RAIN-ON-SNOW (ROS) EVENTS IN THE ITALIAN ALPS AND INCREASED AVALANCHE ACTIVITY

Valt M. *[1,2], Bee C. [1,3], Monti F.[4]

1 Arabba Avalanche Centre - ARPAV, Livinallongo del Col di Lana, BL, Italy
2 AINEVA, Trento, TN, Italy
3 University of Trento - DICAM, Trento, TN, Italy
4 AlpSolut, Livigno SO, Italy

ABSTRACT: On the southern side of the European Alps (Italian Alps), an increase in the number of rain-on-snow (ROS) events has been observed, including during the winter season. Over the past 10 years, several such events have been observed above 6,560 feet (2,000 meters) in elevation, even in January. Overall, winter precipitation, measured in millimetres of precipitation, has not changed over the past 30 years, but the amount of new snow has decreased at all elevations. In February, the average elevation of the rain/snowfall boundary rose by more than 400 m (1,312 ft) in certain areas. Given these changes in the rain/snow regime, an investigation was conducted to determine whether avalanche activity has changed over the past 30 years. The study, based on daily observations from over 200 manual stations, revealed an increase in the percentage of wet-snow avalanches, especially large ones, over the past 10 years.

KEYWORDS: ROS, SNOW, ALPS, SNOWFALL, WET AVALANCHES.

1. INTRODUCTION

Across the Italian Alps, the snow cover area (SCA) has undergone a significant reduction, partially due to rising temperatures (Notarnicola, 2022). Snow cover has decreased most notably at stations below 2,000 m, primarily in Italy's Southern Alps compared to the Northern Alps.

At elevations below 1000 m, the period with snow on the ground has shortened by 22 days on the northern side of the Alps and by 26 days on the southern side, whilst between 1,000 and 2,000 m the decrease was 24 and 33 days respectively, due to the delayed formation of the autumn snowpack but, above all, to the earlier onset of snowmelt (Crespi et al. 2021).

Matiu et al. (2021) highlighted a negative trend in ground snow depth (HS) at 85% of the 800 stations studied across the Alps and a positive trend at only 15%, generally at high-altitude stations, over the period 1971 – 2019.

A decrease in snowfall has also been observed in the Eastern Italian Alps during February at higher altitudes and during January and March at lower altitudes (Valt, 2024), with significant repercussions on snow depths on the ground.

* Corresponding author address:
Mauro Valt,
Arabba Avalanche Centre - ARPAV
Via Pradat 5, Livinallongo del Col di Lana, 32020-BL, Italy;
e-mail: mauro.valt@gmail.com

Bozzoli et al. (2024) analysed 46 historical time series of new snow (HN) data from the Alpine region covering the period 1920 – 2020, highlighting a sharp decline in snowfall, particularly over the last 40 years. A key factor was the role played by rising air temperatures as the primary driver of the snow/rain phase shift, as no significant changes were observed in total winter precipitation, i.e. the sum of the liquid fraction and the water equivalent of the solid fraction.

According to Marty et al. (2017, 2023), snow water equivalent (SWE) has shown a significant decline over the last six decades in the Alps, more pronounced in spring than in winter, with snow becoming increasingly wet and variable. In the Eastern Italian Alps, the reduction in snow cover over the last 30 years (1991 – 2020) is particularly evident in March, with a significant decrease in snow water equivalent (Valt, 2023).

In the Southern Alps, over the period 1961–2025, the snow reliability altitude increased by 233 metres in altitude for every 1 °C rise in mean air temperature (Valt et al., 2022).

Consequently, in line with the conclusions of Bozzoli et al. (2024), an increase in the frequency of rainfall in winter, and in particular in rainfall events falling on the snowpack, is to be expected.

Therefore, in this paper, Section 2 analyses the issue of rain on snow (ROS); Section 3 examines the trend in events over the last 20 years; Section 4 looks at changes in the new snow/rain regime

https://doi.org/10.15788/1790098845

for a number of sample stations; and Section 5 examines the implications for natural avalanche activity.

2. RAIN ON SNOW

Events defined as ROS are attributable to instances of rain falling on the snowpack on the ground. Under typical meteorological winter conditions at high altitude, this phenomenon should be unusual.

Rain on snow triggers melting processes in areas where the snow would normally remain stable and cold, leading to an early onset of thawing and often an equally early disappearance of the winter snowpack, with repercussions also on the SWE (Valt, 2023).

According to Beniston & Stoffel (2016), the rise in temperatures observed in north-eastern Switzerland between 1960 and 2015 contributed directly to an increase in rain-on-snow events in 40% of cases at low altitudes and by 200% at high altitudes. The results of a simple snow model based on air temperature show that the number of ROS events could increase by almost 50% with temperatures 2–4 °C warmer than current levels, before decreasing when temperatures exceed 4 °C, as snow would then be completely absent.

However, according to Sezen et al. (2020), it is not yet entirely clear how climate change will affect ROS due to their complex nature.

The effects of rain on the snowpack are generally still poorly understood. Rain does not directly cause the snowpack to melt, but it alters its energy and mass balance.

In general, the impact of rain changes the shape of the snow grains on the surface and thus leads to a decrease in albedo, with an increase in the snow's energy absorption; it may also increase the snowpack's SWE. If the snowpack is already at temperatures close to the freezing point ($T \approx 0$ °C), rain accelerates snowmelt; whereas if the snowpack is cold ($T << 0$ °C), we observe the formation of ice crusts, lenses and ice columns (Fig. 1).

The snowpack does not act as a uniform medium for rainfall absorption. In fact, water penetrates the snowpack by finding the paths of least resistance, using capillary action to flow through the snow and forming what are known as 'flow fingers' or ice columns, in other words preferential flow paths. The water heats the snow just enough to make its way through these preferential flow paths, thereby facilitating the movement of all the rainwater. It therefore does not need to evenly heat the snowpack.

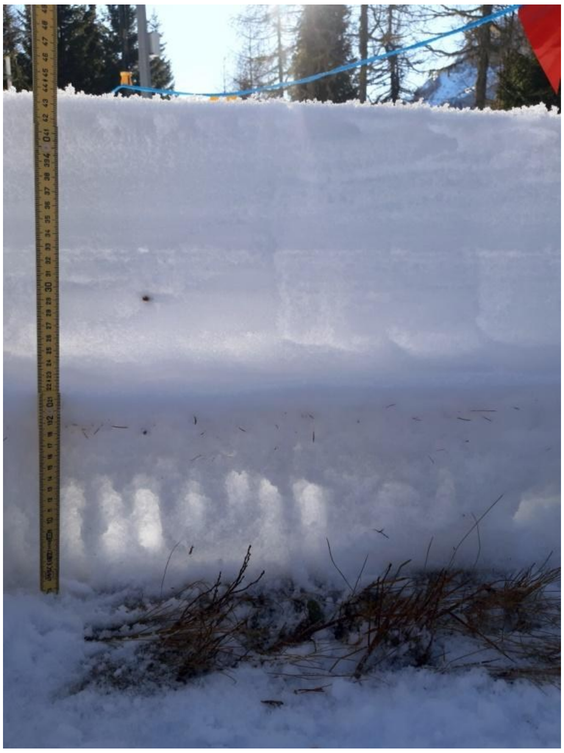

Figure 1: Ice columns in the snowpack ('flow fingers') at Col dei Baldi station (BL), 1,900 m in Spring 2025. Water finds its preferred pathways via gravity and capillarity. Courtesy of Zasso R (CVA).

ROS are also a well-known trigger for avalanches in maritime climates, as rain weakens the bonds between individual snow grains, reducing the structural strength of the snowpack (Conway et al., 1988; Heywood, 1988; Conway & Raymond, 1993; Heywood, 1988; Singh et al., 1997).

Rainfall events alter the stability of the surface snowpack by increasing instability, particularly when snow depths are at least within the normal range. On the contrary, if there is very little snow

Figure 2: Medium-sized avalanches following a rain-on-snow event affecting a ski run, closed at the time of the event.

on the ground, the effects are less pronounced). According to Wever et al. (2016), the preferential can influence the formation of wet snow avalanches (Fig. 2).

In the Arctic, there are documented instances of large spontaneous avalanches triggered by rain on snow in Greenland in April 2016 (Abermann et al., 2019) and winter in 2021–2022, and in Svalbard in January 2010 and March 2011 (Eckerstrofen & Christiansen, 2011; Vickers et al., 2024).

3. ROS IN THE ITALIAN ALPS

3.1 Study area and data

The area under investigation is the southern slope of the European Alps, stretching from the Maritime Alps in the west to the Julian Alps in the east (between 43° and 48° N latitude and 5° and 17° E longitude), where over 200 snow monitoring stations are in operation (Cagnati, 2003).

The snow fields are distributed across a wide range of altitudes and locations, and daily snow and weather observations are carried out at these sites; these observations are fed into the database of the Interregional Association for the Coordination and Documentation of Issues Relating to Snow and Avalanches (AINEVA) of Italy.

The monitoring system for distinguishing between rain-on-snow events, whether in the presence of new snow or in the absence of typical snowfall, is based on various types of observations at the snow fields.

In particular, in the observation model (Cagnati, 2003), meteorological observations defined as ‘weather conditions’ are recorded in field WW: rain is clearly coded to classify its intensity into seven classes (from ‘light intermittent rain’ to ‘rain shower’), to which ‘snow mixed with rain’ is added in the ‘snowfall’ section.

Furthermore, in the ‘snow depth data’ observations, for the fields HS (ground snow depth) and HN (new snow depth), there is a coding system to indicate the ROS even in the absence of an HN measurement and, conversely, to indicate when the new snow has been affected by rain.

By filtering out all these incidents, which are often duplicated in the records but consistent, it is possible to identify days with rain on snow.

This filter was applied to data collected from 2006 to 2025 (20 winter seasons) for over 200 stations situated at altitudes ranging from 155 m to 3,325 m, totalling over 800,000 daily observations.

3.2 Results

In the AINEVA database (2006–2025), days with rain on snow have been grouped into four altitude bands: below 1,500 m, between 1,500 and 1,800 m, between 1,800 and 2,200 m, and above 2,200 m.

It was decided to analyse only those events above 1,500 m in order to look for any signs of a trend, as it is believed that any change in the snow/rain regime may be more evident at these altitudes, not least due to its effects on avalanche activity.

Figure 3 shows the number of days with reported rain above 1,500 m for the period December to February.

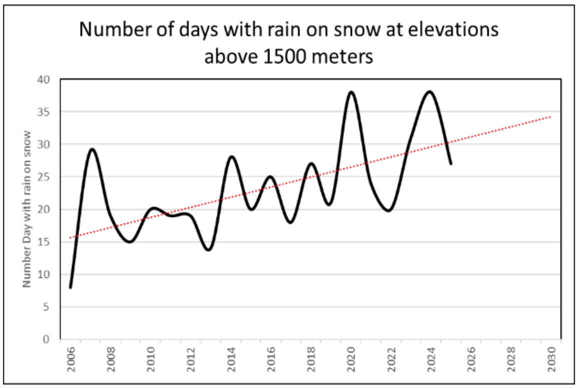

Figure 3: Number of winter days (DJF) with ROS in the Eastern Italian Alps.

4. CHANGES IN SNOW AND RAINFALL PATTERNS IN THE DOLOMITES

4.1 Precipitation

For the stations studied in the Dolomites, the cumulative precipitation trend for the months of December, January and February, calculated over the period 1996 – 2025, is positive (Fig. 4). For January, the trend is modest at all stations, whilst for December and February it is much more pronounced.

The increase in the frequency of rain on snow events, whilst the total amount of precipitation remains the same, indicates that there is more rain in the mountains at the expense of snowfall; this is consistent with the analyses conducted by Bozzoli et al. (2024) on the amount of new snow, by Matiu et al. (2020) on snow cover, and by Valt (2024) on snow water equivalent (SWE).

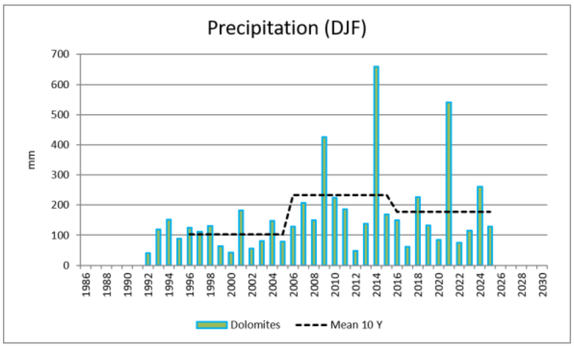

Figure 4: Average precipitation (mm) during the DJF period in the Dolomites. The trend is positive, although the decadal average shows a slight decrease in recent years.

To understand how the snow-to-rain ratio varies, episodes of rain (without new snow) and new snow (including rain) were investigated for a sample area in the Eastern Italian Alps, namely the Dolomites range.

In the Dolomites, at an altitude of 2,000 m, the average seasonal accumulation of new snow is approximately 600 cm (average 1999 – 2020); at 1,600 m it is 400 cm; at 1,200 m it is 240 cm; and at 800 m it is 90 cm.

Data from six stations located at different altitudes were analysed:

- Cima Pradazzo – Passo Valles, 2200 m
- Arabba, 1630 m
- Cortina d'Ampezzo, 1200 m
- Falcade, 1150 m
- Auronzo di Cadore, 850 m
- Cencenighe Agordino, 750 m.

For these stations, daily data on new snow and rainfall over the previous 24 hours are available, recorded at 8.00 am. All precipitation values from rain gauges were taken into account, when 1 mm of rainfall was recorded (67% of measurements) and 5 cm of new snow was observed (50% of observations).

In some cases, during January and February, a lack of precipitation data (generally a few mm) was observed even where new snow was present. This led, at some stations, to there being more snowfall events than precipitation events: this is a well-known and recurring problem in measuring precipitation in cold climates (Cagnati, 2003).

For each station, the number of days with new snow was calculated and compared to the total number of days in the DJF period with precipitation for the decades 1996 – 2005, 2006–2015 and 2016 – 2025. This allows us to observe the trend in the ratio of snowfall to liquid precipitation events (Fig. 6).

In general, the trend for the 2016–2025 decade shows a decrease in snowfall events compared with the previous 2006–2015 decade. The 2006–2015 decade does indeed appear to have had more snowfall than the 1996–2005 period, although the reliability of the input data in some cases – such as for Cortina – raises doubts. Over the last decade, high-altitude stations recorded a higher proportion of snowfall in February compared with previous months, whilst at lower altitudes, rainfall events have become much more frequent.

4.2 Variation of the freezing level in the free atmosphere

Using daily precipitation data from Arabba (1,630 m) for the months of December, January and February, the freezing level height (FLH) measured in the free atmosphere by the Udine Rivolto radiosonde station for the period 1996–2025.

The analysis carried out revealed a higher FLH during snowfall in all winter months.

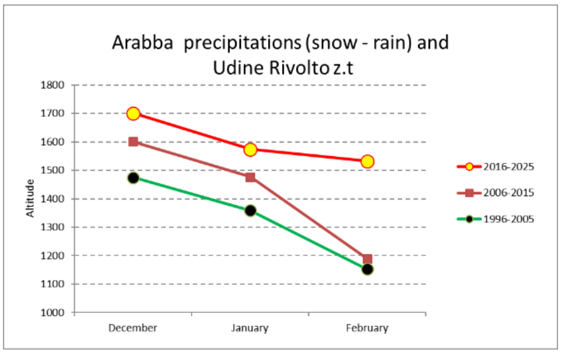

Figure 5: Radiosounding in the Eastern Alps at Udine Rivolto airfield. Trend in the freezing level height (FLH) at 12:00 UTC on days with precipitation during the months of December, January and February.

Fig. 5 shows the trends for the months of December, January and February across the three decades: the FLH drops significantly in January and February for the periods 1996 – 2005 and 2006 – 2015, whilst in the more recent period it rises from December to January before falling slightly. Whilst in December the FLH remains virtually unchanged across the three periods, in January it rises progressively by 100 m in the first decade and 140 m in the second decade, whilst in February it rises by 85 m and 342 m in the same periods, resulting in an overall difference between 1996 – 2005 and 2016 – 2025 of almost 430 m in FLH.

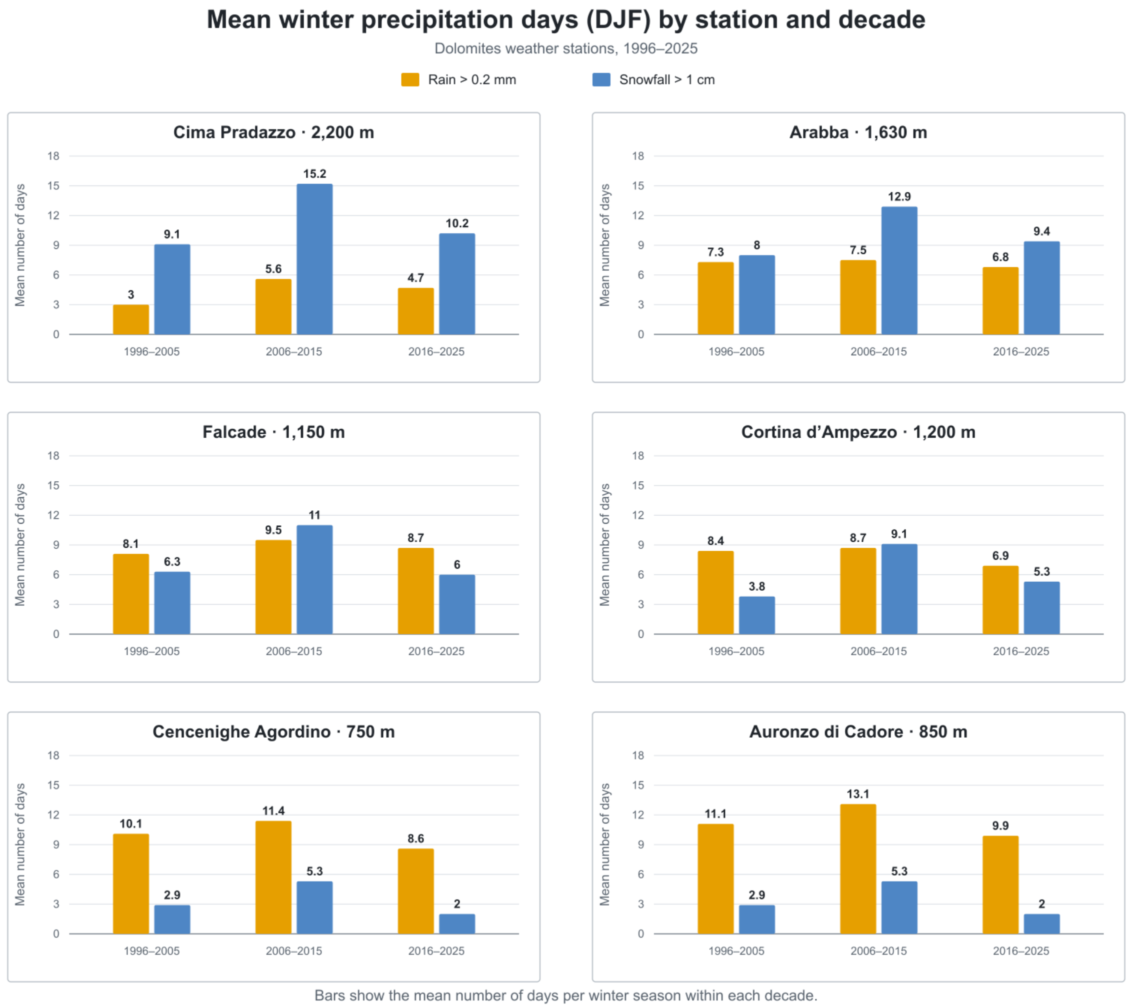

Figure 6: Mean number of days with ROS per decade for selected weather stations in the Dolomites.

4.3 Snow avalanches and ROS

Observing avalanche activity from a manual observation field station is always very difficult during precipitation due to poor visibility; consequently, when analysing data on 'observed avalanches' during snowfall and rain on snow, there is a clear predominance of 'undetectable activity', often associated with "poor visibility" i.e. less than 1,000 m on the horizon'.

Consequently, data on observed avalanches from the entire winter season and across all altitudes were used to assess a correlation with the types of events. The study was conducted over the period 2006 – 2025 and revealed that 17% of avalanche reports occur during episodes of snow on rain (Fig. 7)

Figure 7: Medium-sized avalanches following a ROS event, affecting a National Road in NE Italy.

It is interesting to note that 22% of the reports relate to cases of 'many medium-sized avalanches' and 'single large avalanches'; these percentages, which are higher than the overall figure, suggest that, in the event of rain on snow, the likelihood of medium- and large-sized avalanches is greater (Fig. 8).

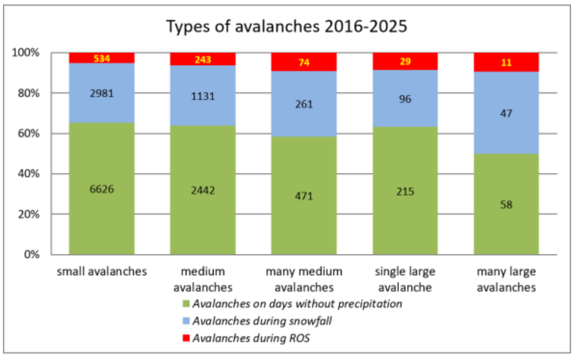

Figure 8: Avalanches during ROS in the last decade by type and avalanche size.

5. CONCLUSIONS

This study analysed observations and measurements taken at more than 200 snow gauge stations across the southern Alps over the last 20 winter seasons to investigate whether episodes of rain on snow have become more frequent. Many studies show that the amount of precipitation, measured as millimetres of rain equivalent during the winter (DJF), has not varied significantly, whilst the amount of new snowfall, the amount of snow on the ground and the SWE are declining, particularly over the last 40 years. We identified an initial trend by analysing certain observations made at snow measurement stations, such as weather conditions and reported snow on the ground (HS) and new snow (HN). Over the last 20 years, episodes of ROS have increased, confirming an upward trend, both in the altitude range most affected by current climate change (1,500 – 1,800 m) and at higher altitudes (1,800 – 2,200 m and above 2,200 m). This upward trend is evident across all three winter months (DJF). Furthermore, an analysis of the number of snow-monitoring stations reporting rain on snow on a daily basis reveals a greater spatial distribution of such events.

An analysis of spontaneous avalanche activity during rain-on-snow events was carried out over the entire winter season, examining data from all stations located at different altitudes in order to obtain more robust information indicating any correlations. The analysed data suggest a potentially higher frequency of many medium-sized avalanches and a few large avalanches during these events.

REFERENCES

Abermann, J., Eckerstorfer, M., Malnes, E., & Hansen, B. U. (2019). A large wet snow avalanche cycle in West Greenland quantified using remote sensing and in situ observations. *Nat. Hazards*, 97(2), 517–534, https://doi.org/10.1007/s11069-019-03655-8.

Beniston, M., 1997. Variations of snow depth and duration in the Swiss Alps over the last 50 years: Links to changes in large-scale climatic forcings, in: *Climatic Change at High Elevation Sites*, Springer, Berlin, Germany, pp. 49–68.

Beniston, M., & Stoffel, M., 2016. Rain-on-snow events, floods and climate change in the Alps: Events may increase with warming up to 4 °C and decrease thereafter, *Sci. Total Environ.*, 571, 228–236, doi:10.1016/j.scitotenv.2016.07.146.

Bozzoli, M., Crespi, A., Matiu, M., Majone, B., Giovannini, L., Zardi, D., Brugnara, Y., Bozzo, A., Berro, D. C., Mercalli, L., & Bertoldi, G., 2024. Long-term snowfall trends and variability in the Alps, *Int. J. Climatol.*, 44(13), 4571–4591, https://doi.org/10.1002/joc.8597.

Cagnati, A., 2003. Sistemi di misura e metodi di osservazione nivometeorologici, AINEVA, Trento, 186 pp.

Conway, H., Breyfogle, S., & Wilbour, C. R., 1988. Observations relating to wet snow stability, in: Proceedings of the International Snow Science Workshop, ISSW '88 Commission, Whistler, B.C., Canada.

Conway, H., & Raymond, C. F., 1993. Snow stability during rain, *J. Glaciol.*, 39(133), 635–642, https://doi.org/10.1017/S0022143000016531.

Crespi, A., Matiu, M., Bertoldi, G., Petitta, M., & Zebisch, M., 2021. A high-resolution gridded dataset of daily temperature and precipitation records (1980–2018) for Trentino-South Tyrol (north-eastern Italian Alps), *Earth Syst. Sci. Data*, 13, 2801–2818, https://doi.org/10.5194/essd-13-2801-2021.

Eckerstorfer, M., & Christiansen, H. H., 2011. Meteorology, topography and snowpack conditions causing two extreme mid-winter slush and wet slab avalanche periods in High Arctic maritime Svalbard, *Permafrost Periglac. Process.*, 22(3), 205–216, https://doi.org/10.1002/ppp.7344.

Fisher, K. C., Haegeli, P., and Mair, P., 2022. Travel and terrain advice statements in public avalanche bulletins: a quantitative analysis of who uses this information, what makes it useful, and how it can be improved for users, Nat. Hazards Earth Syst. Sci., 22, 1973–2000, https://doi.org/10.5194/nhess-22-1973-2022.

Greene, E., T. Wiesinger, K. W. Birkeland, C. Coleou, A. Jones, and G. Statham, 2006. Fatal avalanche accidents and forecasted danger levels: Patterns in the United States, Canada, Switzerland and France, in: Proceedings of the International Snow Science Workshop, Telluride, CO, 1-6 October 2006, 640-649.

Heywood, L., 1988. Rain on snow avalanche events—Some observations, in: Proceedings of the International Snow Science Workshop, Whistler, B.C., Canada.

Matiu, M., Crespi, A., Bertoldi, G., Carmagnola, C. M., Marty, C., Morin, S., Schöner, W., Berro, D. C., Chiogna, G., De Gregorio, L., Kotlarski, S., Majone, B., Resch, G., Terzago, S., Valt, M., Beozzo, W., & Zebisch, M., 2021. Observed snow depth trends in the European Alps: 1971 to 2019, *The Cryosphere*, 15, 1343–1382, https://doi.org/10.5194/tc-15-1343-2021.

Marty, C., Rohrer, M. B., Huss, M., & Stähli, M., 2023. Multi-decadal observations in the Alps reveal less and wetter snow, with increasing variability, *Front. Earth Sci.*, 11, 1165861, https://doi.org/10.3389/feart.2023.1165861.

Marty, C., Tilg, A. M., & Jonas, T., 2017. Recent evidence of large-scale receding snow water equivalents in the European Alps, *J. Hydrometeorol.*, 18(4), 1021–1031, https://doi.org/10.1175/JHM-D-16-0188.1.

McClung, D. M. and P. A. Schaerer, 2006. The Avalanche Handbook. 3rd ed, The Mountaineers, 347 (pp. 345-359).

Notarnicola, C., 2022. Overall negative trends for snow cover extent and duration in global mountain regions over 1982–2020, *Sci. Rep.*, 12, 13731, https://doi.org/10.1038/s41598-022-16743-w.

Sezen, C., Akyürek, Z., & Şorman, A. Ü., 2020. Investigation of rain-on-snow floods under climate change, *Appl. Sci.*, 10(4), 1325, doi:10.3390/app10041325.

Singh, P., Spitzbart, G., Hübl, H., & Weinmeister, H. W., 1997. Hydrological response of snowpack under rain-on-snow events: A field study, *J. Hydrol.*, 202(1–4), 1–20, https://doi.org/10.1016/S0022-1694(97)00004-8.

Valt, M., 2023. La risorsa nevosa sulla montagna veneta (SWE), Report SNPA n. 36/2023, ISBN 978-88-448-1168-6, Delibera del Consiglio SNPA n. 213/23, https://www.snpambiente.it/wp-content/uploads/2023/07/Rapporto_clima_SNPA_2022_14_07_23.pdf.

Valt, M., 2024. Neve, ghiacciai, permafrost: come cambiano le Dolomiti, Prolusione anno accademico 2024-2025, Agordo 2 ottobre 2024, UUA, pp. 1–8.

Valt, M., & Cianfarra, P., 2022. Neve e clima sulle Alpi italiane, *Neve e Valanghe*, 96, 2–15.

Vickers, H., Saloranta, T., Køltzow, M., van Pelt, W. J. J., and Malnes, E., 2024. An analysis of winter rain-on-snow climatology in Svalbard, *Front. Earth Sci.*, 12, 1342731, doi: 10.3389/feart.2024.1342731.

Wever, N., Würzer, S., Fierz, C., and Lehning, M., 2016. Simulating ice layer formation under the presence of preferential flow in layered snowpacks, *The Cryosphere*, 10, 2731–2744, doi:10.5194/tc-10-2731-2016.

Würzer, S., Jonas, T., Wever, N., and Lehning, M., 2016. Influence of initial snowpack properties on runoff formation during rain-on-snow events, *J. Hydrometeorol.*, 17(6), 1801–1815, doi:10.1175/JHM-D-15-0181.1.