SMALL SCALE SPATIAL VARIABILITY OF SNOW DENSITY AND DEPTH OVER COMPLEX ALPINE TERRAIN: IMPLICATIONS FOR ESTIMATING SNOW WATER EQUIVALENT

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ABSTRACT

Snow density is a key property in monitoring the water content of snow-covered regions. However, sampling snow density is a difficult and time consuming task, which explains why few previous studies have analyzed the spatial variability of snow density. In this study we analyzed snow density measurements made in February and April of 2010 and 2011 in three 1–2 km^2 areas within a valley of the central Spanish Pyrenees. Snow density was correlated with snow depth and terrain characteristics including elevation, potential incoming solar radiation, terrain curvature and slope angle. Regression models were used to predict the spatial variability of snow density, and to assess how the error in computed densities might influence estimates of snow water equivalent (SWE).

The variability in snow depth was much greater than that of snow density. The average snow density was much greater in April than in February. However, the spatial variability of snow density was greater among sites in February than in April; in the latter month it varied less and was more consistent among sites and surveys. The correlations between snow depth and density were generally statistically significant but typically not very high, and their magnitudes and signs were highly variable among sites and surveys. The correlation with other topographic variables showed the same variability in magnitude and sign, and consequently the resulting regression models were very inconsistent, and in general explained little of the variance. Antecedent climatic and snow conditions prior to each survey help highlight the main causes of the contrasting relation shown between snow depth, density and terrain characteristics in the three analysed sites during the four surveys. However, as a consequence of the moderate spatial variability of snow density relative to snow depth, the absolute error in the SWE estimated from computed densities using the regression models was generally less than 15%. The error was similar to that obtained by relating snow density measurements directly to adjacent snow depths.

Key words: snow depth and density, snow water equivalent (SWE), spatial variability, Pyrenees

1. INTRODUCTION

Snow water equivalent (SWE) is the most important property of the snowpack from a hydrological point of view, as it provides information about the amount of water in a given snow-covered area. Estimating SWE is the product of snow depth (*ds*) and bulk snow density (ρs). Measuring snow depth is relatively easy and precise, and hundreds of manual depth measurements can be obtained in a single day of fieldwork (López-Moreno et al., 2010; Sturm et al., 2010), while remote or automated methods, such as ground penetrating radar, or terrestrial laser scanning can provide a fully distributed picture of the snow depth for a given transect, slope or valley (Lundberg et al., 2006; Prokop , 2008; Grünewald et al., 2010). In contrast, measuring snow density involves digging pits to obtain vertical profiles of snow density, or weighing snowpack cores to obtain estimates of bulk density (Jonas et al., 2009; Fassnacht et al., 2010). Sturm et al. (2010) reported that the time required to obtain 20-30 snow depth measurements is the required to get a single SWE measurement. Thus, most snow datasets consist of a large number of depth measurements and comparatively few density measurements, which are combined in the so-called double sampling method (Dickinson and Whiteley, 1972). Rovansek et al. (1993) reported an optimal ratio of 14 snow depths per one density measurement. However, most published datasets indicate a much lower ratio, based on the assumption that snow depth has much greater spatial variability than snow density

(Elder et al., 1998; Sturm et al., 2010). Nonetheless, and despite the lower range of variability for snow density relative to depth, it is widely recognized that snow density is subject to marked seasonal and intra-annual variability due to climatic variability (Meløysund et al., 2007; Jonas et al., 2009; Mizukumi and Perica, 2010; Svomova, 2011), and substantial spatial variability in response to factors including elevation gradients, exposure to solar radiation and wind, as well as the slope and landscape type (Onuchin and Burerina, 1996; Grünewald et al., 2010; Sturm et al., 2010). Thus, accurate and efficient SWE computation requires a sound estimation of the temporal and spatial variability of snow density at various scales, yet very few studies have attempted to quantify the within-site spatial variability of bulk snow density. Jonas et al. (2009) reviewed studies carried out in the USA, Canada and Switzerland (Bray, 1973; Janowicz et al., 2003; Sturm and Liston, 2003; Kershaw and McCulloh, 2007) on snow density and SWE measurements involving samples taken 1–10 m apart, and reported that the variability in density was 7–23%.

In estimating SWE many studies have incorporated snow density variability, on the basis that bulk density is positively correlated to snow depth due to the weight of the overlying snow compacting the underlying layers (Kojima, 1966). Lundberg et al. (2006) presented various equations that have been used to relate snow density to snow depth in studies of seasonal snow cover in Canada, Norway, the former USSR and the USA. They also reported a marked increase in the accuracy of SWE estimates based on densities computed using depth, rather than average densities calculated for entire drainage catchments. Jonas et al. (2009) used a set of regressions to calculate the SWE from snow depth for different months and elevations in Switzerland, and concluded that the error in SWE estimates using this approach was not greater than the variability of repeated SWE measurements at a single site. Sturm et al. (2010) applied statistical models based on Bayesian analysis to an extensive dataset for the USA, Canada and Switzerland. The predictor variables were snow depth and time of the year for the various snow climate regions. They found that 90% of the computed SWE values fell within ± 8 cm of the measured values. However, the relation between snow depth and density was not similarly robust at all sites, or for all times of the year and depth classes. Thus, Jonas et al. (2009) reported pronounced variability around the fitted regression for the relation of depth to density in shallow snowpacks. Also, Pomeroy and Gray (1995) reported negligible covariance between these parameters in snowpacks shallower than 80 cm, and very small covariances for deeper snowpacks. Moreover, these studies were based on correlations observed at different times of the year in separated geographical settings. Thus the derived results are not necessarily applicable to snowpack sampled at a given time of the year and in a particular basin or slope.

In the snow seasons 2009–10 and 2010–11 we conducted four intensive field surveys of snow depth and density in the Tena and Portalet valleys, in Spain and France. The surveys were conducted in early February and mid-April in each year, with the aim of sampling typical winter and spring snowpacks. The main purpose of the study was to quantify the spatial variability of snow depth at the local scale (within areas of 1–2 km^2), and to investigate the potential causes of variability, including snow depth distribution and local terrain conditions (elevation, exposure to solar radiation, slope angle and terrain curvature). We investigated the use of regression models (linear, tree and generalized additive models) to predict the spatial distribution of snow density. The errors in densities computed using different models and their implications for estimating SWE were compared with those based on the widely-used procedure of applying average measurements of snow density to adjacent snow depths.

2. DATA AND METHODS

2.1 Snow surveys and measurement of snow density

The snow surveys were conducted in February and April of 2010, and repeated in 2011; they are henceforth referred to as F10 and A10, and F11 and A11, respectively. Three areas (Piedrafita, Balneario de Panticosa and Portalet) in the Tena valley (central Spanish Pyrenees, headwater of the Ebro basin) were surveyed (Figure 1). The main differences between these areas are their geographic positions (from north to south) in the valley, and the general orientation of the surveyed zones: north-facing in Piedrafita, west- and east-facing in Balneario de Panticosa (B. Panticosa), and south-facing in Portalet. Each survey involved 4–5 days (18 days of fieldwork for the four surveys).

Figure 2 shows the evolution of precipitation, temperature and snow depth measured at a meteorological station located in the study area at 2056 m a.s.l. during the study winters. It indicates that the two years were different in terms of climate and snowpack. The 2009-2010 snow season was more cold and humid, and was considered a snowy winter. However, several days prior to the survey F10, there were rainfall events below 1800-1900 m a.s.l. The 2010-2011 snow season was dryer and warmer. The snowpack was thinner than the previous year although it was a “normal year” in terms of snow accumulation. However, the end of March and April was very warm and the snow melted quickly, with the disappearance occurring almost a month prior than in 2009-2010. Several days prior to the F11 survey, a heavy snowfall noticeably increased the snowpack, especially at lower elevations. In the weeks prior to the A10 and A11 surveys, the weather was warm; the snow grains rounded, the snowpack densified, and as a result had a high water content.

The measurement sites were selected randomly, and the number, location, and elevation range of measurements in each area varied for each survey, depending on snow conditions, the presence of snow and the risk of avalanches. The survey elevation ranged from 1517 to 1992 m a.s.l. in Piedrafita, 1710 to 2199 m a.s.l. in Portalet, and 1641 to 3015 m in B. Panticosa; the broad elevation range for surveys in B. Panticosa was as a consequence of avalanche risk and the variable elevation of the snowline in this area. For F10, A10, F11 and A11, respectively, a total of 160, 166, 173 and 148 snow density measurements sets were made. For all sites the minimum number of measurements sets was > 41, and the maximum number at any site was 81. The survey site in each area ranged from 1–2 km^2, and the mean distance between a given measurement and the closest surveyed point was 112 m.

Snow density was measured using a Snow-Hydro snow corer (Fairbanks, Alaska; Sturm et al., 2010). We took particular care to avoid the potential inaccuracies associated with snow samplers, and prioritized measurement quality over the total number of samples collected. The snow corer was inserted into the snow until it contacted the ground, and the resulting snow core was removed, bagged and weighed (± 5 g). If no soil or vegetation was associated with cores sampled in this way, it is possible that the bottom of the snow core has been lost (Sturm et al., 2010). This did not occur often in our study because the ground was generally not frozen and a plug of soil and/or vegetation was typically present. Another potential error in the use of snow samplers is the potential for snow to be pushed out of the path of the corer during its passage through ice layers, resulting in erroneously light samples. To avoid this problem we ensured that the snow core retrieved within the tube was never 5 cm shorter than the depth recorded by the sampler. Where we suspected that the lower part of the core had been lost or the snow had not properly entered the sampler, we dug a pit to control the introduction of the sampler into the snow, and extracted the sampler laterally, as recommended by Jonas et al. (2009). A previous study carried out in the

Pyrenees confirmed that bulk snow density estimates from snow samplers were almost identical to those obtained by sampling snow profiles using a wedge cutter in snowpits (Fassnacht et al., 2010). This was consistent with the conclusions of Sturm et al. (2010), who also used the Snow-Hydro sampler and attributed its accuracy in estimating snow density to its design and large cross-sectional area (30 cm^2). In this study we replicated sampling at each of the sites until at least three density measurements differing by < 5% were obtained. These were averaged to provide the estimate of density at a given location.

2.2 Statistical analysis

Snow density at each location was assessed for its correlation with snow depth and various terrain characteristics including elevation, exposure to solar radiation, slope angle and terrain curvature. These variables may be related to snow density as they can affect the weight of the overlying snowpack (snow depth), the air temperature or incoming energy (elevation, exposure to solar radiation), and the movement of water within the snowpack (slope angle or terrain curvature). Average solar radiation (RAD) received by each cell of the DEM from December to April under clear-sky conditions. This parameter was obtained from a physically based computational model (implemented in the MIRAMON GIS software) that considers the effects of terrain complexity (shadowing and reflection), including slope angle and aspect variables. A detailed description of the model can be found in Pons and Ninyerola (2008). Landscape curvature, defined as the derivative of the rate of change of the landscape, helps to quantify the shape of the landscape surface. Mean (or overall) curvature is a combination of profile and planiform curvature, and is useful for determining local high and low points. In general, the values derived by the "mean curvature" request are almost always equal to the planiform curvature minus the profile curvature. Profile curvature is calculated in the direction of slope; whereas planiform curvature is calculated perpendicular to the direction of slope (Jenness, 2006).

The possibility of partial correlations or interactions between snow depth and the terrain characteristics was also explored. The partial correlation procedure involves the calculation of partial correlation coefficients that describe the linear relation between two variables (snow depth and density in this study), while controlling for the effect of other variables (elevation, exposure to solar radiation, terrain curvature and slope). This process enables the effect of one predictor variable to be isolated from the effects of other variables under conditions of multi-collinearity (where two or more predictor variables are highly correlated). The potential for combined effects of snow depth and various predictors on snow density distribution was investigated by calculating the interaction of snow depth and terrain characteristics. For this purpose, predictors were scaled from 0 to 1 and then multiplied (Millard and Neerchal, 2001).

Linear regression, binary tree regression and generalized additive models (GAMs) were used to predict snow density from snow depth and terrain characteristics. López-Moreno et al. (2010) have provided a full description of the regression procedures. Linear models enable predictions based on the linear relations between the response and predictor variables. Classification tree models are non-parametric models based on recursive splitting of the information from predictor variables, which minimizes the sum of the squared residuals obtained in each group. Finally, GAMs are non-parametric extensions of generalized linear models (GLMs), which estimate response curves using a non-parametric smoothing function rather than parametric terms. Models were created for each site (Piedrafita, Portalet and B. Panticosa) and each survey (F10, A10, F11 and A11), producing a total of 12 models.

The terrain characteristics (elevation, potential incoming radiation, curvature and slope angle) were derived from a 20-m digital elevation model, provided by the Hydrological Authorities of the Ebro basin.

Model accuracy was assessed by cross-validation. This involved initial splitting of the data into a number of subsets (8 in this study). In turn, each subset was omitted and the model was fit to the remaining cases. The resultant equation was then applied to the omitted subset to calculate its predicted value (López-Moreno et al., 2010). The SWE was calculated from the measured snow depth and the density obtained from the various regression models, which enabled assessment of the impact of the error in snow density calculation on the estimation of SWE. The error in density and SWE was quantified using the standardized mean absolute error, which was computed from the mean of the absolute differences between the calculated and measured density and SWE, divided by the mean of all measurements.

We also associated measurements of snow density to measurements of adjacent snow depth, a common procedure referred to as the double sampling strategy (Dickinson and Whiteley, 1972). For this purpose we classified sampled points for each site and survey date into different sized groups from a cluster analysis using the distance matrix between all measurements as cases (see Fig. 3 for an example of classification of measurements into different numbers of groups). This allowed us to examine the effect of different numbers of snow density measurements on the distribution of density and SWE in a given area. We then took individual values of density for each group and associated these to the remaining depth measurements. This procedure was repeated for each group using all the measurements belonging to that group and provided the mean error for a different number of density measurements. As proposed by Steppuhn (1976) for the optimization of areal SWE, and as used in later experiments by Grünewald et al.

(2010), we considered only the density measurement at the average depth for each group.

3. RESULTS

3.1 Spatial variability of snow depth and snow density

Figure 4 shows the average and range of snow depth and density for each survey and at each site, and Table 1 provides statistics related to each survey. In all cases the variability of snow depth was much greater than that of snow density, although the spatial variability associated with the latter was marked. The coefficient of variation (CV) for snow depth was always > 0.28, reached 0.76 (F11 in Piedrafita), which was > 0.4 higher than that of the vast majority of sites and surveys. The survey carried out in F10 yielded the highest mean snow depth but the least spatial variability, but in F11 the opposite was observed (the lowest mean snow depth but the greatest variability). There was not a particular site that systematically exhibited the highest or lowest variability.

The CV for snow density ranged from 0.05 (A10 in Piedrafita) to 0.32 (F11 in Piedrafita), but in most cases CV was close to or > 0.1. The density was greater in April (overall averages of 453 and 455 kg m^{-3} in A10 and A11, respectively) than in February (316.2 and 306 kg m^{-3} in F10 and F11, respectively). The snow density in April was very similar among the sites during both surveys even if intra-annual differences were evident for February in Piedrafita and B. Panticosa, whereas in Portalet almost identical average densities were recorded in the two years. The maximum mean snow density was recorded in Piedrafita during F10, A10 and A11, and the minimum density was found at this site during F11. The maximum density was recorded in Portalet during F11 and the minimum during A11. Neither the maximum nor the minimum density was recorded in B. Panticosa during any of the surveys. In general, the spatial variability of snow density was greater and more variable among sites in February (values ranged from 0.07 to 0.32) than in April (values ranged from 0.05 and 0.09). There was no clear relation between mean snow density or depth and its coefficient of variation at any site. As occurred for snow depth, the maximum or minimum CV in snow density was not consistently found at any particular site.

3.2 Correlation of snow density with snow depth and other topographical variables

Figure 5 shows the correlation between snow depth and density in the three study areas during the four surveys. In general, we found no robust relations between snow depth and snow density at any of the study sites. The magnitude and sign of the correlations were extremely variable between sites and surveys. Even if statistically significant correlation was found for February 2010 between depth and density for the sites Portalet Piedrafita and B. Panticosa the correlation was positive for the first site ($r = 0.78$; $a < 0.05$), and negative for the latter two ($r = -0.33$; $a < 0.05$; $r = -0.53$; $a < 0.05$) respectively. Two months later snowpack was denser in the three sites and thinner in Piedrafita and Portalet, although it remained with a similar depth in B, Panticosa. At this time, the correlation in Portalet in A10 was still positive, but the Pearson´s coefficient was much lower ($r = 0.37$; $\alpha < 0.05$). However, the negative correlations observed in February in Piedrafita and B. Panticosa shifted to significant positive correlations in April ($r = 0.46$; $\alpha < 0.05$ and $r = 0.26$; $\alpha < 0.05$, respectively). Similar variability among sites and surveys was observed during 2011. In this case Piedrafita showed the strongest positive correlation in February ($r = 0.84$; $\alpha < 0.05$), but this had decreased markedly by April ($r = 0.35$; $\alpha < 0.05$). In Portalet the correlation was positive and statistically significant in February ($r = 0.46$; $\alpha < 0.05$), whereas in April, when snowpack was denser and thicker in the three sites, it was still positive but not statistically significant ($r = 0.19$; $\alpha > 0.05$). In B. Panticosa the relation was negative and statistically significant in February ($r = -0.30$; $\alpha < 0.05$), but positive and not statistically significant in April ($r = 0.16$; $\alpha < 0.05$). No notable differences were found in the sign and significance of the relations between snow depth and density during the surveys conducted in February and April. As indicated above, independent of the sign of the correlation, in very few cases were the relations strong, with most Pearson´s correlation coefficients being < 0.5 or > -0.5. When all cases were considered independently of site, no significant relations were found between snow depth and density.

The bivariate-correlation between snow density and the various topographic factors was also quite variable among sites and between surveys, as shown in Table 2. Thus, the correlation was statistically significant between snow density and elevation at Piedrafita for all surveys. However, the correlation was positive for A10, F11 and A11 but negative for F10. In Portalet, elevation showed a significant positive correlation with snow density during F10, A10 and F11, but during A11 the correlation was not statistically significant. In B. Panticosa, the correlation with elevation was negative and statistically significant during F10 and F11, positive and statistically significant during A10, and there was no significant relation during A11.

During A10, exposure to solar radiation showed a positive and statistically significant correlation with snow density in Portalet and B. Panticosa, but in Piedrafita the correlation was negative (-0.24; $\alpha < 0.05$). For the remaining surveys there were almost no significant correlations with radiation, with the exception of Portalet during F10. Terrain curvature only showed a positive and statistically significant correlation with snow density in B. Panticosa during F10, and in Portalet during F11. Slope had a negative and statistically significant correlation with snow density in the three study areas during the F10 survey. However, a positive and statistically significant correlation was found in Portalet during A10, in Piedrafita during F11, and in B. Panticosa during F11 and A11. As occurred with snow depth, the Pearson´s correlation coefficients between terrain characteristics and snow density rarely exceeded 0.5.

Table 2 also shows the partial correlation coefficients between snow density, snow depth and the considered topographic variables. Results confirm that the observed bi-variate correlations between snow depth and snow density were largely unaffected by other variables. Thus, there was only a slight decrease in the correlation coefficients when the terrain characteristics were simultaneously considered in relation to snow depth. The strongest correlations observed (Portalet during F10 and Piedrafita during F11; r = 0.79 and 0.85, respectively) declined markedly but remained very high when the effect of elevation was removed (r = 0.68 and 0.74), and this result was largely unaffected by other terrain characteristics. Although in some surveys the correlation coefficients also decreased when partial correlations were considered, the statistically significant bivariate correlation between snow depth and snow density was non-significant when the effect of terrain characteristics was considered.

Table 2 further shows that there was no clear evidence of an interaction between snow depth and other terrain characteristics that could adequately explain the spatial variability of snow density, as these interactions did not markedly increased the correlation coefficient. In most cases snow depth alone explained as much as any other variable. However, in some cases there were appreciable increases in the correlation coefficient. For example, the correlation increased from 0.26 to 0.62 in B. Panticosa during A10, when the interaction between snow depth and exposure to solar radiation was considered. However, such increases in explained variance were uncommon, and no systematic interactions were found for any site or survey.

3.3 Prediction of the spatial distribution of snow density: implications for the calculation of SWE

Table 3 shows the variables selected as predictors by the multiple linear regression models (stepwise selection), the coefficient of determination obtained for each model, and the resulting errors in density and SWE estimates. The errors in density and SWE estimates are also plotted in Figure 6A. Snow depth was introduced as a predictor in the regression models except in Panticosa and Portalet during A10 and A11. However, the magnitude and sign of the weighting coefficients for snow depth in the models differed markedly among sites and surveys. In some cases slope, radiation or elevation was selected as the only predictor, or they complemented snow depth in predicting the spatial distribution of snow density.

With the exception of Portalet during F10 ($r^2 = 0.62$) and Piedrafita during F11 ($r^2 = 0.79$), the linear models explained < 40% of the variance in snow density variability. The snow density predicted from linear models was associated with absolute errors of approximately 20% in several cases (Portalet during F10, Piedrafita during F11, and B. Panticosa during F10, A10 and F11). In other cases the errors in density estimates ranged from 5–10% (all sites during A11, Piedrafita during F10, Piedrafita and Portalet during A10, and Portalet during F11). In general, the predictions of snow density were more accurate during April than February, and particular differences in accuracy were found when the three areas were compared. When the predicted density was used to estimate the SWE, the absolute errors ranged from 4.1 to 28.9% among sites and surveys. In 8 of the 12 combinations of site and survey, the error in SWE exceeded 10%. When the models considered interactions among variables (e.g. regression tree models) or non-linear relations (e.g. GAMs), the estimation of snow density or SWE did not result in improvements over linear models. Thus, Table 3 and Figure 6B and 6C show that the values of the standardized MAE for snow density and SWE estimations were generally higher when density was calculated using trees or GAMs than when linear regression models were used.

Figure 7 shows the error in snow density and SWE estimates when we associated measurements of snow density with measurements of adjacent snow depth. For this analysis we classified the sampling points for each site survey into groups of different sizes using a cluster analysis based on the distance matrix among all measurements. From Figure 7 it is evident that in most of the site surveys we can expect an average error of 5–10% ± 5% (1 standard deviation) in snow density and SWE estimates using this procedure. In some cases the error was much greater than 10%, as occurred with respect to density in B. Panticosa during F10 and Piedrafita during F11, and for SWE in B. Panticosa during F10 and A11, Piedrafita during F11 and A11, and Portalet during A11. Surprisingly, the accuracy in prediction of snow density and SWE did not clearly improve when the number of density measurements was enhanced. Thus, with an increase in the number of measurements from 1 to 10 the observed decrease in error estimates was marginal. When the density value obtained from the measurement location that exhibited the mean snow depth was associated with the other depth measurements of each group, we generally found that the error was very similar to or greater than the average error obtained from random resampling. In several cases the error exceeded the ± 1 standard deviation range (B. Panticosa during F11, A10 and A11; Piedrafita during F11 and A11).

4. DISCUSSION

Measurements of snow depth and density were made during four surveys in a valley of the central Pyrenees, providing valuable information about the spatial distribution of snow density in three areas each comprising 1–2 km^2. This is one of few studies of this type, and the first carried out in the Pyrenees, a mountainous area characterized by more temperate conditions than the Alps, Scandinavia and North America, where snow density dynamics has been previously analysed.

Some of the results of this study concerning the spatial variability of snow depth and density are consistent with studies conducted in other geographical areas. We found that snow depth exhibited greater spatial variability than snow density, as reported previously (Dickinson and Whitely, 1972). For most of the site surveys we found that the CV of snow depth ranged from 0.27 to 0.76, while for snow density it ranged from 0.05 to 0.32. In most cases (see Table 1) the difference in the variability in depth and density was similar to the four-fold dynamic range reported by Sturm et al. (2010) for a north Alaska dataset. The local scale variability we found in our 1–2 km^2 study areas in the Pyrenees (CV from 5 to 32%), where the mean distance between a measurement and its closest survey point was 112 m, is very similar to that reported in previous studies (7–23%) that analyzed within-site snow density variability using sample spacing of 1–10 m (Bray, 1973; Janowicz et al. 2003; Sturm and Liston, 2003; Kershaw and McCulloh, 2007; Jonas et al., 2009).

Although the surveys were conducted during only two snow seasons, the evolution of snow density appeared to follow a clear seasonal pattern involving a progressive increase in density of the snow pack from winter to spring, when the maximum density was observed. This is a consequence to the existence of persistent positive temperature at high elevation in March and April in both years (see Figure 2), leading to melting conditions and compactation of the snowpack. This is consistent with findings reported by Jonas et al. (2009) for the Swiss Alps, and Mizukami and Perica (2009) for the western USA, Lundberg et al., (2006) for Sweden and Pomeroy and Gray (1995) for sub-arctic regions.In a similar finding to that reported in the latter study, we found that although the climatic conditions differed markedly between the two snow seasons, the snow density in April varied little between the years. In general, the snow density was greater and more spatially variable between sites in February (CV = 0.07–0.32) than in April, when the density was higher and more consistent among sites and surveys (CV = 0.05–0.09). This result has noticeable implications for predicting spring runoff from manual snow measurements, as maximum SWE is normally recorded in April in the majority of the Pyrenean range (López-Moreno and García-Ruiz, 2004; López-Moreno et al., 2009) and uncertainty of density estimation at the basin scale is much lower than during the cold season.

We found no robust relations between snow depth and snow density at our study sites. On few occasions did the coefficient of correlation between depth and density exceed 0.5, but more importantly we found that the correlations were remarkably variable in both magnitude and sign between sites during a given survey, and between surveys at a given site. This result indicates that at small spatial scales and considering a particular time, it is not possible to find a robust relation between snow depth and density such as has been previously reported when more extensive datasets referred to multiple geographic locations and different periods of the snow season were used (Lundberg et al., 2006; Jonas et al., 2009; Sturm et al. 2010). Thus, the previous studies reported robust depth and density relations that varied throughout the season but tended to be location dependent. These relations enabled calculation of the SWE using only snow depth data, with errors very close to the expected variability associated with the measurement procedure (Jonas et al., 2009). The divergence between our results and those of the studies noted above is related in part to the different spatial scales involved; this study covers small areas with a high density of measurements while the other studies use data collected over a regional and continental scales.

The resolution of the density data used by others is in the range of kilometers (e.g., Lundberg et al., 2006 used 11 stations over 12386 km^2; Jonas et al., 2009 used 37 sites over the Swiss Alps), while our data were collected at approximately 100 meter intervals, or two to three orders of magnitude finer. The correlation length of our data was less than 150 meters, based on variogram analysis (see Deems et al., 2006). This correlation length is much finer than can be computed from the operational data (Fassnacht and Deems, 2006). The variability of snow density at short distances is affected by additional factors such as the compaction effect of the overlying snow on the underlying snowpack, which is the main argument to explain the relation between snow depth and density. This variability can be due to several reasons, such as the existence of preferential flow paths of melting water within the snowpack, the irregular accumulation of fresh snow due to wind redistribution and the small scale variability of temperature and incoming solar radiation in mountain areas (Molotch et al., 2005).

Datasets containing more data covering more geographical settings and dates of the winter can smooth the local variability. This can be seen in the pronounced variation about the fitted regression between the snow depth and density (Pomeroy and Gray, 1995; Jonas et al., 2009). Such datasets retain the main signal that normally associates denser snow in deeper snowpacks. Also, the climate characteristics of the Pyrenees, where melting events can occur at different elevations throughout the snow season may introduce a higher complexity in the characteristics of the snowpack during winter time than in other areas where cold conditions are usually more persistent during the accumulation period. The analysis of partial correlations showed that the correlations found between snow depth and density in this study were not affected by multi-collinearity with terrain characteristics including elevation, incoming solar radiation, terrain curvature and slope angle, none of which showed a robust relation with the spatial distribution of snow density.

The different relation between snow depth, density and topographic variables among sites and surveys found in this study can be related with specific antecedent meteorological and snow conditions in each specific site or survey. An example is the extreme variability in the sign and magnitude of the correlation between snow depth and density found in February 2011 when the snow depth ranged from 50 to 100 cm. At that time there was new snow immediately prior to the survey (Figure 2). Older snow layers where very thin and highly metamorphosed and compacted, so fresh snow represented a considerable fraction of the total snow depth at that time. Thus, at spots where more fresh snow accumulated, lower densities were measured. In this particular survey, accumulation of fresh snow was very variable due to the effect of wind blowing and possibly the irregular spatial distribution of precipitation, hence it resulted in a highly variable response of snow density to snow depth amongst the three sites. Snow conditions were very different in February 2010. At that time, rain occurred in Piedrafita and Panticosa sites prior to the snow surveys (Figure 2). Rain noticeably increased the water content of the upper layers of the snowpack, which yielded a higher bulk density for a thinner snowpack. This yielded the negative correlation between depth and density at these sites. However, Portalet, that is located at the northernmost location of the valley, received much less precipitation, since the moisture came from the south, and it is likely that most of it occurred as wet snow rather than rain due to its higher elevation. At this site, the observed relation between snow depth and density was positive. The periods before the April surveys in both years were characterized by melting conditions due to the persistence of temperatures warmer than 0 degrees Celsius. Thus, the snowpack was isothermal at all sites and the distribution of density was more regular. At this time, the relation between depth and density more similar to the trends reported in previous larger scale studies at (Jonas et al., 2009; Sturm et al., 2010).

The marked variability in the correlations between snow density and snow depth or other terrain characteristics among sites and surveys showed that the linear regression models used to predict the spatial distribution of snow density were inadequate in terms of the selected predictor variables and their coefficients; in general these models explained only a small proportion of the variance. Furthermore, neither the use of a non-linear regression model (GAM) nor assessment of the interactions among variables using regression tree models improved the snow density predictions. Further research should assess the adequacy of the resolution of the digital elevation model used to derive the terrain characteristics (20 m of grid size) on the accuracy of the models, as previous research suggests that density may vary at the meter scale (Fassnacht et al., 2010; Grünewald et al., 2010). However, the use of digital elevation models at higher spatial resolutions is limited for many mountain areas and also it could be problematic due to georeferencing of the density measurements with respect to the usual accuracy of the most commonly used GPS systems (2-10 meters of accuracy). Since the spatial variability of snow density was much less than that of snow depth, the inability to adequately predict the spatial distribution of snow density had only a moderate effect on the estimates of SWE in each site survey. Thus, linear models provided standardized absolute errors ranging from 4.1 to 28.2%, and in 9 of the 12 combinations of site and survey the error was less than 15%. In the absence of a large number of density measurements, the association of density measurements with adjacent snow depths has been reported to be a reliable procedure for estimating SWE (Sturm et al., 2010). In most cases we found the average error ranged from 5 to 15%, with an uncertainty of approximately 5% ± 1 standard deviation. The use of the snow density measured at the mean snow depth in the survey or a subset of the survey (Steppuhn, 1976) was not found to improve the areal estimation of SWE. This was a consequence of the inconsistent relation between snow depth and density in our dataset.

Future studies in the Pyrenees and other mountain areas should analyze snow density variability at different temporal and spatial (resolution and extent) scales than considered in this study. This would enable comparison with previous reports, and assessment of whether the climatic conditions in the Pyrenees explain the different relation we found between snow depth and density relative to that reported for other mountain areas. In addition, long-term monitoring of snow density during different periods of the snow season would improve understanding of the seasonal variability of snowpack characteristics, and be of use in the monitoring of mountain water resources.

5. CONCLUSIONS

Four surveys conducted at three 1–2 km^2 sites in a Pyrenean valley revealed that snow depth variability was much greater than the variability in snow density. Thus, the CV of snow depth ranged from 0.27 to 0.76, whereas for snow density it ranged from 0.05 to 0.32. The snow density in April was much greater than in February. The spatial variability of snow density was greater among sites in February (values ranged from 0.07 to 0.32) than in April, when the variability was less and more consistent among sites and surveys (values ranged from 0.05 to 0.09). Snow depth is generally statistically correlated with density, but in this study the correlation coefficients were generally low, and the magnitude and sign of the correlations were highly variable amongst sites and surveys. Correlations with other topographic variables showed the same variability in magnitude and sign, which resulted in the regression models being very inconsistent and, in general, explaining only a small proportion of the variance. This paper did not aim to explain why the density varies based on the snowpack processed, but rather provided insight into performing snow surveys. Distributed meteorological information and the layered conditions of the snowpack would help to provide a physical reasoning of such variability in the response of snow density to snow depth and other terrain characteristics. We have discussed the relevant influence of the antecedent climatic and snow conditions to each survey on observed spatial distribution of snow density during each survey in the three different sites. However, as a consequence of the moderate spatial variability of snow density, the SWE estimates derived from computed densities did not usually exceed 15% (although in some cases they reached 30%). In April when accumulated snowpack explain most of the spring runoff in the Pyrenees, snow density is less variable than in mid winter, which represents a noticeable advantage for SWE estimation from manual measurements. The association of snow density to adjacent snow depth measurements seems to be a reliable procedure in cases where the number of density measurements is limited. Thus, the average error using this procedure generally ranged from 5 to 15% (± 5% for 1 standard deviation). No clear relation was found between sample size and improved estimates of the SWE.

ACKNOWLEDGEMENTS

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Figure Captions

Figure 1. Location of the Tena Valley (Iberian Peninsula) and the three study sites. Points indicate the sampling locations in each survey.

Figure 2. Evolution of precipitation (bottom panels), temperature (middle panels) and snow depth (top panels) in an authomatic weather station located at at 2056 m a.s.l. in the Tena valley. Grey bands indicate the periods when snow surveys were conducted.

Figure 3. Example of a survey (Piedrafita, A10) classified by different numbers of groups. Classification was based on cluster analysis using the matrix of distance between measurements as cases.

Figure 4. Summary of depth and density measurements for each survey and site. Dots indicate average depth and density. Thick bars indicate the 90th and 10th percentiles, and the thin bars represent the maximum and minimum values measured in each survey. The number of measurements and the elevation range sampled in each survey are shown in the bottom left corner of each panel. Arrows indicate the change in mean depth and density from February to April in both analyzed years.

Figure 5. Correlation between snow depth and density at the three study sites during the four surveys.

Figure 6. Standardized mean absolute error (%) for SWE (squares) and density (triangles) estimation for the different models: (A) linear, (B) tree and (C) GAM model for the 3 sites separately and for all sites taken together.

Figure 7. Error in snow density (dashed grey line and triangles) and SWE (solid black line and squares) estimates for density measurements based on adjacent snow depths. Crosses indicate the average error from replicates of all cases belonging to each group; lines indicate ± 1 standard deviation; triangles indicate the error when the

measurement that exhibited the mean snow depth was associated to the rest of depth measurements of each group. Cases where the error was > 20% are not shown in the plots.

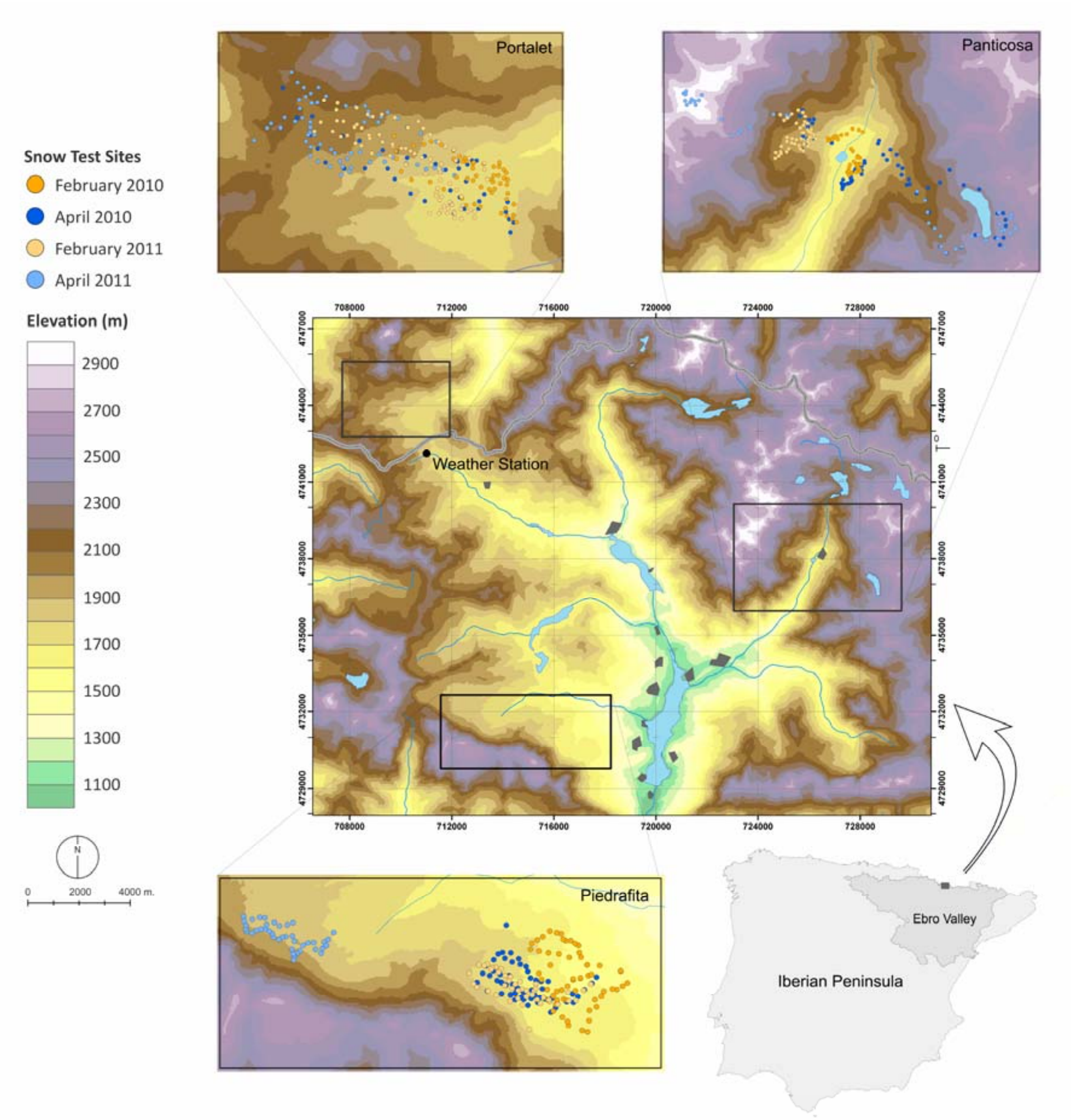

Portalet
Panticosa
Piedrafita
Snow Test Sites
February 2010
April 2010
February 2011
April 2011
Elevation (m)
2900
2700
2500
2300
2100
1900
1700
1500
1300
1100
N
0
2000
4000 m.
708000
712000
716000
720000
724000
728000
4747000
4744000
4741000
4738000
4735000
4732000
4729000
Weather Station
Ebro Valley
Iberian Peninsula

Figure 1.

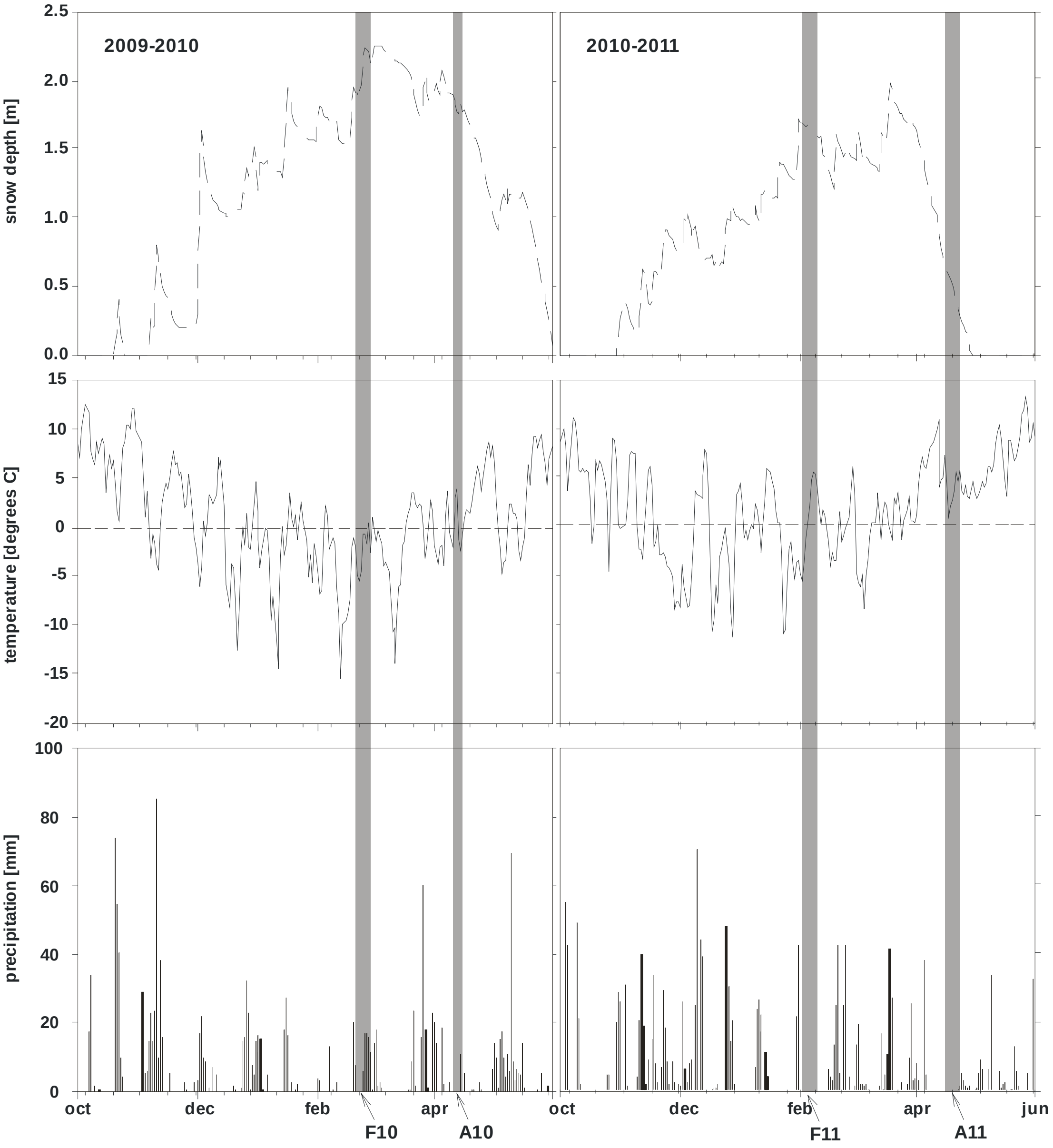

2009-2010
2010-2011
snow depth [m]
2.5
2.0
1.5
1.0
0.5
0.0
temperature [degrees C]
15
10
5
0
-5
-10
-15
-20
precipitation [mm]
100
80
60
40
20
0
oct
dec
feb
apr
oct
dec
feb
apr
jun
F10
A10
F11
A11

Figure 2.

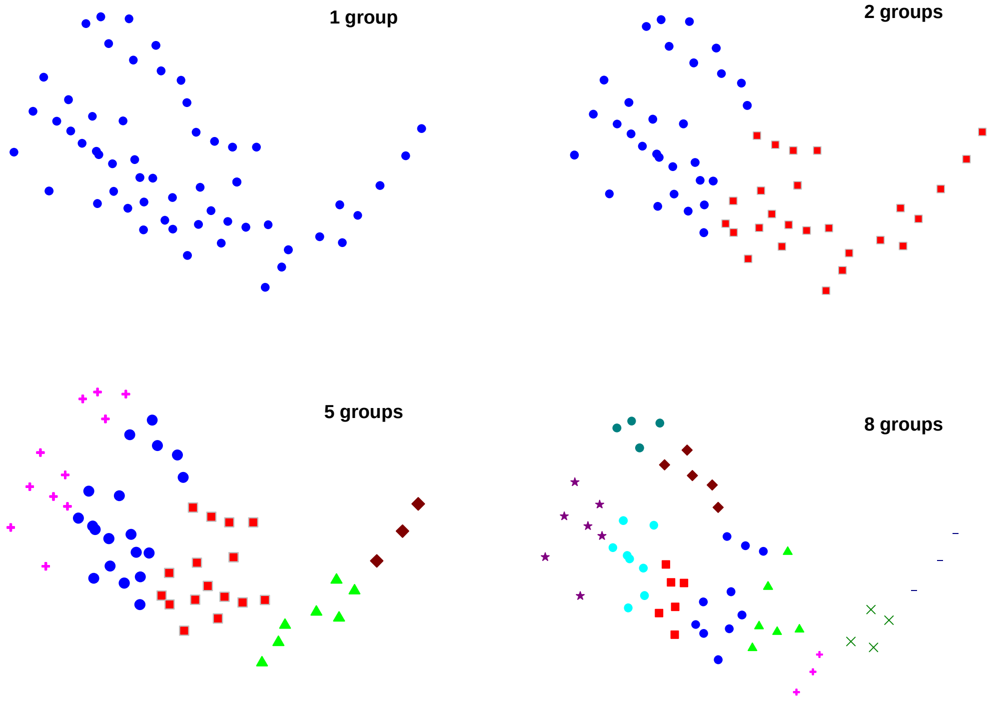


Figure 3.

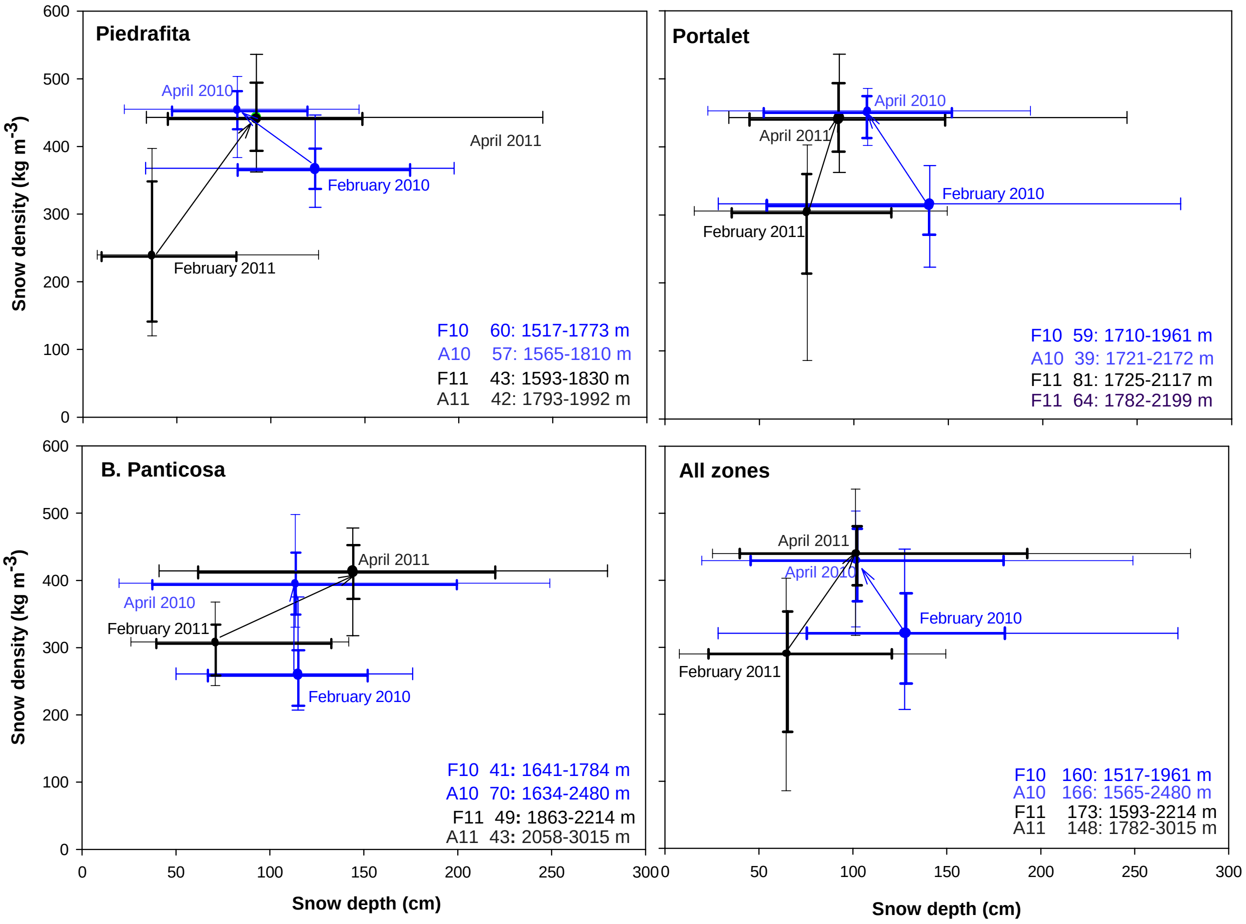

Piedrafita
April 2010
April 2011
February 2010
February 2011
F10 60: 1517-1773 m
A10 57: 1565-1810 m
F11 43: 1593-1830 m
A11 42: 1793-1992 m
Portalet
April 2010
April 2011
February 2010
February 2011
F10 59: 1710-1961 m
A10 39: 1721-2172 m
F11 81: 1725-2117 m
F11 64: 1782-2199 m
B. Panticosa
April 2011
April 2010
February 2011
February 2010
F10 41: 1641-1784 m
A10 70: 1634-2480 m
F11 49: 1863-2214 m
A11 43: 2058-3015 m
All zones
April 2011
April 2010
February 2010
February 2011
F10 160: 1517-1961 m
A10 166: 1565-2480 m
F11 173: 1593-2214 m
A11 148: 1782-3015 m
Snow density (kg m-3)
Snow depth (cm)
0
100
200
300
400
500
600
0
50
100
150
200
250
300

Figure 4.

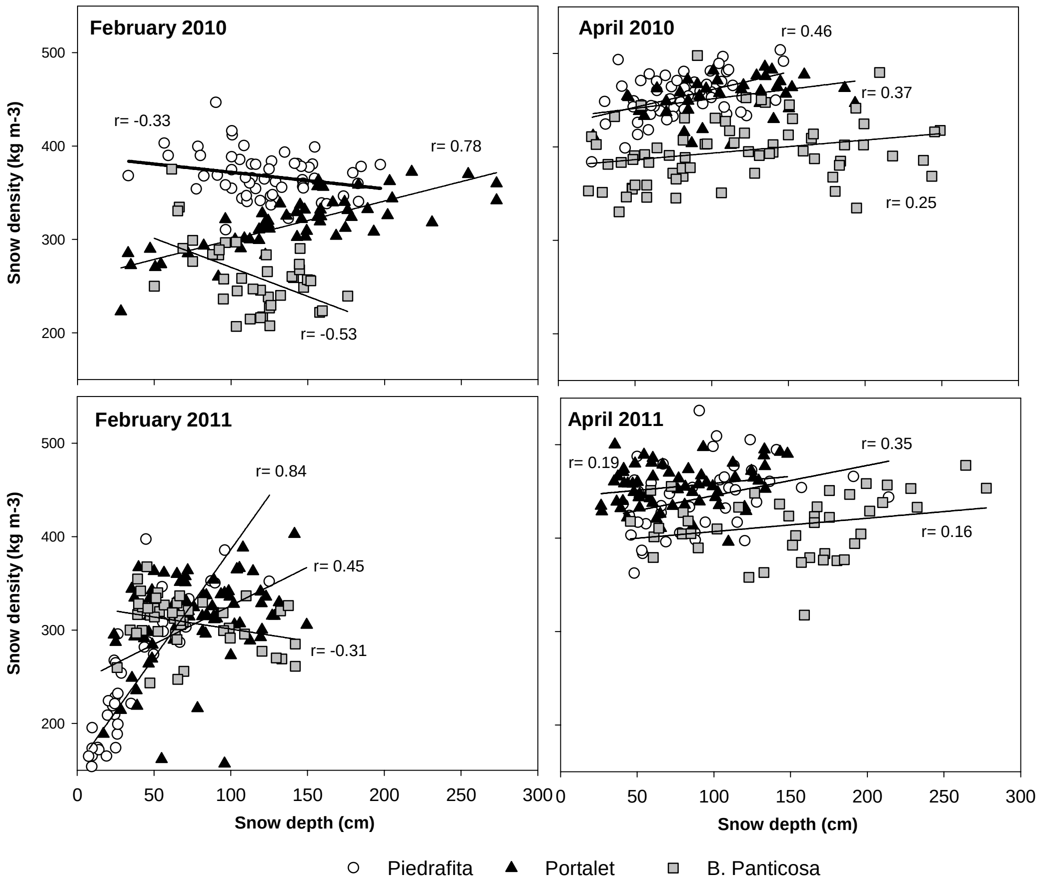
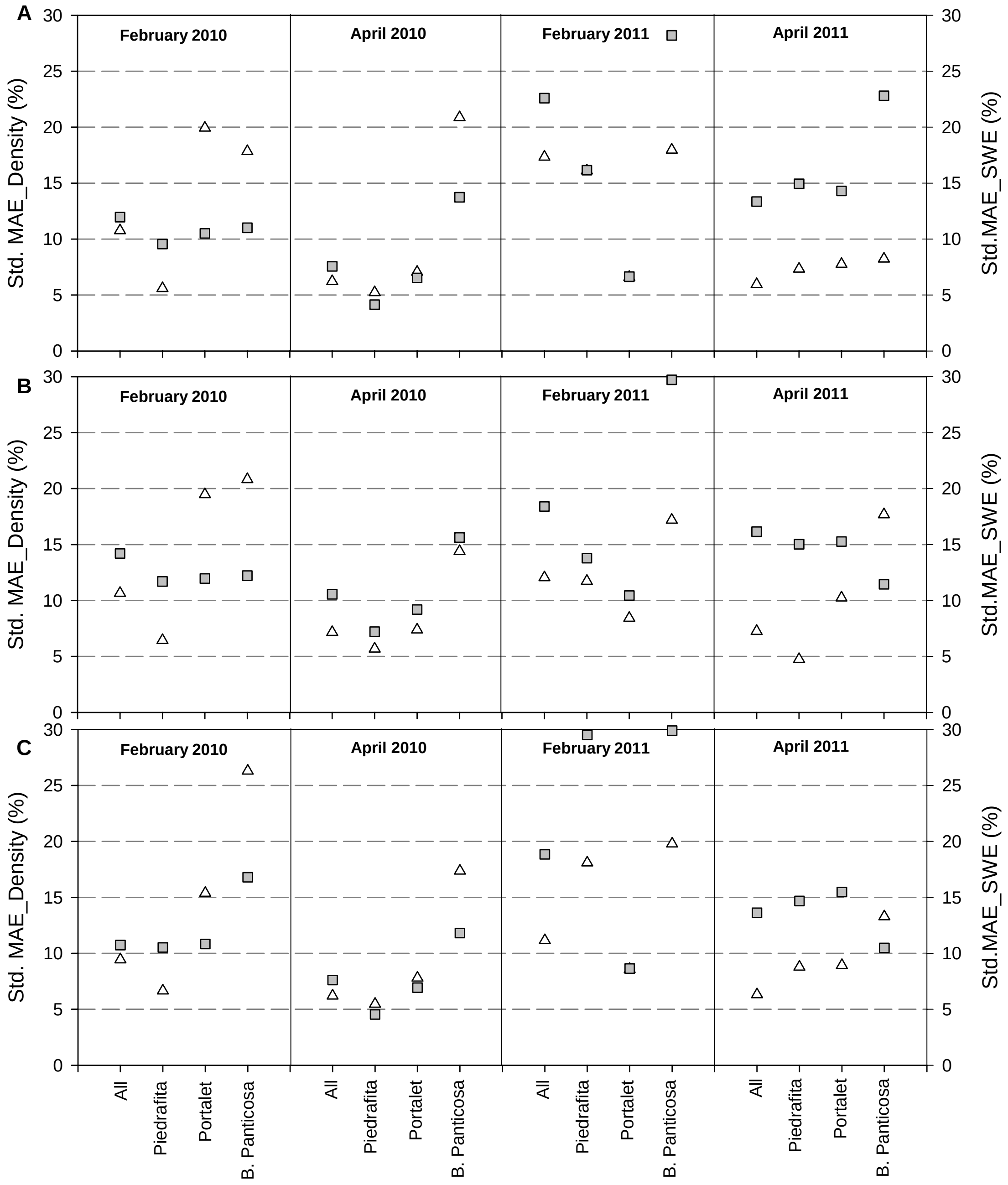

February 2010
r= -0.33
r= 0.78
r= -0.53
April 2010
r= 0.46
r= 0.37
r= 0.25
February 2011
r= 0.84
r= 0.45
r= -0.31
April 2011
r= 0.19
r= 0.35
r= 0.16
Snow density (kg m-3)
Snow density (kg m-3)
500
400
300
200
0
50
100
150
200
250
300
Snow depth (cm)
Snow depth (cm)
○ Piedrafita
▲ Portalet
▨ B. Panticosa

Figure 5.

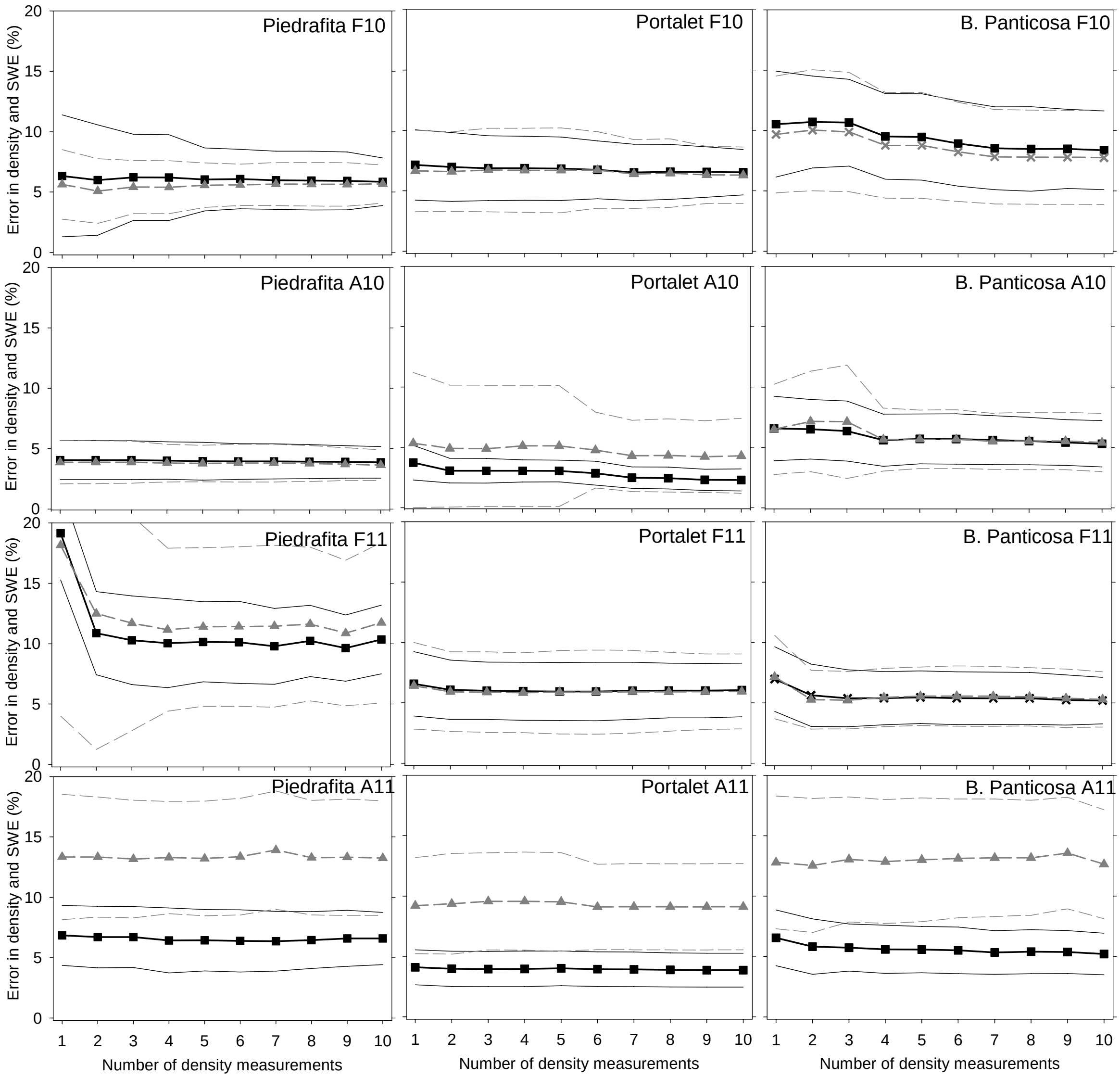


690

691

692 **Figure 6.**

693



694

695

696 **Figure 7.**

697

Table 1. Snow depth and density statistics for each site and survey.

		Snow depth				Snow density			
		F10	A10	F11	A11	F10	A10	F11	A11
All	Average	140.2	106.4	76.4	76.8	316.2	452.6	305.8	455.2
	Std. Deviation	55.3	39.7	33.3	33.4	29.3	21.7	58.1	22.9
	CV	0.39	0.37	0.44	0.43	0.09	0.05	0.19	0.05
	Range Max-Min	174.5	160.6	189.0	158.3	47.2	18.5	103.6	22.9
	RangeC90-C10	117.4	94.5	129.7	86.8	23.7	13.7	49.8	13.4
	Range C75-C25	44.0	51.6	78.9	50.6	10.0	6.2	15.8	7.3
Piedrafita	Average	122.8	81.3	36.8	92.0	367.8	454.2	239.8	443.0
	Std. Deviation	34.2	28.9	27.8	39.7	24.2	23.6	75.9	37.8
	CV	0.28	0.36	0.76	0.43	0.07	0.05	0.32	0.09
	Range Max-Min	133.7	153.8	320.1	188.2	37.1	26.4	115.5	39.3
	RangeC90-C10	65.7	68.2	95.5	85.5	18.3	12.5	68.5	21.9
	Range C75-C25	36.2	39.1	55.2	56.2	8.4	6.4	42.5	10.8
Portalet	Average	114.9	114.7	71.2	149.2	260.9	395.4	308.3	414.0
	Std. Deviation	30.8	62.6	32.7	58.1	36.0	33.8	27.6	33.4
	CV	0.27	0.55	0.46	0.39	0.14	0.09	0.09	0.08
	Range Max-Min	109.6	199.9	163.0	155.5	64.5	42.3	40.3	38.7
	RangeC90-C10	65.0	155.8	139.5	143.9	25.0	20.9	24.1	17.6
	Range C75-C25	35.9	104.1	73.9	89.1	14.1	10.0	10.6	10.5
B. Panticosa	Average	127.2	101.5	65.0	102.0	320.8	429.1	290.1	439.9
	Std. Deviation	43.6	50.1	35.6	53.1	51.2	40.1	63.5	35.1
	CV	0.34	0.49	0.55	0.52	0.16	0.09	0.22	0.08
	Range Max-Min	192.4	225.9	234.2	246.3	74.7	40.3	109.2	49.7
	RangeC90-C10	84.1	125.8	149.5	128.2	41.6	24.7	61.0	19.7
	Range C75-C25	39.4	66.9	78.4	71.8	23.6	14.4	22.0	9.9

Table 2. Bivariate correlation, partial correlation (with snow depth), and interactions between snow density, snow depth and terrain characteristics. Bolded numbers indicate statistically significant correlations ($\alpha < 0.05$).

		Bivariate correlations			**Partial correlations between snow depth and density controlled by terrain characteristics**			**Correlation between snow density and snow depth interacting with snow depth**		
		Piedrafita	Portalet	B. Panticosa	Piedrafita	Portalet	B. Panticosa	Piedrafita	Portalet	B. Panticosa
F10	Snow depth	**-0.33**	**0.79**	**-0.53**						
	Elevation	0.04	**0.34**	**-0.37**	**-0.33**	**0.68**	**-0.46**	**-0.33**	**0.81**	**-0.58**
	Radiation	-0.19	0.18	-0.10	-0.33	**0.74**	-0.53	**-0.33**	**0.48**	-0.20
	Curvature	0.06	0.08	**0.29**	**-0.33**	**0.73**	**-0.53**	**-0.17**	0.14	**-0.54**
	Slope	**-0.37**	**-0.34**	**-0.40**	**-0.27**	**0.70**	**-0.41**	**-0.40**	**0.30**	**-0.51**
A10	Snow depth	**0.46**	**0.37**	**0.26**						
	Elevation	0.10	**0.58**	**0.21**	**0.45**	**0.23**	**0.23**	**0.46**	**0.41**	**0.44**
	Radiation	**-0.24**	**0.29**	**0.49**	**0.19**	**0.19**	**0.13**	0.15	**0.46**	**0.62**
	Curvature	0.10	-0.11	-0.02	**0.36**	**0.34**	**0.26**	0.01	0.10	0.12
	Slope	0.05	**0.30**	-0.16	**0.29**	**0.26**	**0.26**	**0.28**	**0.23**	**0.28**
F11	Snow depth	**0.85**	**0.46**	**-0.30**						
	Elevation	**0.62**	**0.39**	0.07	**0.74**	**0.28**	**-0.30**	**0.87**	**0.53**	**-0.30**
	Radiation	0.02	**0.26**	0.17	**0.85**	**0.41**	**-0.27**	**0.57**	**0.47**	**-0.28**
	Curvature	-0.04	**0.26**	-0.13	**0.85**	**0.43**	**-0.30**	**0.42**	**0.48**	**-0.25**
	Slope	**0.30**	0.12	**0.29**	**0.83**	**0.46**	**-0.26**	**0.83**	**0.46**	**-0.41**
A11	Snow depth	**0.35**	0.19	0.16						
	Elevation	0.16	0.14	0.09	**0.31**	0.17	0.14	**0.35**	0.20	0.16
	Radiation	0.03	0.02	0.19	**0.35**	0.19	0.16	**0.30**	0.20	0.20
	Curvature	-0.16	0.12	-0.04	**0.34**	0.19	0.16	0.11	0.10	0.16
	Slope	0.08	0.09	**0.57**	**0.35**	**0.19**	**0.14**	**0.21**	0.17	**0.21**

Table 3. Summary statistics for the linear, tree and generalized additive models for predicting snow density distribution using snow depth and terrain characteristics.

			Linear regression models			Tree models		Generalized additive models (GAMs)	
			Explained variance (r^2)	Std_MAE (%)	Error in SWE estimation (%)	Std_MAE (%)	Error in SWE estimation (%)	Std_MAE (%)	Error in SWE estimation (%)
F10	All sites	Slope	34	10.8	12.0	10.7	14.2	9.4	10.74
	Piedrafita	Snow depth	34	5.6	9.6	6.4	11.7	6.7	10.52
	Portalet	Snow depth	62	19.9	10.5	19.5	12.0	15.4	10.83
	Panticosa	Snow depth; slope	24	17.8	11.0	20.8	12.2	26.3	16.80
A10	All sites	Snow depth, elevation, radiation, curvature, slope	34	6.2	7.6	7.2	10.6	6.2	7.62
	Piedrafita	Snow depth	21	5.2	4.1	5.7	7.2	5.5	4.54
	Portalet	elevation	33	7.1	6.5	7.4	9.2	7.8	6.93
	Panticosa	radiation	24	20.9	13.7	14.4	15.6	17.4	11.81
F11	All sites	Snow depth, elevation, radiation, curvature, slope	37	17.3	22.6	12.1	18.4	11.2	18.84
	Piedrafita	Snow depth, elevation, radiation,slope	79	16.1	16.2	11.7	13.8	18.1	29.52
	Portalet	Snow depth, radiation	21	6.6	6.6	8.4	10.4	8.6	8.64
	Panticosa	Snowdepth, slope	31	18.0	28.2	17.2	29.7	19.8	31.14
A11	All sites	Elevation, slope	16	6.0	13.3	7.3	16.1	6.3	13.62
	Piedrafita	Snow depth, radiation	21	7.3	14.9	4.7	15.0	8.8	14.68
	Portalet	Slope	14	7.8	14.3	10.3	15.3	8.9	15.49
	Panticosa	Slope, radiation	39	8.2	22.8	17.7	11.5	13.3	10.48