow the development of a highly heterogeneous snowpack, which leads to the corresponding variability in the percentage contribution of evaposublimation to total snow ablation.

6 Conclusions

In this study we have quantified the evaposublimation rates and the rest of the energy balance terms of the seasonal snowpack in the semiarid region of Sierra Nevada (37°N). The 15 field ~~tests~~ data sets performed succeeded in validating the physically based snow model designed by Herrero et al. (2009). Although the measurement based on manually weighed trays is a traditional and not automated method, it achieves high accuracy thanks to the technical characteristics of the current weight measuring instruments. The measurements have confirmed the constant presence of evaposublimation from the snow in this semiarid environment, detecting maximum rates of 0.11 mm h^{-1} in periods that were neither particularly dry nor particularly windy. Melting snow on warm days can reach much higher rates, up to 4.18 mm d^{-1}, but its effect takes place in shorter periods than those affected by evaposublimation, which is more persistent for different meteorological conditions. Throughout the period when the snow is accumulated on the soil surface, evaposublimation occurs during 60% of the time, while snowmelt only occurs during 10%. With these data, the energy–balance snow model was calibrated using two main parameters, both associated with turbulent fluxes: the ~~aerodynamic~~ roughness length of the snow z_0 and the sensible–heat transfer coefficient in windless conditions K_{H0}. K_{H0} was set to 1 W m^{-2} K^{-1}, while z_0 was found to range between 0.1 mm over recent snow with an icy surface and 1.0 mm over mature snow with big grain size and an irregular surface. The mean value for z_0 was 0.61 mm.

The model satisfactorily reproduced the evaposublimation and melting rates during the monitored periods. Situations with simultaneous melting and evaporation were also correctly simulated. From these results, the continuous performance of the model at the Refugio Poqueira monitoring site (at 2500 m ~~.~~a.s.l.) during the 2008-2015 period, produced an estimated evaposublimation value between 94 and 204 mm per year, from a total snowfall of 320 to 676 mm per year, which accounts for between 24 and 33% of the total annual accumulated snow. On a daily basis, the evaposublimation rate reached a mean value of 1.2 mm d^{-1}; a maximum of 7.2 mm d^{-1} with hourly peaks of 0.49 mm h^{-1}being simulated on very windy days.

Regarding the energy balance, we were able to estimate that 32% of the cooling energy is due to the latent–heat transfer term, which is ~~significant~~considerable. Wind is the key element that establishes the final weight of this term in the energy budget for every season. Due to its proximity to the sea, and its high altitude compared to the neighbouring mountains, Sierra Nevada is a wind–exposed mountain range, which explains the relevant influence of this term on the snow regime over the mountain range.

The annual energy and mass balance over the snowpack is sensitive to small changes in variables governing the weather regime and/or their timing. Due to the elevational gradients and the seasonal and annual climate variability, high variability of the weather drivers can usually be found both spatially and over time in semiarid high mountain environments. Since simultaneous and intense monitoring of the snowpack is not feasible over these areas, the availability of a reliable snow model to infer the distribution of evaposublimation throughout Sierra Nevada, and to further simulate the evolution of the snowpack is an important and useful tool. In these regions, the impact of this return of water to the atmosphere is appreciable on the hydrology and on the availability of water as a resource. The results shown in this study are a first and essential step for estimating the influence of snow dynamics on runoff and water storage in the area, and for assessing water planning in the short and medium term. The implications for adaptation strategies are also relevant in a scenario of change in the energy budget regime.

7 Data availability

All the data and models used in this study are available through Pangaea database or can be provided by the corresponding author upon request.

Appendix A: Snow mass and energy balance equations

The instantaneous mass and energy balance in the 1–layer control volume per unit of surface area is described as follows:

$$\frac{dm}{dt} = R - E + W - M \tag{A1}$$

$$\frac{d(m \cdot u)}{dt} = K + L + H + G + R \cdot u_R - E \cdot u_E + W \cdot u_W - M \cdot u_M \tag{A2}$$

where m denotes the water mass in the snow column (snow water equivalent SWE), and u is the internal energy per unit of mass (U for total internal energy). Regarding mass fluxes, R denotes the precipitation; E represents water vapour diffusion (~~evaposublimation~~evaposublimation–deposition/condensation); W is the mass transport due to wind; and M is the melting water. The energy fluxes are the solar or shortwave radiation, K; the thermal or longwave radiation, L; the exchange of sensible heat with the atmosphere H; the heat exchange with the soil G; and the advective heat terms associated with each of the mass fluxes (u_R, u_E, u_W and u_M) which refer to the unitary internal energy of each of the mass fluxes considered.

Eq. (A1) and Eq. (A2) form a coupled set of first order, nonlinear ordinary differential equations. They are solved with a first order finite difference approximation with a 5–min step time and an iterative algorithm (Herrero et al., 2009) that can reduce the time step in situations of numerical instability.

Precipitation, directly measured by the weather station in every case, is partitioned into rain or snow using the wet bulb temperature, T_w. This is taken as the temperature for the rain, which is considered frozen if $T_w \leq 0$°C. T_w can be estimated from the temperature of the air, T_a, the relative humidity of the air, W_a, and the atmospheric pressure, P_a, using Normand's Rule (e.g., Stull, 2000).

The shortwave albedo of the snow, α, is a property of the snowpack surface that changes with time, usually decreasing as the snow grain size increases. In this model, if no measurements are available, α is parametrised as a function of the snow surface age between a maximum value of 0.8 for recent snow and a minimum of 0.4 for old snow. The ageing process is predicted with a linear decay with time (Baker et al., 1990; Pimentel et al., 2013) slower for cold snow (0.006 day^{-1}) than for melting snow (0.018 day^{-1}). New snowfall refreshes α at a rate of 0.05 mm^{-1} of new SWE.

The equivalent atmospheric emissivity, ε_a, is used to calculate the incoming longwave radiation, L_{down}, from the atmosphere. The model can work with direct measurements of L_{down} where available, or estimate ε_a from the near–surface temperature, relative humidity and clearness index (related to solar radiation and cloudiness) using the empirical expression of Herrero and Polo (2012).

The turbulent energy diffusion terms for water vapour ~~U_E~~ LE as well as for sensible heat H can be resolved by basing calculations on the physics of turbulent transfer near the ground, as explained, for example, in Dingman (2002):

$$U_E \, LE = E \cdot uE = \frac{K_{UE}}{\Phi_M \Phi_V} \frac{K_{LE}}{\Phi_M \Phi_V} v_a (e_{sn} - e_a) \tag{A3}$$

$$H = \left(\frac{K_H}{\Phi_M \Phi_H} v_a + K_{H0} \right) (T_a - T_{sn}) \tag{A4}$$

where K_{UE} K_{LE} is the bulk latent–heat transfer coefficient; K_H is the bulk sensible–heat transfer coefficient; K_{H0} is the sensible–heat transfer coefficient in windless conditions ; v_a is the wind speed at the reference altitude; e_a is the air vapour pressure at the reference altitude; e_{sn} is the saturation vapour pressure for the snow temperature, T_{sn}; T_a is the air temperature at the reference altitude; and Φ_M, Φ_V and Φ_H are the stability–correction factors for non–adiabatic temperature gradients, introduced to account for the buoyancy effects that may enhance or dampen the turbulent transfers because of the temperature gradient over the surface. There are numerous empirical expressions for these correction coefficients, depending on the Richardson number or the Monin–Obukhov length (Price and Dunne, 1976; Anderson, 1976; Oke, 1987; Cline, 1997; Jordan et al., 1999). However, application to actual wind and temperature conditions may lead to values of these coefficients that fall outside the limits for which they were empirically defined. This fact, as well as the uncertain improvement in the accuracy of the results with their application (e.g. Hock, 2005), has led certain authors to reject them completely (Tarboton and Luce, 1996; Herrero et al., 2009), or limit their use to smaller ranges (Koivusalo and Kokkonen, 2002).

K_{UE} K_{LE} and K_H are defined as follows:

$$K_{UELE} = u_E 0.622 \frac{\rho_a}{P_a} \frac{k^2}{\left[ln\left(\frac{z_a - z_d}{z_0}\right)\right]^2} \tag{A5}$$

$$K_H = \rho_a c_a \frac{k^2}{\left[ln\left(\frac{z_a - z_d}{z_0}\right)\right]^2} \tag{A6}$$

where ρ_a is the mass density of air in $kg \cdot m^{-3}$ kg m^{-3}; c_a is the heat capacity of air (at constant pressure, 0.001005 $MJ \cdot kg^{-1} \cdot K^{-1}$ MJ kg^{-1} K^{-1}); P_a is atmospheric pressure in kPa; 0.662 is the ratio between molecular weight of air and molecular weight of water vapour; k is the dimensionless von Karman's constant (0.4); z_a is the height at which wind velocity is measured, z_d is the zero–plane displacement (0 for snow and ice) and z_0 is roughness height. $z_0 + z_d$ is the nominal surface level at which logarithmic boundary layer profile predicts zero velocity. As a consequence of the Ideal Gas Law, mass density of air decreases in altitude with atmospheric pressure P_a. Thus, from P_a (kPa), T_a (K), and the gas constant for air R_a (0.288 for the units given), ρ_a can be calculated as follows:

$$\rho_a = \frac{P_a}{T_a R_a} \tag{A7}$$

The K_{UE} K_{LE} term includes the unitary internal energy u_E advected to E, and it appears in Eq. (A2). If $e_{sn} > e_a$, evaporation occurs and u_E is the advected heat of the water vapour that moves out from the surface layer into the air above measured. The internal energy of this flux as it moves out of the snow into the atmosphere will be that of water vapour with the temperature of the surface T_{sn} with respect to the selected reference state. Therefore, the calculation of u_E is indifferent to the initial state of water on the surface of the snow, and is the same for sublimation (with frozen surface) and evaporation.

$$u_E = \lambda_v + ce_v T_{sn}, \quad \text{if } e_{sn} > e_a \tag{A8a}$$

$$u_E = ce_v T_a, \quad \text{if } e_{sn} < e_a \tag{A8b}$$

where λ_v is the latent heat of vaporization (2.47 $MJ \cdot kg^{-1}$MJ kg^{-1}) and ce_v is the heat capacity of water vapour (0.001850 $MJ \cdot kg^{-1} \cdot K^{-1}$MJ kg^{-1} K^{-1} at standard conditions *STP*). If $e_{sn} < e_a$ water vapour molecules enter the surface at T_a, where they condense. Their unitary internal energy will be that of Eq. (A8b).

The snow density ρ_{sn} is mainly needed in the model for the calculation of the snow depth h_{sn}. It is considered uniform in the snowpack, and its evolution is calculated from an initial value for new snow ρ_{sn-min} that is gradually modified in time through percolation, refreezing (both due to meltwater and rain), deposition/condensation, and new snowfall. There are two kinds of maximum density, one, ρ_{sn-max}, is due to grain growth associated with percolation, and the other, ρ_{sn-frz}, is a possible maximum density reached through internal refreezing of water. Density increase due to percolation is represented by a parametrisation that makes use of melting rate M, a growth coefficient $k_{\Delta\rho}$ with units of kg l^{-1} mm^{-1}, and a normalized density Θ_{sn}:

$$\Delta\rho_{sn} = M \cdot k_{\Delta\rho} \cdot \Theta_{sn}(\rho_{sn}) \tag{A9}$$

$$\Theta_{sn} = \frac{\rho_{sn} - \rho_{sn-min}}{\rho_{sn-frz} - \rho_{sn-min}} \tag{A10}$$

with ρ_{sn-min} = 0.1 kg l^{-1}, ρ_{sn-max} = 0.5 kg l^{-1}, ρ_{sn-frz} = 0.65 kg l^{-1}, and $k_{\Delta\rho}$ = 0.008 kg l^{-1} mm^{-1} if $\rho_{sn} < \rho_{sn-max}$, 0 otherwise. These values were selected for agreement with the densities measured in the study area in Herrero (2007), which were between 0.05 kg l^{-1} for new snow to 0.55 kg l^{-1} for old melting snow, reaching up to 0.70 kg l^{-1} when ice layers are present as a sign of major refreezing. After snowfall or deposition/condensation, ρ_{sn} is recalculated as the weighted average of the old–snow density and ρ_{sn-min}.

Acknowledgements. We are grateful to Sergio Torres, Agustín Millares, Zacarías Gulliver, Marta Egüen, and Rafael Pimentel for their help in the field work. This study was funded by the Spanish Ministry of Economy and Competitiveness – MINECO (project CGL2011–25632, "Snow dynamics in Mediterranean regions and its modelling at different scales. Implications for water resource management" and project CGL2014–58508R, "Global monitoring system for snow areas in Mediterranean regions: trends analysis and implications for water resource management in Sierra Nevada"). We thank Werner Eugster and one anonymous reviewer whose comments helped to improve this manuscript.

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Table 1. Instruments and specifications used on the portable weather station deployed during the field surveys at the northern study sites.

Model	Manufacturer	Observation	Range and accuracy
WXT510 Weather	Vaisala	Wind speed	~~0?60~~ 0...60 ±0.3 m s^{-1}
~~Transmiter~~ Transmitter		Air temperature	~~-52?~~-52...+60 ±0.3°C
		Relative humidity	~~0?100~~ 0...100 ±3%
		Barometric pressure	~~600?1100~~ 600...1100 ±0.5 hPa
109 Probe	CS	Snow Temperature (2 levels)	~~-50?~~-50...+70 ±0.36°C
CS300	CS	Solar radiation (360–1120 nm)	~~300?1100 nm~~0...1750 W m^{-2} ±5%
CR200	CS	Datalogger	~~-40?~~-40...+50°C

~~Sensors in the portable weather station used during the field surveys at the northern study sites and their technical characteristics.~~

Table 2. Instruments and specifications used on the permanent weather station at the Refugio Poqueira monitoring point.

Model	Manufacturer	Observation	Range and accuracy
HMP45C	Vaisala	Air temperature	~~-40?~~-40...+60 ±0.3°C
		Relative humidity	0.8~~?100~~ ...100 ±3%
RPT410F	Druck	Barometric pressure	~~600?1100~~ 600...1100 ±0.5 hPa
SP–Lite	Kipp&Zonen	Solar radiation (400–1100 nm)	~~400?1100 nm~~0...1500 W m^{-2} ±5%
CGR3	Kipp&Zonen	Longwave radiation (4500–42000 nm)	~~4500?44000 nm~~-250...+250 W m^{-2} ±5%
05103–45 Alpine	Young	Wind vector	~~0?60 m/s~~ 0...100 ±0.3 m s^{-1}
CR10X	CS	Datalogger	~~-40?~~-40...+50°C
T–200B w/Alter Shields	Geonor	Precipitation	~~0–600~~ 0...600 ±0.1 mm

~~Sensors in the permanent weather station at the Refugio Poqueira monitoring point and their technical characteristics.~~

Table 3. Summary of the 15 data sets extracted from the 10 field campaigns with their date, duration, sky condition (N, night; S, sunny; O, overcast; C, cloudy), main weather drivers (wind speed (U); relative humidity (RH_a); air temperature (T_a)), measured evaposublimation (E_{obs}) and melting (M_{obs}) rates, measured snow albedo (α) and main topographic features of the test sites.

Test	Date	Duration (h)	Solar Sky radiation condition	W U (m s^{-1})	RH RH_a (%)	T T_a (°C)	M_{obs} (mm h^{-1})	E_{obs} (mm h^{-1})	α	Slope (°)	Aspect	SN f
1	12–Mar–2015	8.6	N	3.2	32	4.0	0.00	0.041	0.53	15	SW	S
2	10–Apr–2014	4.6	S	2.1	34	10.5	4.18	0.044	0.62	23	SW	N
3	27–Feb–2014	2.4	O	7.2	81	-1.0	0.00	0.041	0.8	3	W	N
4	28–Jan–2014	5.2	S	4.3	46	-1.0	0.00	0.113	0.59	7	NW	N
5	23–Jan–2014	4.3	S	8.4	70	-4.4	0.00	–	0.63	2	W	N
6	28–Nov–2013	3.3	C	1.3	86	-3.4	0.00	0.020	0.75	20	N	N
7	15–Mar–2013	5.0	S	1.3	49	3.2	1.51	–	0.62	5	S	S
8a	1–Mar–2011	12.8	N	2.4	62	-9.3	0.00	0.000	0.8	8	S	S
8b	2–Mar–2011	5.3	S	1.9	55	-7.7	0.00	**-0.036**	0.8	8	S	S
8c	2–Mar–2011	2.6	S	1.6	63	-4.2	0.00	0.031	0.8	8	S	S
9	29–Apr–2010	10.1	N	3.6	47	9.3	–	0.015	0.45	2	S	S
10a	10–Mar–2009	11.8	N	5.6	15	3.9	0.00	0.111	0.67	12	S	S
10b	11–Mar–2009	3.5	S	0.5	46	9.2	1.19	0.000	0.67	12	S	S
10c	11–Mar–2009	13.8	N	2.6	37	4.9	0.00	0.047	0.67	12	S	S
10d	12–Mar–2009	3.0	S	2.4	25	5.0	0.11	0.025	0.67	12	S	S

Summary of the different test periods with their date, duration, solar radiation state (N, night; S, sunny; O, overcast; C, cloudy), main weather drivers (W, wind speed; RH, relative humidity; T, air temperature), measured evaposublimation (E_{obs}) and melting (M_{obs}) rates, measured snow albedo (α) and main topographic features of the test sites.

Table 4. Summary of the simulated (sim) results (M, melting; E, evaposublimation; C, deposition/condensation) from the energy balance model for each data set period, together with the simulated energy flux terms (shortwave radiation (K); longwave radiation (L); sensible–heat exchange (H); latent–heat exchange (LE)) and the calibrated values for the model parameters (roughness length (z_0); and constant sensible–heat transfer coefficient in windless conditions (K_{H0}= 1 W m^{-2} K^{-1})).

Test	M_{sim} (mm h^{-1})	E_{sim} (mm h^{-1})	C_{sim} (-E_{sim}) (mm h^{-1})	Error M (mm h^{-1})	Error E (mm h^{-1})	K_{sim} (~~MJ m^{-2} h^{-1}~~ W m^{-2})	L_{sim} (~~MJ m^{-2} h^{-1}~~ W m^{-2})	H_{si} (~~MJ m^{-2} h^{-1}~~ W m^{-}
1	0.00	0.041	–	0.00	0.000	~~0.00~~ 0.0	~~-0.27~~ -75.0	~~0.39~~ 108.
2	4.17	0.046	–	-0.01	0.002	~~1.37~~ 380.6	~~-0.22~~ -61.1	~~0.37~~ 102.
3	0.00	0.049	–	0.00	0.008	~~0.26~~ 72.2	~~-0.16~~ -44.4	~~0.04~~ 11.
4	0.00	0.112	–	0.00	0.002	~~0.60~~ 166.7	~~-0.33~~ -91.7	~~0.11~~ 16.
5	0.00	0.131	–	0.00	–	~~0.71~~ 197.2	~~-0.35~~ -97.2	~~-0.04~~ -11.
6	0.00	0.010	0.000	0.00	-0.011	~~0.08~~ 22.2	~~-0.04~~ -11.1	~~0.06~~ 16.
7	1.52	0.042	–	0.01	–	~~1.14~~ 316.7	~~-0.60~~ -166.7	~~0.08~~ 22.
8a	0.00	0.002	0.002	0.00	0.000	~~0.00~~ 0.0	~~-0.27~~ -75.0	~~0.19~~ 52.
8b	0.00	0.004	0.003	0.00	0.037	~~0.37~~ 102.8	~~-0.36~~ -100.0	~~0.14~~ 38.
8c	0.00	0.029	–	0.00	-0.002	~~0.57~~ 158.3	~~-0.32~~ -88.9	~~-0.04~~ -11.
9	0.75	0.019	0.002	–	0.000	~~0.01~~ 2.8	~~-0.14~~ -38.9	~~0.43~~ 119.
10a	0.00	0.130	–	0.00	0.019	~~0.02~~ 5.6	~~-0.32~~ -88.9	~~0.62~~ 172.
10b	1.20	0.003	–	0.01	0.003	~~0.82~~ 227.8	~~-0.50~~ -138.9	~~0.08~~ 22.
10c	0.00	0.041	–	0.00	-0.006	~~0.01~~ 2.8	~~-0.25~~ -69.4	~~0.30~~ 83.
10d	0.14	0.042	–	0.03	0.017	~~0.46~~ 127.8	~~-0.34~~ -94.4	~~0.26~~ 72.

~~Summary of the simulated results (M, melting; E, evaposublimation; C, condensation) from the energy balance model for each test period, together with the simulated energy flux terms (K, shortwave radiation; L, longwave radiation; H, sensible–heat exchange; U_E, latent–heat exchange) and the calibrated values for the model parameters (z_0, aerodynamic roughness length; and constant K_{H0}= 1 W m^{-2} K^{-1}, sensible–heat transfer coefficient in windless conditions).~~

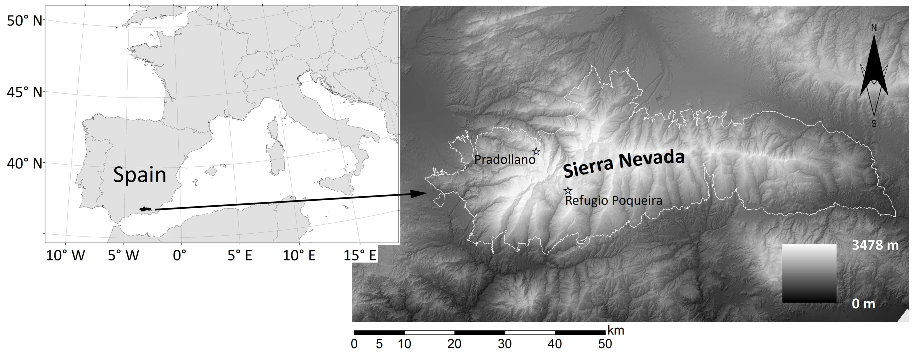

Figure 1. Location of Sierra Nevada in southern Spain (left) and Digital Elevation Model (m) of the study area (right). The enlargement shows the limits of the Sierra Nevada National Park (white line) and the location of the Refugio Poqueira monitoring site (2500 m a.s.l.) and the town of Pradollano (2100–2300 m a.s.l.).

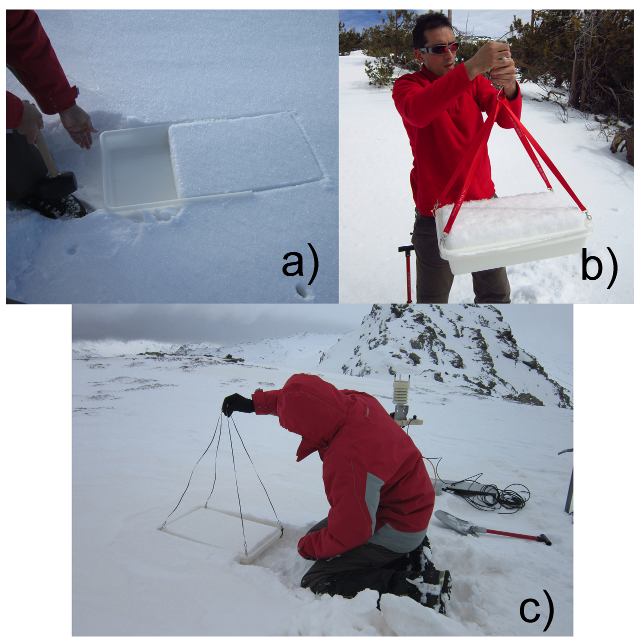

Figure 2. Photographs of the evaporation pan with lysimeter used in this study. In the sequence we can see a) the load of the snow sample by sliding of the upper tray; b) handling of the complete device during weight; c) reposition of the device to its measuring position

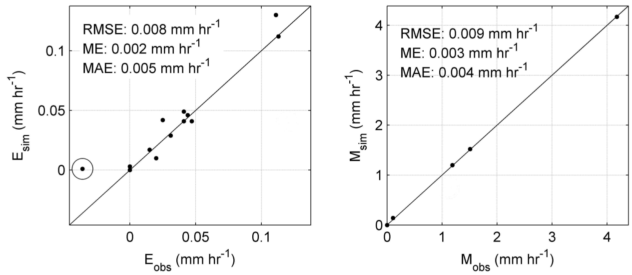

Figure 3. Measurements versus model estimates of evaposublimation (E) and melting (M) for the different test periods using the calibrated values for each test in Table 4. Each plot includes the root mean square error ($RMSE$), the mean error (ME), and the mean absolute error (MAE). The line indicates a 1:1 relationship between observed (obs) and simulated values (sim).

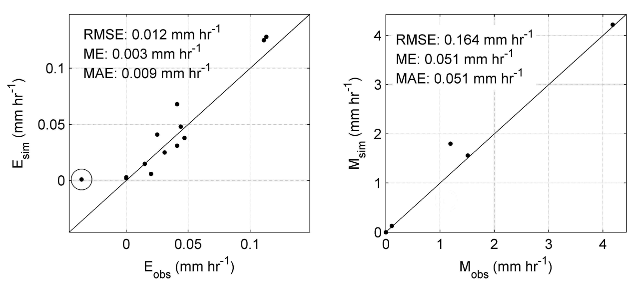

Figure 4. Measurements versus model estimates of evaposublimation (E), melting (M) and evaposublimation fraction from total ablation ($E/(E+M)$) for the different test periods using a constant z_0 of $0.61 mm$0.61 mm. Each plot includes the root mean square error ($RMSE$), the mean error (ME), and the mean absolute error (MAE). The line indicates a 1:1 relationship between observations observed (obs) and simulated values (sim).

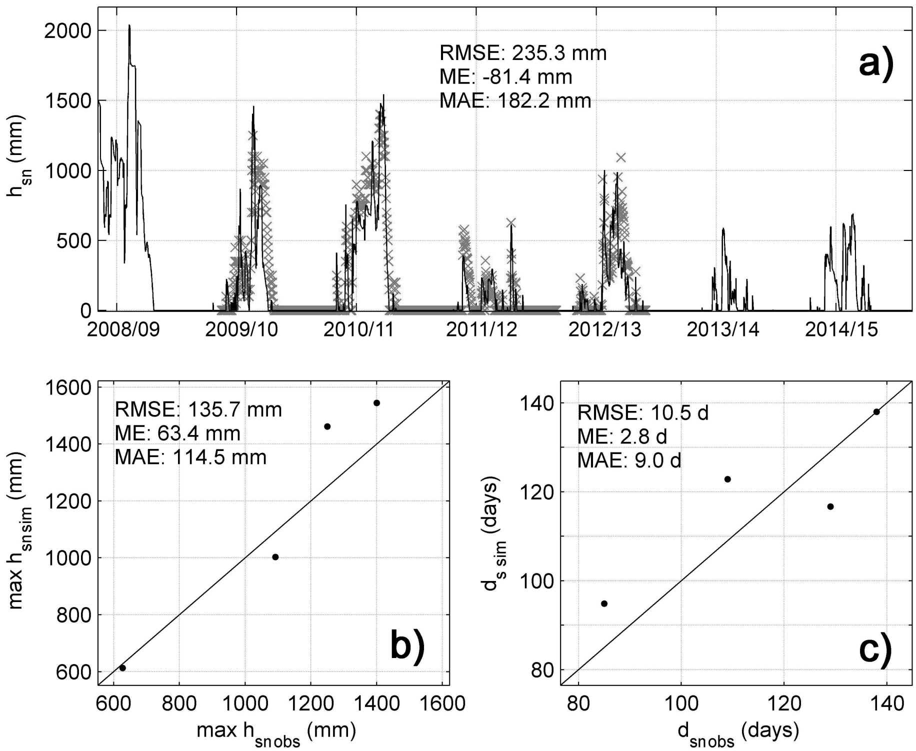

Figure 5. a) Snow depth in mm simulated for each snow season at the Refugio Poqueira site from the hydrological year 2008/09 to 2014/15. The grey crosses show the observed snow depth for years 2009/10 to 2012/13. b) Observed (obs) versus simulated (sim) annual maximum snow depth in mm at this site. c) Observed versus simulated annual duration of the snow depth in days at this site. The line at b) and c) indicates a 1:1 relationship between observed and simulated values. Each plot includes the root mean square error ($RMSE$), the mean error (ME), and the mean absolute error (MAE).

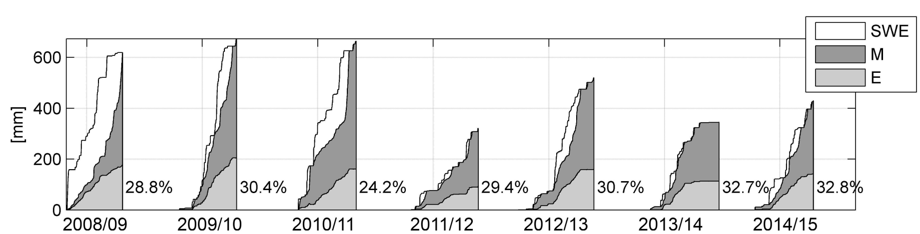

Figure 6. Cumulative snowfall together with the stacked cumulative snowmelt (M) and cumulative evaposublimation (E) (in mm) for each snow season at the Refugio Poqueira site from the hydrological year 2008/09 to 2014/15. The white area between the snowfall and the stacked M and E represents the instant ~~SWE~~ snow water equivalent (SWE) during the year. The percentage at the end of every season indicates the ratio of annual evaposublimation compared to total ablation.

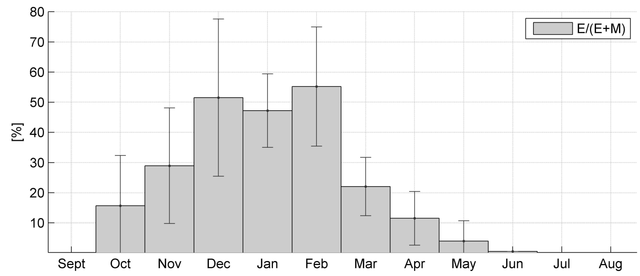

Figure 7. Mean monthly ratio of evaposublimation compared to total ablation during the year at the Refugio Poqueira site for the study period 2008–2015. Whiskers represent standard deviation from the mean.

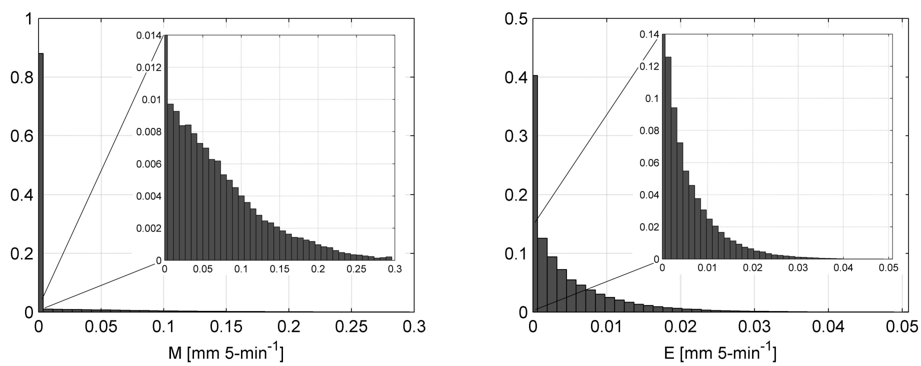

Figure 8. ~~Pdf~~ Probability density function of the mean snowmelt (M) and evaposublimation (E) rates in mm 5–min^{-1} at the Refugio Poqueira site from the hydrological year 2008/09 to 2014/15. The zoom on each plot shows the distribution without the influence of the zero–values.

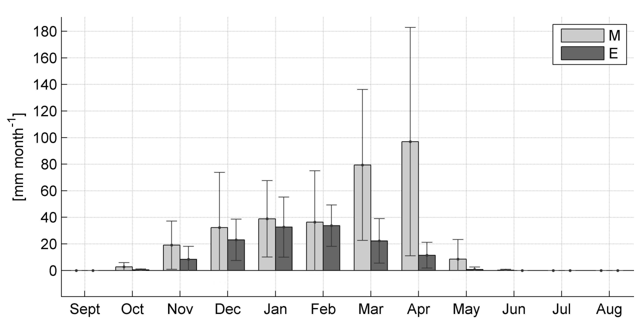

Figure 9. Mean monthly snowmelt (M) and evaposublimation (E) rates in mm month^{-1} during the year at Refugio Poqueira site for the study period 2008–2015. Whiskers represent standard deviation from the mean.

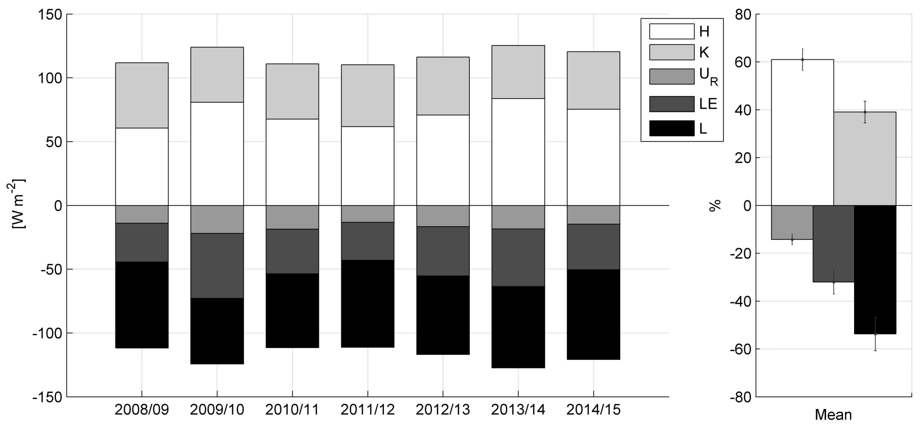

Figure 10. Annual mean energy balance (W m^{-2}) over the snowpack at the Refugio Poqueira site from the hydrological year 2008/09 to 2014/15 and average proportions of the fluxes, warming as positive (exchange of sensible heat (H) and shortwave radiation (K)) and cooling as negative .(heat advected to precipitation (U_R), exchange of latent heat (LE) and longwave radiation (L))

~~Figure. Mean monthly energy balance over the snowpack in W m^{-2} during the year at the Refugio Poqueira site for the study period 2008–2015. Whiskers represent standard deviation from the mean.~~

Reply to Anonymous Referee #1

In this document, we include the reviewer's comments in black plain font, and our response embedded in the text, in blue italics. Line numbers refer to those of the version in track changes mode.

General comments:

This work details on evaposublimation rates from snow in the Spanish Sierra Nevada. It is based on direct observations over several years as well as numerical simulations using a snow model that has been trained to match observations. The study highlights the hydrological relevance of evaposublimation in meteorological conditions prevalent in the study area, in particular considering its frequency of occurrence.

Although there are quite a few studies that have reported on evaposublimation rates from other parts of the world, I do appreciate the effort put into these measurements. Its combined evaluation in conjunction with the model simulations is generally solid. Calibrating the snow model using fluxes rather than states (but using the latter for validation) makes a welcome component. A missed opportunity is that there appears to be no systematic data available on snow surface characteristics that could have been compared to zo values presented in Table 4. Nevertheless this study should in my opinion be published after addressing the specific comments listed below.

We are really grateful to anonymous referee #1 for the time and effort spent reading and correcting this manuscript. Thank you for the positive comments. We fully agree with the comment about the lack of data on snow surface characteristics, and, in fact, this is something that will be considered in the design of the future fieldwork experiments.

Specific comments:

(2/26) Shouldn't "latter" be "former", if you include sublimation losses from snow intercepted in forest canopy?

Well, it is not a trivial question, indeed. It is true that sublimation losses from the intercepted snow can be small or huge, depending on the kind of trees and their density, snow density, total precipitation, temperature regime ... But, on the other hand, in unforested areas we expect stronger winds and we can also find sublimation from the blowing snow. It all depends on several factors for each particular environment, and how some processes dominate over the rest of them. This complexity makes it unfortunate trying to explain in a short sentence that, in fact, does not contribute significantly to the idea of the paragraph. So, following this, we have removed it in the new versions to avoid excessive simplifications (2/32).

(3/11) Why should this be a problem of the device? A snow lysimeter is to measure snowpack runoff, not snowmelt rates.

We fully agree. It is not a problem of the device, but a problem for the modeller, who wants to use these runoff data as if they were snowmelt for testing energy balance models. We have *rephrased the text on snow lysimeters to be more precise in the statements. Please, see the next comment.*

(3/25) You highlight the simplicity and low costs for traditional manual measurements versus the need for constant maintenance of automatic devices such as snow pillows. But isn't it the manual measurements that require constant maintenance?

Of course it is; we were in fact thinking about the complexity of maintaining as much as possible non-disturbed conditions, but the phrasing leads to different conclusion. We have changed the text about the lysimeters and the snow pillows together with the previous comment (3-16-24):

"1) Snow water equivalent sensors (Jonhson and Marks, 2004) and snowmelt lysimeters with snowpillows (Tekeli et al., 2005) are used in conjunction with the methodology developed for studying evapotranspiration on agricultural lands. Snow lysimeters are a suitable field method for estimating the permeability of a snowpack (Datt et al, 2010). The main problem is that the snow conditions above these automatic devices may differ from those in the natural snow because of the disturbance of the snow-ground interface (Dingman, 2002) or the appearance of snow bridging. Besides, there is a poor correspondence between the meltwater produced at the snow surface and the water arriving at the base of the snowpack on a unit-area basis, which is a problem when we want to test snow energy balance models (Kattelmann, 2000). Moreover, in semiarid mountain areas, the snow pillow measurements are adversely influenced by the typically shallow snow cover and the frequently high wind speed (Schulz and de Jong, 2004)."

We have also depicted a less idealistic picture about the pan method (4/9-11):

"The main disadvantage of this method is that it provides us with discrete results that have to be obtained manually, and, with respect to EC, that it needs some adequate measures or estimates of the parameters used for calculating the turbulent exchange of latent and sensible heat"

(5/14) Please mention if any of your data were affected by snow-vegetation interactions.

Following this, we have included some wording: "always on sites without snow-vegetation interactions" (5/17)

(5/15) Section 3.1 is a bit lengthy to my taste, given that this is a published model; irrespective of modifications that should of course be described here or in the appendix.

We have cleaned up this section (6-12-7/2) and moved to Appendix A some of the model details with less influence on the main goals of this work (17/14-25). We have maintained the considerations about the calibration parameters.

(5/31) Will probably be handled by the type editor, but I suggest to refer to "Appendix A".

Corrected at 6/15 and 7/1

(6/16) You may want to add here that L_down is available for simulations at Poqueira, but not for Pradollano.

This was already outlined in the later section "Meteorological data during field surveys". We have changed the text there to emphasize this difference (9/25).

(6/35) But z0 is not constant for simulations presented in Table 4.

It is constant if we consider that each data set test is an independent simulation from the rest of tests in the table. This allows us to calculate a mean z0 that is used, as constant, for the continuous simulation from 2008 to 2015, presented in section 4.3 and in Fig. 3 to 9.

(7/16) In the abstract you mention 15 field campaigns, here it is 10. Find a consistent wording to discriminate between campaigns (10) and data sets (15).

This misleading wording has now been corrected throughout the manuscript. Now we only have references to the 10 field campaigns and the 15 data sets/meteorological states.

(7/22) You use the term evaposublimation referring to evaporation and/or sublimation, but for the revers process only the term condensation is used without specifically addressing possible deposition (resublimation). I suggest using consistent terminology throughout the manuscript (see also at 14/2)

Yes, this is true and we have revised this wording throughout the paper. Deposition and condensation are mentioned together as "deposition/condensation", in many occasions throughout the text, actually. In correspondence, however, we dare not to "coin" a word like "condeposition" or "depocondensation".

(7/30) Consider adding a photo of your device. Why/how would the lower tray inhibit further evaporation?

The lower tray, once the upper one is on it, forms a closed container that prevents meltwater from evaporating out of it.

We have added some explanatory photographs of the device and its handling (27/Fig. 2)

(8/10) Accuracy is more relevant than precision.

Following this, we have corrected this in the revised text (8/31)

(8/28) "Surroundings" is a bit unspecific, within how many meters of the station?

We have rephrased the sentence as follows: "The tests on the southern face of Sierra Nevada were carried out in an area within a radius of 20 m from the permanent weather station at the Refugio Poqueira monitoring site..." (9/14)

(9/1) Did you account for different instrument heights when modelling N/S sites?

Yes, we did. The height of the anemometer, za in Eqs. (A5) and (A6), is an input parameter to the model.

(9/21) It seems contradictory to name E measurements more reliable if you have to omit 2 of those values over 1 omitted M value.

Yes, it is true, and "reliable" is not the proper word to be used here. Both of the rejected measures of E were due to handling errors that were apparent at a glance as they involved a visible mass exchange between the tray system and its placement site (because of the wind or some accident). What we meant but did not state clearly was that once the experimental work for a given test has been successfully completed, the measurements of E are more prone to be correct than those of M, which depend on a clean drainage through the disturbed bottom surface of the snow. To clarify this, we have rephrased the paragraph (10/11-15):

"The melting measurement relies on the correct drainage from the upper tray, which may sometimes be incomplete. We paid special attention to avoid the refreezing of meltwater in the drain holes, which was not observed in any of the performed tests. Three observations, one related to M in test 9, and two other related to E in tests 5 and 7, had to be rejected because they presented measurement errors due to accidents during the experimental work."

(9/24) Better to provide specific reasoning to delete those values from your results. Outlier removal is a sensitive matter.

This has been addressed in the answer to the previous comment.

(10/1) Reword "quasi-constant", this process is not quasi-constant, it may occur most of the time. Moreover, "60% of the time" doesn't seem to match "almost always".

We agree. It has been change to "On the contrary, evaposublimation is a continuous phenomenon, albeit at low rates." (10/22)

(10/15) "favorable" for what, for evaposublimation? Then you should probably mention wind.

Yes, we did not mention this. We have rewritten this as: "...favourable weather conditions for evaposublimation (cold days with low relative humidity and gentle wind speeds around 5.0 m s-1)" (11/3)

(10/20) Delete "in agreement with the actual conditions" or provide data, in particular if you have some!

Following this, we have removed it in the revised text (11/8)

(10/34) "correctly"? Moreover, did you allow K_H0 to vary between experiments or did you force K_H0 to be constant?

This term has been replaced by "adequately". (11/22)

With respect to K_H0, the sensitivity analysis showed that the model is much more responsive for changes in z0 than in K_H0. Moreover, the initially calibrated value for K_H0 was always close to 1W m-2 K-1, a value quite often found in other works in the literature. So in the final simulations we fixed this value.

(11/8) The three highest errors in E stem from these 2 two periods, so I do not necessarily agree with this statement.

As we explain in the following paragraph in the manuscript, the error for test 8b should not be considered since it is not due to the calibrated value of z0 or K_H0, but rather to some problem in the modelling of the deposition/condensation process. No valid combination of values for these parameters was capable to simulate the measured deposition/condensation amount.

As for the error in test 10a, it accounts for 17% of the measured evaposublimation rate in this test, which reaches 0.110 mm h-1, a value not that high.

Finally, the error in 10b, is undoubtedly large (68%).

On the other hand, there are 4 tests left, 3 of them with moderate evaposublimation rates and with low error values, and some of them associated to very different meteorological conditions. Moreover, tests 10.X also involved melting, which is simulated with low error values.

Taking all this into consideration, we think this statement can be maintained as it is. (11/29-32)

(12/1) The order of statements seems strange. Given that you used flux data to calibrate your model, it should primarily replicate the flux terms, and eventually also the states, not the other way around.

It is correct. But as in this section we are talking about the validation, which is tested against the observations of snow depth, it makes sense to express it in this order. Besides, the reference allows us to show that the good representation of the timing in the snow cycles supports the conclusion about the calibrated fluxes remaining well simulated during validation. (12/27-29)

(12/34) Just out of curiosity, is G too small / irrelevant to be shown?

We have considered it negligible in the modelling.

(13/25) Please restrict this statement to your field site or the meteorological conditions in the Sierra Nevada. Moreover, from Table 3 it seems there are 3 instances of observed zero or negative E.

Following this comment, we have changed the sentence as follows: "The measurements confirm that, for the study sites in Sierra Nevada, the evaposublimation rate is..." (14/20)

As for the comment on the observed zero values, we meant zero for evaposublimation or deposition/condensation, not only evaposublimation. This is corrected in the revised version. So, in Table 3 we can find 2 instances of observed zero values. But the value of E in test 8a is a false 0 (please see (10/23-30 and 11/33-34),, as it is in fact a sequence of evaposublimation followed by a deposition/condensation equivalent in magnitude. The only real zero value appears in test 10b.

After the Reference's comment, this sentence is redefined: "Only in one (10b) of the 15 measured meteorological states did evaposublimation or deposition/condensation appear to be inhibited:..." (14/22)

(14/2) What/where is "in the Alpine summer"?

It is a bizarre way of saying: "in the Alps during the summer". Corrected. (14/30)

(14/14) What do you mean by "high resolution"? I don't agree with your reasoning. You observed condensation at Poqueira, this is where you do have local meteorological data. Speaking of surface hoar formation and associated mass fluxes: you may want to look at a Stössel et al (2010, doi:10.1029/2009WR008198).

Thank you for the reference. This is something we would like to further investigate in future research, so we will use it.

We meant high spatial resolution, that is, <10 m according to Feick et al (2007). Our sentence is certainly misleading so we have changed it as follows (15/8-11):

"The simulation of hoar growth in complex terrain is a difficult task since it demands data of the local wind regime with a spatial resolution under 10 m (Feick et al, 2007), which was not accomplisheded for the tests in Poqueira, located 10 to 20 m away from the station."

(22/Table 1) This table is incomplete, please add a header and remove misprinted characters such as the "?".

(23/Table 2) This table is incomplete, please add a header and remove misprinted characters such as the "?".

Both have been added/removed in the revised text (24/Tables 1 and 2)

(23/Table 3) "Solar radiation" seems not the best term for what is presented in the column below.

We agree. We have changed the term by "sky condition" (25/Table 3)

(25/Figure 2) The third panel on the right could be removed.

(26/Figure 3) The third panel on the right could be removed.

Both have been removed.(28/Figs 3 and 4)

(27/Figure 4) Remove 2008/09 data, which is not a complete winter season, also considering that manual measurements commenced in 2009/10.

Actually, 2008/09 is a complete snow season. The simulation starts just before the first snow event of the water year, which was also of considerable magnitude. That is the reason why it may seem from the figure that the simulation was started with an initial condition of an already accumulated snowpack, but this is not the case.

Despite the field tests started in 2009/10, once we obtained a calibrated version of the model from this data, we decided to use all the available data-period at the Poqueira station. 2008 is the starting date for the meteorological measurements at Refugio Poqueira weather station with its present configuration. This allows us to include all the observed variability in the snow regime at this site. In fact, the 2008/09 season was outstanding because of the large amount of accumulated snow and the persistence of the snowpack. (29/Fig 5)

(28/Figure 5) Combining Figure 5) with Figure 4a) seems to indicate very low snow densities in years such as 2011/12 and 2013/14. Are these values correct?

We have checked the results and they are correct. The snow densities are always in the expected range, according to the parameterization of the snow density in Appendix A (Eqs (A9) and (A10)). These interannual figures may not be the best way to capture the evolution of the snow density. Besides, in these two years (2011/12 and 2013/14) there was a very poor snow presence with a snowpack that melted systematically and quickly after each snowfall. (29/Fig 5 and 29/Fig 6)

(29/Figures 7-10) These Figures take quite some space, but there is comparably little text in the body of the paper associated with these figure. Consider deleting two of the figures or extending the associated text.

We agree with the reviewer. We have removed Figs 7 and 10 and consequently adapted the associated text. The other 3 figures are commented in two complete paragraphs at the end of the section "Results" that we consider important because they describe the mean values and the monthly variability of the mass and energy fluxes.

Reply to Referee #2 Werner Eugster

*In this document, we include the reviewer's comments in black plain font, and our response embedded in the text, in blue italics. Line numbers refer to those of the **version in track changes mode**.*

General comments:

The authors modeled snowmelt and evaporation/sublimation losses from a snow pack in the Sierra Nevada, Spain, using a point energy budget model over 7 winter seasons (2008/9 to 2014/15). Their model suggests that 24 to 33% of the annual ablation of the snow pack is not via meltwater, but via gaseous vapor losses ("evaposublimation").

Although I have some critical remarks, I find the paper sound, relevant and suitable for the journal after the necessary revisions.

My own background is rather in eddy covariance flux measurements which are not employed here, and hence some critical remarks relate to the fact that from reading the paper I got the impression that the authors would have really profited from eddy covariance flux measurements, which are no longer as difficult to perform as e.g. Hock (2005) thought more than 10 years ago. There are probably 3 sites in Spain that might have data for follow-up studies:

Castellar de N'Hug, Spain, Pyrenees: https://fluxnet.ornl.gov/site/4055

Lanjaron, Spain, Sierra Nevada: https://fluxnet.ornl.gov/site/4060

Laguna Seca, Spain, Sierra Nevada: https://fluxnet.ornl.gov/site/4058

With eddy covariance one could directly measure sensible heat flux and thus the somewhat weakly justified assumption made by the authors that the turbulent transfer coefficient for sensible heat, KH0 = 1 W m−2 K −1 could have been omitted. Moreover, z0 could have been derived from the direct measurement of momentum flux and horizontal wind speed, and the bascially tuned value for z0 of 0.61 mm (both given on page 11, line 31) would have led to a more vigorous testing of the model.

If you add latent heat flux measurements, then of course eddy covariance flux measurements become more demanding, but already a simple sonic anemometer would provide the information mentioned above.

Having said so, I still think that the authors did a good job with the approach they used and I hope that addressing the following major points helps to improve the paper before final acceptance.

We thank Prof. Dr. Eugster for his reading of our paper and the insights into the using of eddy covariance techniques for the study of the evaposublimation presented here. Also the rigor with which he has addressed the treatment of the boundary layer theory (and the rest of the concepts in the paper in general) is very much welcome and appreciated.

We are not experts in that field of eddy covariance, but we agree with his suggestion of following up this analysis of evaposublimation with some detailed data obtained with eddy covariance measurements. In fact, we have an ongoing study together with researchers working in the two fluxnet sites located in Sierra Nevada, Lanjarón and Laguna Seca, and we had even done some preliminary analysis over their EC data. These sites could not be used for the current work, however, due to different reasons. Firstly, their location was not selected to perform specifically measurements over snow but rather of different processes. The Lanjarón site is located at an altitude of approximately 2250 m and this EC system was operative during 2009. It consisted of two EC towers, one of which was located over burnt pines that were left standing for the selected post-fire treatment, while the other was only operative from June to December. The Laguna Seca site was located at an elevation of 2267 m and its EC system was operative for two years (2007-2008). Despite we have access to some useful measurements over snow of roughness and latent heat flux, this site is located quite far away from the two monitoring sites for snow in this paper. Secondly, since these two sites were not intended to study the snow, these stations were not provided with specific sensors for snow monitoring, like snow depth, rain gauge, or camera. The distance between both groups of dataset makes it complex to use directly these EC measurements to derive conclusions in our work without further and rigorous analysis, and without additional measurements over these sites. That is the reason why we have not used them in the present work.

Nonetheless, we fully agree that the use of eddy covariance data will derive a sound validation/contrast of the estimations of this work and its conclusions, and it is a desirable further step in our future design of field and experimental work. In this sense, we also note the interesting article by Eugster & Merbold (2015) that will be of help in the future design of these improved experiments to measure evaposublimation from the snow at these mountainous sites. Likewise, in these future experiments the measurement of z0 will be a priority, for sure, even when EC sensors were not available.

Major Points

1. 2/21-22: "The evaposublimation rate depends on the vapour pressure gradient between the surface of the snow and the air, which is mainly influenced by the local wind intensity, and hence, by the complex turbulent phenomena occurring in the boundary layer." – I think you should more clearly phrase that in the first place you need a lot of energy to evaporate or sublimate water. It is not primarily the vapor pressure gradient that drives the flux, it is the heat supply to the snow surface (which is of course related to all gradients). Please rephrase. Actually on line 30 on same page you have a remark about solar radiation, but not a general picture of the relevance of energy fluxes.

We cannot but agree with this comment; reading this piece of text, it is clear that the unfortunate selection of words has made this sentence mean something different from what it was intended for. To convey the referee's comments to the paper, we have rephrased these initial sentences in the paragraph (2/22-28):

"One of the mass balance fluxes in the snowpack is the water vapour exchange between the snow surface and the atmosphere. It is directly linked to the latent heat flux and it is governed by the complex turbulent phenomena occurring in the boundary layer. The evaposublimation

process requires a high amount of energy available at the snowpack to complete the phase transition (e.g., Strasser et al., 2008). The evaposublimation rate can be calculated as a function of the vapour pressure gradient between the surface of the snow and the air, and it is decisively influenced by the local wind intensity and turbulence."

2. 3/21-22: You mention that eddy covariance flux measurements "are complex, fragile, and require large, clear, low–angle areas to function optimally". This is not really correct. The measurements actually function quite nicely, but the key issue is that they are point measurements, and although they might be very accurate point measurements, the relation of these point measurements to the surface area is a challenge. See point 3 below. As an example: why do large eddy simulation (LES) people simply use arrays of ultrasonic anemometers to obtain field data? Because they can use exactly such point measurements to validate their models.

These comments about the fragility of EC sensors, based on others' experiences, were meant to be ascribed to EC over snow under high mountain climatology. After the reviewer's comments, we have changed and added several sentences throughout the paper to depict a more realistic and updated state of the art regarding the Eddy Covariance (EC) techniques. We have also included some text to show the advantages that EC would bring to this study, especially regarding the omission of the two calibration parameters, as pointed out by the Referee.

Changes in the introduction (3/30-4/1 and 4/9-11):

"EC instrumentation is quickly evolving during the last years, and successful applications under a wide variety of environments can already be found (e.g. Reverter et al 2010, Eugster and Merbold, 2015, Knowles et al, 2015), as it is no longer as complex and fragile as it used to be. EC provides very accurate point measurements, even though the translation of these point data to a surface area still represents a challenge nowadays (Eugster and Merbold, 2015). However, experiments using EC systems are still expensive and time consuming, as the data obtained demand complex and rigorous analysis with corrections and post--processing to ensure measurement accuracy (Reba et al., 2009)."

"The main disadvantage of this method "(evaporation pan) "is that it provides us with discrete results that have to be obtained manually, and, with respect to EC, that it needs some adequate measures or estimates of the parameters used for calculating the turbulent exchange of latent and sensible heat"

3. 13/8-10: The authors write "The validity of the application of boundary layer theory to determine the turbulent fluxes over the snow, especially on complex mountainous terrains, is not clear (Hock, 2005)" – which sounds quite special. I double-checked the Hock (2005) reference and thus do not think that this wording can withstand a careful check. First, several statements in Hock (2005) are by now outdate, e.g. the idea that the eddy covariance technique "require[s] sophisticated instrumentation with continuous maintenance, which render them unsuitable for operational purposes. Consequently, such studies are rare and restricted to short periods of time". In the meantime there are many such continuous measurements. Second, this means that all other statements are focusing on the flux-gradient

method that she is interested in, thus it cannot be deduced that her judgment applies to all possible approaches. Third, the fact that some authors "lack an explanation in terms of boundary layer theory" (page 378, left column) does not mean that such a theory is not valid.

What would be an acceptable summarization of the Hock (2005) paper in this context could be written e.g. with the wording "Flux-profile and bulk transfer approaches have been shown to be problematic over sloping terrain to determine turbulent fluxes (Hock, 2005)". It is essential to make clear that it is not a problem of the theory, but of the flux-gradient or bulk method that Hock (2005) talks about. In principle one could use eddy covariance, but also there could be issues since this is a point measurement and the relation to the footprint area influencing that measurements is challenging (if you need a more detailed explanation then please consult Eugster and Merbold, 2015).

You use exactly that boundary-layer theory in your modeling approach (e.g. equations A3 and A4) and there you found a more appropriate wording for summarizing the information given by Hock (2005).

This was, in fact, a clear misunderstanding of Hock (2005) and a lack a rigor on our part when summarizing her work. We thank the Referee for pointing out this inconsistency. Following his remark, we have changed this piece of text accordingly (14/2-5):

"The turbulent heat transfer terms are probably the most uncertain contribution to solving the energy budget over the snow. Flux--profile and bulk transfer approaches have been shown to be problematic over sloping terrain to determine turbulent fluxes (Hock, 2005)"

4. Data availability: it would be great if the data could be placed in a long-term archive, such as www.pangaea.de (which is free of charge for the authors)

This is an interesting suggestion that we have followed. Data submission is in process and they will be soon available at www.pangaea.de.

Details

1/9 and many more places: "m.a.s.l." has one period too much: there is never a period after m for meters. Thus "m a.s.l."

This has been revised throughout the text

1/10: "The ratio is changeable" – do you mean "variable"? or what does this actually mean?

Please, see next comment.

1/11: "timing of the meteorological inputs, generally unforeseeable in this semiarid region" – there is something wrong here. I do not really get what you want to express. The timing of INPUT sounds incorrect in this context, and thus I do also not understand the connection with "unforeseeable" (maybe you mean that forcasting weather conditions does not work in this semiarid region? But are you sure there is no skill at all in such forecasts?) - please rephrase.

We apologize for this phrasing. We tried to emphasize the highly variability that both rainfall and snowfall regimes exhibit here in southeastern Spain, which has a major influence on the *snow persistence and metamorphosis during the cold season. This variability causes that the starting and ending date of the snow in a given water year, its duration, and the maximum accumulated snow water equivalent, among other variables, change hugely between consecutive years, for example. We have rephrased the sentence to clarify it (1/11):*

“"This ratio is very variable throughout the year and between years, depending on the particular occurrence of snowfall and mild weather events, which is generally quite erratic in this semiarid region."

1/16: "as the latitude descends" – please rephrase, the latitudes stay in place. My understand is that you wanted to say "at increasing altitudes with decreasing latidude".

This sentence has been changed following this comment (1/17)

2/13: only use the word "significant" in the context of statistical significance tests. If it does not relate to statistics, then use other words that do not have a special meaning in scientific texts. But here there is an error: "significant data series" does not sound correct anyway. Maybe you wanted to say something about data availability (no gaps, long time series?)

Yes, in this case the Referee has mentioned, we meant “continuous”. Following this comment, we have replaced “significant” throughout the manuscript with more precise terms.

2/15: "source of distributed data" – probably "source of spatial data"?

Following this comment, we have replaced this word in the revised version (2/17).

2/20: what do you mean with "latent heat balance"? Probably "latent heat FLUX"?

Yes, this was an editing mistake. We have corrected this word in the revised version (2/24).

5/3: what is an "alter-shielded rain gauge"? Please explain in more detail or give a reference where I could inform myself about this term that I do not know.

This is a term commonly found in the bibliography (eg. Fassnacht, 2004) given to a rain gauge equipped with an alter shield (Alter, J. C. 1937. Shielded storage precipitation gauges. Mon. Wea. Rev. 65. 262265) “to improve snow catch in windy conditions”. We have added this explanation and the interesting reference of Alter (1937) about the original design to the text (5/18).

5/20 and many places elsewhere: you seem to have had some trouble with the characterset and all these question marks most likely should have a specific meaning. Please search for all question marks in the text and make sure that in the revisions you get the correct characters everywhere.

It was a typo error related to the hyphens present in 5/20 and in tables 1 and 2.

6/4: do not use computer code writing in text passages. Here you should use ≤

This has been corrected (17/15).

6/19: add "Appendix" before A

This has been added in the revised version (6/15 and 7/1).

6/25: you cite Calanca (2001), but he does not primarily look at the aerodynamic roughness length, but at the roughness length for temperature. This topic again is related to the issue that you did NOT use eddy covariance flux measurements. With EC flux measurements you would bypass this issue. The information that the Calanca (2001) reference relates to actually would rather fit the information on line 34, same page. Best would be to rewrite and make sure the confusion between aerodynamic roughness (z0) and roughness length for temperature (θ0) is resolved.

Calanca (2001) measures both z0 and zT (your θ0) and he reaches in his work some conclusions valid for both of them and for their ratio; that is the reason why we used his work as a reference in the text. However, following this comment, we could identify some misleading use on our side of the different terms involved in the concept of roughness, and we have modified this paragraph accordingly (7/6 and 7/16-17).

7/11-12: "According to Braithwaite (1995), uncertainty in z0 may cause larger errors than neglecting stability." – this actually is a strong argument why you should try out eddy covariance in follow-up research! With EC you measure both z0 and z/L (or better: you can compute these two from the raw measurements).

We fully agree with the Referee and our future steps will for sure follow the EC measurements approach.

8/22 and Tables 1 and 2: here is an error: the ±5% uncertainty does not relate to the range of wavelengths that the sensor is sensitive to, but to the units of measurements, which are W m−2 . All other sensors except radiation sensors in the tables have range of measurement in correct units ± uncertainty, please give the same for radiation sensors and specify their wavelength sensitivity elsewhere (e.g. for snow temperature you mention 2 levels, you could do the same for solar radiation and write 300–1100 nm in parentheses).

We thank the Referee for this comment; we have corrected this mistake in Tables 1 and 2 and (9/8).

9/2: "The air vapour pressure was determined by the standard psychrometric method." – I am not convinced about this: the standard psychrometric method uses a dry bulb and wet bulb temperature sensor. You however do not mention a wet bulb sensor, but a relative humidity sensor on page 8, last line. Thus, you calculated vapour pressure differently - please correctly inform us how you calculated it from temperature and relative humidity (most likely you used some equation like the Magnus equation to determine saturation vapor pressure at air temperature, then used relative humidity to calculate actual vapor pressure).

The Referee is absolutely right, and this was a mistake on our side. We actually use the empirical equation in Dingman (2002), which has the same mathematical form as the Magnus Tetens formula and differs only in the parameters. This information has been corrected in the text (9/22):

"The air vapour pressure was calculated from T_a and RH_a using the empirical relation in Dingman (2002)."

9/2: "using a standard pyranometer in both cases" – I do not agree. In Tables 1 and 2 you show that you use a CS300 at one site and an SP-Lite at the other. Both are silicon photovoltaic detector sensors, that are calibrated against a standard pyranometer, but they are NOT standard pyranometers! Please reword. For more information: https://www.campbellsci.com/cs300-pyranometer, http://www.kippzonen.com/Product/9/SP-Lite2-Pyranometer

Again, we apologize for this misleading wording. The use of "standard" is quite unfortunate, and we really meant "common" pyranometers. We have replaced this adjective by the more precise " silicon photovoltaic" (9/23).

9/27: "Moreover, temperature was found to be a necessary but not sufficient driver for melting." – In fact, it is the sensible heat flux, which is a function of the temperature GRADIENT. Please be more precise in your wording.

Following this comment, we have changed the sentence (10/17):

"Moreover, temperature was found to be a necessary but not sufficient cause for melting."

9/28 and elsewhere: you are not consistent in how you print physical units such as ◦C or mm h−1 , sometimes in italics, sometimes not. Please homogenize (see the guidelines)

We have revised the text and homogenized the format of units accordingly to the guidelines of the journal.

9/29: "positive heat input from shortwave radiation" – this is another shortcut that students tend to misunderstand. Please reword and make sure it is clear that shortwave radiation is a high-level form of energy which first needs to dissipate to heat, but shortwave radiation by itself is NOT a heat input.

Following this comment, we have rewritten the sentence as "positive heat input caused by the dissipation of shortwave radiation" (10/19)

10/1: what is meant with "quasi-constant"? is it "continuous" (in opposition to sporadic)?

Yes, this was what we meant; we have replaced this term by "continuous" (10/22).

10/20: how did this calibration go for z0? This was not described.

Following this comment, the following explanation has been added to the text: z0 "was estimated by minimizing the sum of the mean errors in E and M". This explanation was added to the text (11/9). See also the answer to comment 10/31.

10/24: "which is circled" – in this figure you also circled values around zero, which do not look like outliers. Please clarify and maybe use two different ways of circling (e.g. circle outliers and use a rectangular box for a zoom).

The circle is highlighting the same test in the three panels of Fig. 2. This test appears as an outlier only in the left panel, what means that it is an outlier for E, but not for M and E/(E+M), as melting is not observed nor simulated.

Following the other Reviewer, the right panel if Fig. 2 has been removed

10/31: "only measured" – I thought you did NOT measure z0, but modeled it. This confusion I have here may relate to the point above: calibration normally requires a standard, but I am not aware of any calibration standards for z0. My best guess is that you made an optimum parameter estimate for z0 in your model, but neither "measurement" nor "calibration".

Yes, "measured" is not the correct word. We have changed it to "estimated" (11/20). And we have also replaced "calibrated" in comment 10/20 to "estimated" (11/8).

11/5: what do you mean with "absence of K flux"? You defined K as the turbulent exchange coefficient, but here you probably meant "absence of sensible heat flux"?

K refers to the shortwave radiation (Eq (A2)), while K followed by a subindex refers to the respective turbulent exchange coefficients associated to each energy flux in the balance equation. Following this, to avoid confusion, we have rewritten the sentence: "as the absence of shortwave radiation (K flux in Eq. A2)"…" allows us to better adjust the calibration parameters in the energy balance" (11/28).

11/17: "Unless proven otherwise" – there are no proofs in the empirical sciences, thus please reword. According to Popper you can only disprove hypotheses, but not prove them.

This expression is wrong and, in fact, unnecessary. We have removed it (12/6).

11/17-19: this whole sentence is not understandable for me. Please rephrase.

We have rewritten the whole sentence as: "This difference in the deposition/condensation rate is not likely to be due to a measurement error but to a modelling issue. The model succeeded in reproducing the sequence of deposition/condensation and sublimation but missed the deposition/condensation rate by an order of magnitude. Further work is needed to test this deviation by the model and identify its sources." (12/7-11)

11/26: use "small" in place of "low". And use "substantially" in place of "significantly" - unless you made a statistical test (but then please tell the reader which test and which p value)

Following this comment, we have replaced both terms in the text (12/17 and 12/19).

11/33: what do you mean with "the model smoothly reproduced"?

We mean that the model reproduced the patterns adequately, without strong shifts. After this comment, we have simply removed this adverb (12/26).

Tables: Table captions should be on top of the tables.

It is right. This was corrected, together with the figure captions, which were on top when they should be under the figure, according to the journal editing guide.

Tables 1 and 2: replace the question mark with the correct characters

As stated in a previous comment, this has been corrected throughout the text.

Table 1: Transmitter should have two t; CS300 should have a range given in W m−2 to which the ±5% information applies

This has been corrected, also in agreement with comment 8/22 (24/Table 1).

Table 2: same here for SP-Lite and CGR3; m/s should be m s−1

Done (24/Table 2)

Table 3: W is normally the mean vertical wind speed. For horizontal wind speeds, it is more convenient to use U.

Changed (25/Table 3). Moreover, we have noticed that W was already in use as the mass transport due to wind in Eq (A1)

Table 4: You give K, L, H, UE in MJ h−1 . This could be converted to W, but the issue is that this is NOT a flux density. The correct unit would be W m−2 . My best guess is that MJ h−1 is a typo and should be MJ h−1 m−2 . In any case: double-check and report in W m−2 .

Yes, this is a typo: the "m-2" were missing on the table. The model uses MJ h-1 internally, and we missed to change the units to W in the Table, as we did in Figs. 9 and 10. This has been corrected (26/Table 4).

UE is in my view not a commonly used symbol for latent heat flux. Please consider using LE or λE instead.

Despite not being the most commonly used notation, the adoption of UE as the product E.uE is consistent and highlights the fact that the unitary internal energy of water at a given state may result from different antecedent processes (i.e., warming/cooling and/or change of phase); this is interesting when evaporation and sublimation (or their reverse process) may alternatively or simultaneously occur. However, both suggestions from the Referee are actually much more frequent in literature; following this comment, we have replaced U_E by LE, together with K_UE, now K_LE, throughout the document.

Figure 2: figure captions should explain all items found in the figure. Here we lack the information about RMSE, ME, MAE, and the information about the indices "sim" and "obs" (the latter simply require a mentioning in parentheses after the respective full words).

Following this comment, we have added the whole information when needed. (28/Fig. 3, 28/Fig 4, 29/Fig 5 and Table 2).

Figure 4: why are there no snow depth measurements from the first winter and the two most recent winters on the plot?

2009-2013 was the period with snow depth measurements available for this study. (29/Fig 5)

Figure 5: explain what SWE means. The percentages are written next to the area showing snowmelt, which is confusing. Move the percentages to evaposublimation (lower part; you could also reverse the arrangement and give snowmelt at the bottom of the graph and put evaposublimation on top of it).

Following this comment, we have moved the text with the percentage values to the bottom of the graph and written out SWE (29/Fig 5).

Figure 6: write out Pdf. Is this figure really needed? Could it eventually be produced as a logarithmic plot (maybe as log(x+1))?

We have written out Pdf (Fig 6). With this figure we bring attention onto the different occurrence of evaposublimation and melting fluxes, and the comparison of their respective order of magnitude We did try the logarithmic version, but the resultant plot did not improve much the visualization. (30/Fig 8)

Figures 7 and 8: you use symmetric uncertainty bars showing standard deviation. Standard deviation is one of the two parameters of a normal distribution. Are your data really normally distributed? If not then rather give some confidence interval (e.g. 95%, but also 50% would be OK as long as it is clearly described in the caption).

We just wanted to show the value of the standard deviation for each set of simulated monthly values (that is, 7 values in each set) in the graph, to highlight the annual variability that is observed in this area, which the model captures. We are aware that the data are too few to adjust a function or to obtain a confidence interval, and that is the reason why no further analysis was performed

Figures 9 and 10: abbreviations in the plot should be explained in the captions.

They have been explained in the captions in all cases (31/Fig 10)

References

Eugster, W. Merbold, L. (2015) Eddy covariance for quantifying trace gas fluxes from soils. SOIL, 1:187-205, doi:10.5194/soil-1-187-2015