SNOWCOVER DENSITY AND SNOW WATER EQUIVALENT IN THE ITALIAN ALPS

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ABSTRACT: This article considers snowcover height and density based on 6,100 measurements carried out in 7 winter seasons (2010-2016) by Italian avalanche. The 2010-2016 period was characterised by very snowy winters (2014), normal winters and winters with snow scarcity (2016), therefore representative of a large inter-annual variability. Data was collected by expert people on the field. Measurements were carried out through horizontal sampling for single snow layers, with statistical integration of missing layers, using the Yeti software by AINEVA. Based on measurements, the Snow Water Equivalent value of each relief was calculated. Figures gather measurements from November to May, in the altitude range between 640 m and 3,300 m, with snow thickness values ranging from 10 to 350 cm, aggregated according to the SOIUSA code. The first data processed show an average density of 308 kg m^{-3} and a major difference between the areas near to the sea, i.e. the Maritime Alps, Venetian Prealps and Julian Alps, with an average density of more than 335 kg m^{-3}, and continental areas like Cotian Alps and Graian Alps, with average values of less than 291 kg m^{-3}. For the Italian Alps too, a variation of the average density based on season, altitude and snowcover thickness is confirmed, as shown in the northern side of the Alps and in North America.

KEYWORDS: snowpack bulk density, Snow cover, Snow Water Equivalent, SWE

1. INTRODUCTION

The snowpack bulk density (ρb) is a physical quantity necessary to determine Snow Water Equivalent (SWE) of the snowpack.

Knowing the spatial distribution of the SWE, it is possible to calculate the water balance of the mountain basins (Cianfarra et al., 2009) and its contribution to the outflow in spring (Barnett et al. 2005, Hock et al., 2006).

The SWE is given by the relation:

$$SWE = HS * \rho b \qquad (1)$$

HS (m) being the local snow depth and ρb (kg m^{-3}) the associated bulk density.

The direct measurement of SWE, with vertical cores (Berni and Giancanelli, 1966) requires specialized personnel and the measurements are always few in comparisons with the available measurements of HS in the mountains. The values of ρb are given by the relationship between the SWE and the Hs. Therefore, by parametrizing such relationship, it is possible to determine the SWE of a point with the only measure of the HS (Jonas et al., 2009).

Different methods for the characterization of SWE and associated variability has been proposed on regional studies. Bocchiola and Rosso (2007) have proposed a daily statistical distribution of the SWE for the central Alps, Pistocchi (2016, 2017) compared the results of the works of Jonas et al. (2009) and Sturm et al. (2010), Valt and Moro (2009) identified the density characteristics of the snowpack in the eastern Alps.

In this study, we present the analysis of 6000 SWE measurements distributed in the Italian Alpine arc for the period 2010-2016, following the method proposed by Jonas et al., (2009), with the aim of characterizing the SWE at a mountain scale, as previously done for the variation of the snow cover (Valt and Cianfarra, 2010) and the new snow density (Valt et al., 2018).

2. SNOW DATA

Monthly snow core drilling are performed monthly on the Italian Alpine arc to determine the SWE, but do not cover the entire Alpine arc with temporal and spatial continuity. In fact, such measurements are expensive, as the need to be carried out by specialized technicians.

Differently, the Italian avalanche services have an extensive network of snow height and density measurements. The data are collected several times a month throughout the Alps, according to

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unified standards (Cagnati, 2003). In this work the data on avalanche services are used.

The HS is measured with a graduated rod, while the density is measured, for each homogeneous layer, by weighting a known volume (0.5 dm^3) of snow sampled with an aluminum or Teflon cylindrical tube. The coring tube measures approximately 18 cm in length and 6 cm in diameter. The snow core is weighed with a spring / electronic dynamometer with an accuracy of +/- 5 g. The statistical procedure adopted for the calculation of the bulk density, as well as the integration of the layers having a thickness lower than the coring tube diameter, is described in Valt et al. (2013). The SWE based on stratified density measurements has been compared to the available single vertical snow core (Berni and Giancanelli, 1966). It has been verified that the differences between the two methods is within 5 % (Valt, 2017).

The database used in this work includes more than 6000 SWE measurements taken from 150 stations distributed in the Italian Alps (Fig. 1), with elevation ranging from 640 m to 3400 m a.s.l., for 7 snow seasons (from 2009-2010 to 2015-2016). During this period, the southern slope of the Alps was characterized by a high variability of HS. The 2013-2014 season was extremely snowy (over 0.90 percentile) while the 2015-2016 season was poorly snowy.

Following Jonas et al. (2009), the values of ρb lower than 50 kg m^{-3} and higher than 600 kg m^{-3}, as well as values associated HS higher than 3.5 m, has been removed.

The distinction in areas of the Alps was carried out according to the SOIUSA classification (Marazzi, 2005) (Fig. 1).

In Fig.2 shows the distribution of *SWE, HS e ρb* (from left to right panel respectively).

Similarly to the results obtain by Jonas et al. (2009), SWE and HS present a log-normal distribution while ρb is normally distributed.

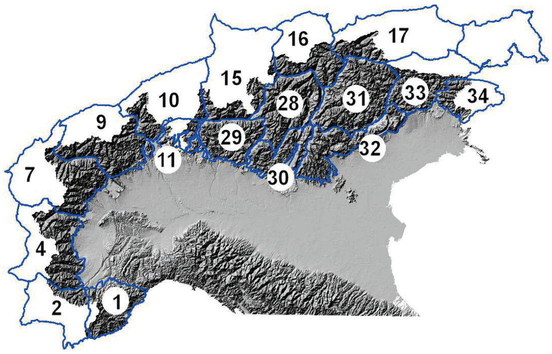

Fig.1. Subdivision SOIUSA of the Italian Alps (see Table.2).

3. RELATIONSHIP BETWEEN E WATER EQUIVALENT, DENSITY AND DEPTH OF SNOW

Snow depth, bulk density and water equivalent are related to each other according to Eq. (1). The pair-wise correlations between these three snow cover properties are presented in Fig. 3. The correlation between HS and ρb and between SWE and ρb is low, while HS and SWE it are highly correlated (R = 0.92).

The linear correlation between HS and SWE is given by the equation:

$$\rho b = 20{,}402 \cdot HS + 285{,}22 \qquad (2)$$

The SWE, the HS and the ρb are linked by the equation (1), substituting the ρb with the equation (2), we obtain an adaptation:

$$SWE = (20{,}402 \cdot HS + 285{,}22) \cdot HS \qquad [3]$$

Jonas et al. (2009) related the data of HS and SWE of Switzerland with the following power regression:

$$\rho b = 60{,}1 \cdot HS^{0{,}89} + 237 \qquad (4)$$

Using the same power regression, for the Italian Alps, the resulting equation is

$$\rho b = 300{,}15 \cdot HS^{0{,}0709} \qquad (5)$$

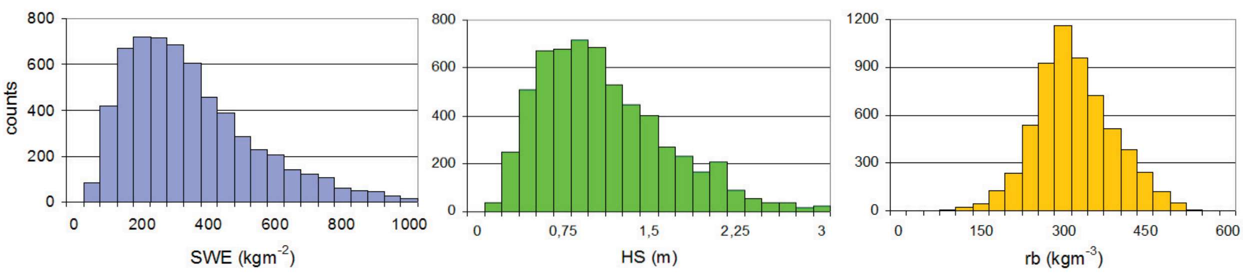

Fig.2. Distribution of SWE, HS, ρb data, Italian Alps (n.6100)

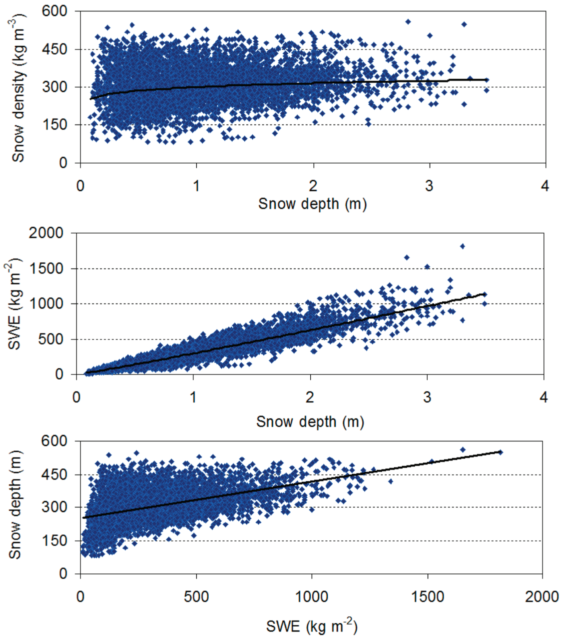

Fig.3. The relationship between SWE, HS and ρb.

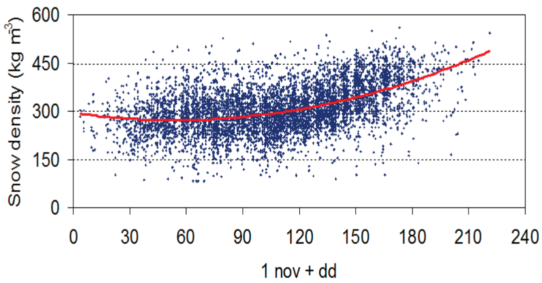

Fig. 4. The effect of season on bulk snow density.

A direct plot of ρb versus time shows that the bulk density gradually increases over the course of the winter season (Fig. 4). This effect has been reported by many previous studies (Anderton et al., 2004; Elder et al., 1991; Mizukami and Perica, 2008; Sturm and Holmgren, 1998 Jonas et al. 2009) and corresponds to the increasing compaction of snow due initially to settling and later to snow cover ripening.

The altitude has a minor effect on the bulk density during the early snow season (from December to February) (Fig. 5). In March, due to the effect of increasing air temperature and associated melting processes, the density is higher at low altitudes (<1400 m). In April and May, the bulk density increase for all altitude, but faster for altitude lower than 2000 m.

4. PARAMETERIZATION OF THE BULK SNOW DENSITY

The aim of the present work is to describe how the density of the snowpack on the southern slope of the Alps varies and to find a characteristic ρb value to facilitate the monitoring of the SWE as proposed by Jonas et al. (2009) using only the values of HS.A similar approach is used in an operational way to estimate the SWE of the Piave River basin (1400 km^2) using the Snow Cover Area data obtained from the MODIS images and applying the characteristic density values for the Eastern Alps (Cianfarra and Valt, 2015, Valt and Moro, 2009).

Following Jonas et al. (2009), the database was separated into the 3 altitude classes for each month of the snow season. A linear regression is then applied on each subclass. The resulting coefficient, associated number of data and correlation are reported in Table 1.

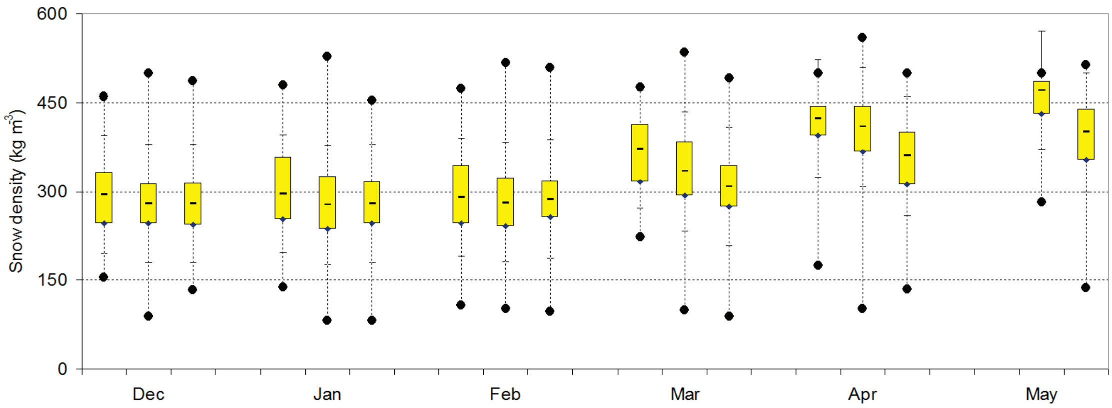

Fig. 6. The effect of altitude on bulk snow density. Data are staggered with respect to site altitude (right:≥ 2000 m a.s.l.; center: ≥ 1400 m and < 2000 m a.s.l.; left <1400 m a.s.l..

	Altitudes (asl) >2000 m [b,a]; (n,R)	Altitudes (asl) >1400 m and < 2000 m [b,a]; (n,R)	Altitudes (asl) < 1400 m [b,a]; (n,R)
November	[263,11] ; (90,8)	[282,-40] ; (35,-21)	n.a.
December	[254,24] ; (474,18)	[252,49] ; (268,25)	[322,-73] ; (50,-16)
January	[250,30] ; (735,24)	[267,18] ; (499,11)	[311,26] ; (89,-8)
February	[254,27] ; (718,26)	[254,28] ; (598,27)	[281, 18] ; (158,11)
March	[302,5] ; (776,5)	[336,0] ; (585,0)	[389,-30] ; (142,-23)
April	[370,-10] ; (438,9)	[404,3] ; (290,-3)	[403,15] ; (34,9)
May	[384,5] ; (91,5)	[401,55] ; (9, 36)	n.a.

Table 1. Look-up table for regression coefficients [b,a]. The bulk snow density can be calculated from snow depth according to Eq.(6). (n, R) denote the number of data records used for the regression and the correlation coefficients in % respectively.

The regression regionalization can also be done on a geographical base, following the SOUISA classification (Table 2).

SOIUSA Classification		Density	[b,a] ; (n,R)
1	Alpi Liguri	320	[370, -39] ; (29, -20)
2	Alpi Marittime	341	[310, 20] ; (190, 18)
4	Alpi Cozie	297	[286,9] ; (680, 6)
7	Alpi Graie	295	[289, 5] ; (495, 3)
9	Alpi Pennine	300	[292, 8] ; (809, 2)
10	Alpi Lepontine	327	[262,39] ; (109, 30)
11	Prealpi Luganesi	300	[n.a, n.a] ; (3; n.a)
15	Alpi Retiche occidentali	295	[244,40] ; (144,25)
16	Alpi Retiche orientali	306	[290,14] ; (47,10)
17	Alpi dei Tauri Occidentali	305	[291,17] ; (26,5)
28	Alpi Retiche meridionali	291	[251,32] ; (429,33)
29	Alpi e Prealpi Bergamasche	302	[289,10] ; (145, 9)
30	Prealpi Bresciane e Gardesane	308	[294,15] ; (82,11)
31	Dolomiti	297	[256,40] ; (809,31)
32	Prealpi Venete	335	[318,24] ; (524,15)
33	Alpi Carniche	316	[297,22] ; (809,17)
34	Alpi e Prealpi Giulie	335	[289,36] ; (230,32)

Table 2. Look-up table for regression coefficients [b,a]. The bulk snow density can be calculated from snow depth according to Eq.(6). (n,R) denote the number of data records used for the regression and the correlation coefficients in % respectively.

5. CONCLUSION

With the present work, the characteristic density values of the snowpack of the southern slope of the Alps are shown to improve the SWE estimate. The study, which is still preliminary, followed the methodology of Jonas et al. (2009) applied to Switzerland, with interesting comparisons.

Over 6000 measures of SWE, HS and density of 7 winter seasons were analyzed. Linear regression between bulk density and snow depth are given as function of elevation, season and geographic area. The future development of this work is a further consolidation of the database in order to be able to make more robust statistical analysis.

6. ACKNOWLEDGEMENTS

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7. REFERENCES

Barnett, T.P., Adam, J.C., and D.P., Lettenmaier, 2005: Potential impacts of a warming climate on water availability in snow-dominated regions. Nature 438 (7066), 303–309.

Berni A. and E. Giancanelli, 1966: La campagna di rilievi nivometrici effettuata dall'ENEL nel periodo febbraio – giugno 1966. Energia elettrica, n. 9, 542-533.

Bocchiola D. and R. Rosso, 2007: The distribution of daily snow water equivalent in the central Italian Alps. Water Resources, 30 (2007), 135-147.

Cagnati, A., 2003: Strumenti di misura e metodi di osservazione nivometeorologici: manuale per i rilevatori dei servizi di previsione valanghe. AINEVA, Trento, 133 pp.

Cianfarra P., F.,SAlvini, and M. Valt 2009: Monitoring the spatio-temporal evolution of the snow cover in the eastern Alps from MODIS data. Geophysical Research Abstract- Vol. 11, EGU 2009-8703-2009

Cianfarra, P. and M. Valt, 2014: Monitoraggio dell'equivalente in acqua della neve da dati MODIS. Il caso dell'Alto Piave. Neve e valanghe, n.83, 28-34.

Elder, K., Rosenthal, W., and R.E. Davis, 1998: Estimating the spatial distribution of snow water equivalence in a montane watershed. Hydrological Processes 12 (10–11), 1793–1808.

Jonas, T., Marty, C., and J, Magnusson, 2009: Estimating the snow water equivalent from snow depth measurements in the swiss alps. J. Hydrol. 378, 161–167.

Hock, R., Rees, G., Williams, M.W., and E.Ramirez, 2006: Preface – contribution from glaciers and snow cover to runoff from mountains in different climates. Hydrological Processes 20 (10), 2089–2090 (special issue).

Mizukami, N., and S. Perica, 2008: Spatiotemporal characteristics of snowpack density in the mountainous regions of the Western United States. Journal of Hydrometeorology 9 (6), 1416–1426.

Pistocchi A., 2016: Simple estimation o snow density in an Alpine region, Journal o Hydrology: Regional Studies 6 (2016) 82-89.

Pistocchi A., S., Bagli, M., Callegari., C., Notarnicola and P. Mazzoli, 2017: On the Direct Calculation of Snow Water Balances Using Snow Cover Information , Water, 2017,9,848: doi:10.3390/w9110848.

Sturm, M., Taras, B., Liston, G.E., Derksen, C., Jonas, T., and J. Lea, 2010: Estimating Snow Water Equivalent Using Snow Depth Data andClimate Classes. J. Hydrometeorol. 11, 1380–1394, http://dx.doi.org/10.1175/2010JHM1202.1

Sturm, M., and J. Holmgren, 1998: Differences in compaction behaviour of three climate classes of snow. Annals of Glaciology 26, 125–130.

Valt M. and D. Moro, 2009: Average snowcover density in eastern Alps Mountain. Geophysical Research.

Valt, M. and P. Cianfarra, 2010: Recent snow cover variations and avalanche activities in the Southern Alps. Cold Regions Science and Technology Volume 64, Issue 2, November 2010, Pages 146-157.

Valt, M., Guyenonn, N., Salerno, F., Pietrangeli, A., Salvatori, R., Cianfarra, P., and E. Romano, 2018: Variability of new snow density in the Italian Alps: 10 years of distributed measurements. Hydrological Processes. *(In press).*

Valt M., 2018: Criticità nelle misure per la stima dello SWE- IV Interconfronto SWE - Val di Susa 19-20 marzo 2018, (in press).