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SNOW-AVALANCHE AND CLIMATIC CONDITIONS IN THE LIGURIAN SKI RESORTS (NW-ITALY)

Abstract: Brandolini P., Faccini F., Fratianni S., Freppaz M., Giardino M., Maggioni M., Perotti L. & Romeo V., *Snow-avalanche and climatic conditions in the Ligurian ski resorts (NW-Italy).* (IT ISSN 0391-9839, 2017).

Liguria Region is characterized by a 240 km-long coastal arc, and a largely mountainous territory. Consequently, its characteristic and famous Mediterranean-type climate is far from being uniform. Climatic diversity of Liguria reflects some fundamental morphological factors, such as southern exposures and the presence of a major mountain ridge with suitable climatic conditions for winter sports. Nevertheless, the permanence and stability of snow on the ground is related to local factors, such as the prevalent southern aspect, slope steepness, air temperature and wind intensity.

The highest Ligurian peak is the Saccarello Mount (2200 m) at the borders with Piemonte and the French Department of the Alpes Maritimes, while the highest mountain in the Ligurian Apennines is the Maggiorasca Mount (1804 m). Near these areas there are two "historical" ski resorts established in the mid-60s: Santo Stefano d'Aveto, bordering the ski areas of Emilia-Romagna, and Monesi di Triora to the West, in the province of Imperia; both resorts have been subject to significant investment in the development of tourist activities and accommodation.

The unique climatic conditions of Liguria and the established trends in climate require careful assessment of avalanche hazard, considering the increased flow of tourists and the poor perception of the associated risk in a region traditionally linked to "marine" leisure activities. During 2011, an avalanche in Santo Stefano d'Aveto caused the loss of a human life.

The paper presents a preliminary contribution aimed at assessing avalanche susceptibility in the two ski areas of Liguria: starting from the analysis of historical avalanches, several parameters have been analyzed, such as hazardous nature of the terrain, the weather and snow conditions and the interaction with human activities and infrastructures.

Key Words: Snow avalanche, hazard, climate, Liguria

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La Liguria è caratterizzata da un arco costiero lungo 240 km aperto verso mezzogiorno tra il confine francese e quello toscano. Il territorio si presenta quasi esclusivamente montano a causa delle catene alpine e appenniniche che si ergono a brevissima distanza dalla costa.

L'assetto climatico, nonostante la latitudine piuttosto elevata caratterizzato dal tipico regime Mediterraneo, non è uniforme, in quanto influenzato da numerosi fattori, quali esposizione e presenza di uno spartiacque tirreno-padano contraddistinto da quote elevate. Sulla costa il clima è temperato caldo, quindi temperato sub-litoraneo in una strettissima fascia fra l'entroterra e le aree pedemontane, infine sub-continentale sulle montagne più alte, dove si raggiungono oltre 2000 mm annui di precipitazioni e temperature invernali rigide.

Nelle aree superiori a 1000 m si verifica pertanto una situazione climatica adatta allo sviluppo di sport invernali, tradizionale prerogativa dell'area Alpina. La permanenza e la stabilità di neve al suolo è tuttavia legata a fattori locali come l'esposizione a Sud, la pendenza del versante, la temperatura dell'aria e le caratteristiche del vento.

La vetta più alta della Liguria è il Monte Saccarello (2200 m), nel Parco Regionale delle Alpi Marittime, al confine tra il Piemonte e il Dipartimento francese delle *Alpes Maritimes*, mentre la montagna più alta dell'Appennino Ligure è il Monte Maggiorasca (1804 m), situato nel Parco Regionale dell'Aveto.

In prossimità di queste aree vi sono due storici comprensori sciistici realizzati alla metà degli anni '60: Santo Stefano d'Aveto a Levante, al confine tra l'Area Metropolitana di Genova e l'Emilia, e Monesi di Triora a Ponente, in Provincia di Imperia. Entrambi i comprensori hanno ricevuto importati investimenti pubblici per lo sviluppo di attività turistiche e ricettive.

Le condizioni climatiche peculiari della Liguria e i riconosciuti trends climatici richiedono tuttavia l'attenta valutazione della pericolosità da valanga, anche in considerazione del rapido aumento di flusso turistico e, non ultimo, della scarsa percezione dei rischi tipici delle aree montane in una regione tradizionalmente associata ad attività balneari e costiere. Nel 2011 una valanga a Santo Stefano d'Aveto ha causato la perdita di una vita umana.

Il lavoro presenta un contributo preliminare finalizzato alla valutazione della suscettività da valanga nelle due aree sciistiche liguri: partendo dall'analisi dell'archivio storico delle valanghe del Corpo Forestale dello Stato, sono stati analizzati diversi parametri relativi alla pericolosità geomorfologica, al clima, alle condizioni della neve e, non ultimo, all'interazione con le infrastrutture e le attività antropiche.

Termini chiave: Valanga di neve, pericolosità geomorfologica, clima, Liguria.

INTRODUCTION

In the last decade, an increased pressure of tourism on Italian ski areas has been surveyed (ISNART, 2012) with the subsequent pulse of expansions, renovations and construction of new facilities. In addition, access and transit through not controlled and not populated areas of the snowy mountains intensified during recent years, due to increased trekking and off-piste skiing. "Trendy" outdoor activities, such as freeride, snowshoeing, ski touring, increasingly look for high altitude snowy trails, even during seasons with little snow; these trails are located in areas maintaining long snow cover, but with marked avalanche hazard. As a consequence, snow avalanche risks raised: not-urbanized and remote hazard areas (originally risk-free, because there were no exposed assets) have become risk areas (Romeo & Scarpelli, 2002).

Mountain territories of the Liguria Region are not immune to the general phenomenon of increased tourists fruition and related avalanche risk. Nevertheless, due to its geographical location, and the geomorphological setting of its extensive mountain range bordering the Mediterranean, the Liguria Region also shows peculiar meteorological and snow characteristics that differ from the rest of the Alps and Apennines (Meneguzzo & Romeo, 2004; Romeo & Fazzini, 2008).

Despite the fact that Liguria's landscapes are usually associated with marine and coastal environments distributed along a 240 km-long coastal arch, Liguria shows the typical characteristics of a hilly and mountainous region (Faccini & *alii*, 2005; Brandolini & *alii*, 2007). Flat areas are virtually nonexistent, and more than 10% of its territory is higher than 1000 m a.s.l., including sectors of the Alps and the Apennines.

Within the Ligurian mountains, areas above 1200 m a.s.l. have been historically exploited for tourism due to their climate and environmental conditions suitable for winter sports (fig. 1) (Sacchini & *alii*, 2012a, 2012b). The highest peak of the Ligurian Alps is the Saccarello Mount (2201 m), at the borders with the Piemonte Region and the French Department of Alpes-Maritimes); here the ski area of Monesi-Triora is located. The highest peak of the Ligurian Apennines is the Maggiorasca Mount (1804 m), within the Upper Aveto valley, at the border between the provinces of Genoa, Parma and Piacenza; its slopes host the ski domain of Santo Stefano d'Aveto.

Careful assessments of the avalanche hazard within Ligurian mountain areas are needed, for environmental, economic and social conditions:

- sudden weather changes are possible;
- an increase number of skiers is expected;
- a poor perception of the risk associated with avalanches is possible, given the stereotype of a region traditionally linked with the sea.

Indeed, the Ligurian ski resorts have been historically affected by snow avalanches that resulted in economic damages and casualties, such as the Santo Stefano d'Aveto avalanche of 2011, causing one victim.

A national snow avalanche inventory by the Italian Forestry Corp (CFS: Corpo Forestale dello Stato, now under Carabinieri) is available since 1955. This is a database offering an overview of avalanche events through Italy and a detailed description of events causing damages and victims. In the Liguria Region, snow avalanche monitoring and forecasting is provided by the METEOMONT service, managed by CFS since 1978 (Fazzini & *alii*, 2005).

Monitoring and historical data allow better knowledge of snow avalanche hazards and risks: thanks to the availability of the CFS, we aim to provide a preliminary snow-avalanche hazard assessment in the two ski resorts of Liguria, as a contribution to regional planning and future development of risk mitigation strategies in tourist mountain areas.

Particularly, we address our efforts to the:

- analyses of climate and snow conditions of the two areas in relation to recorded meteorological events and historical avalanches;
- application of GIS methodologies for terrain analyses in order to identify potential avalanche starting areas, considering geomorphological and land use features.

APPROACHES TO SNOW AVALANCHE MAPPING

The identification of avalanche-prone areas can be addressed by the following two different approaches:

1) the "static" approach is based on terrain characteristics, i.e. the analysis of predisposition to snow avalanche occurrence (i.e., susceptibility) within a certain area;
2) the "dynamic" approach, i.e. a more comprehensive approach considering also the possible snow avalanche release on the basis of analyses of both terrain characteristics and snowpack stability.

The "static" approach leads to the identification of areas likely to be exposed to snow avalanches. In Italy, areas susceptible to snow avalanches have been represented on maps, such as: the *Carta di Localizzazione Probabile delle Valanghe*, CLPV, (map of Probable Avalanche Localization or *Monografia Militare delle Valanghe* (Monographs Military Avalanche) and the *Piani delle Zone Esposte a Valanghe*, PZEV (Plans of the Zones Exposed to Avalanche (Barbolini & *alii*, 2005, 2011).

The "dynamic" approach also considers the snowpack stability: it leads to the preparation of the Snow and Avalanche Bulletin, providing daily to weekly hazards classification at regional level: hazards are defined according to the release probability of avalanches of a certain size (Barbera & *alii*, 2012; EAWS, 2003).

Regarding the first approach, territorial agencies and research institutions developed appropriate methodologies to identify areas potentially affected by avalanches.

A classical method used by territorial agencies, although unevenly in Italy, is the preparation of the CLPV;

here, possible avalanche paths are identified by: photo-interpretation and field survey (in the summer), investigation on the snow covered ground, interviews to witnesses of past avalanche events, study of previous events recorded in a variety of historical and technical archives.

More recent methods for the identification of avalanche areas are based on the use of GIS technologies with improving possibilities for storage, processing, updating and presenting data.

In particular, research has moved towards translating the present knowledge about the predisposing factors to avalanches into GIS procedures, in order to define potential areas of avalanche release, given a single input of the digital elevation model (DEM)

Maggioni & Gruber (2003), Maggioni (2005) and Bühler & *alii* (2013) proposed a method that, from a DEM, derives potential avalanche release areas on the basis of: slope angle, aspect, curvature, forest coverage, proximity to ridge, altitude and terrain roughness.

The result is a map highlighting avalanche Potential Release Areas-(PRA). Ghinoi & Chung (2005) have instead classified the terrain in terms of susceptibility to avalanche, cataloguing every pixel of the DEM with an index of propensity to release, based on statistical relationships between topographic parameters, obtainable from the DEM, and the release areas of historical events.

The ATES method (Statham & *alii*, 2006; Campbell & Gould, 2013) provides maps of an area by classifying its potential exposure to avalanches; it is a suitable method to support hikers' selection of the best path to follow on snowy terrains.

These maps are "static", since they do not take into account the presence of the snowpack, which evolves over time. Julián & Chueca (2012) and Chueca & *alii* (2014), in addition to the slope angle, curvature and surface coverage, also consider the minimum of the isotherm region at 0 °C for the winter months, beginning to combine the static information with snow and weather parameters, variable in time.

The process of avalanches release is very complex, therefore it is difficult to realize an integrated comprehensive tool considering all aspects; however, mapping tools like those described above represent useful aid for the management of the avalanche hazards.

STUDY AREA

The still active ski resorts in the Liguria Region are Santo Stefano d'Aveto (1017 m) in the Genoa Metropolitan Area (Upper Aveto Valley, Ligurian Apennines – Eastern Liguria) and Monesi di Triora (1376 m) in Province of Imperia (Upper Tanarello Valley, Ligurian Alps – Western Liguria) (fig. 1). Other popular mountain resorts for winter sports, such as Nordic skiing, hiking with snowshoeing and ski touring, are Alberola and Calizzano in the Province of Savona, and the areas of the Colle Melosa and Mt. Beigua in the Ligurian Alps, and Antola, Aiona and Penna mountains in the Ligurian Apennines (Brandolini & *alii*, 2008; Faccini & *alii*, 2012).

The ski resort of Santo Stefano d'Aveto was realized in 1965 with the construction of a cable car and a ski lift on the southern slope of Mt. Bue (1775 m), of two drag lifts on the northern slope of Mt. Maggiorasca (1804 m). Approximately 10 km of ski slopes, mainly located on the south-facing slopes that descend until Rocca d'Aveto

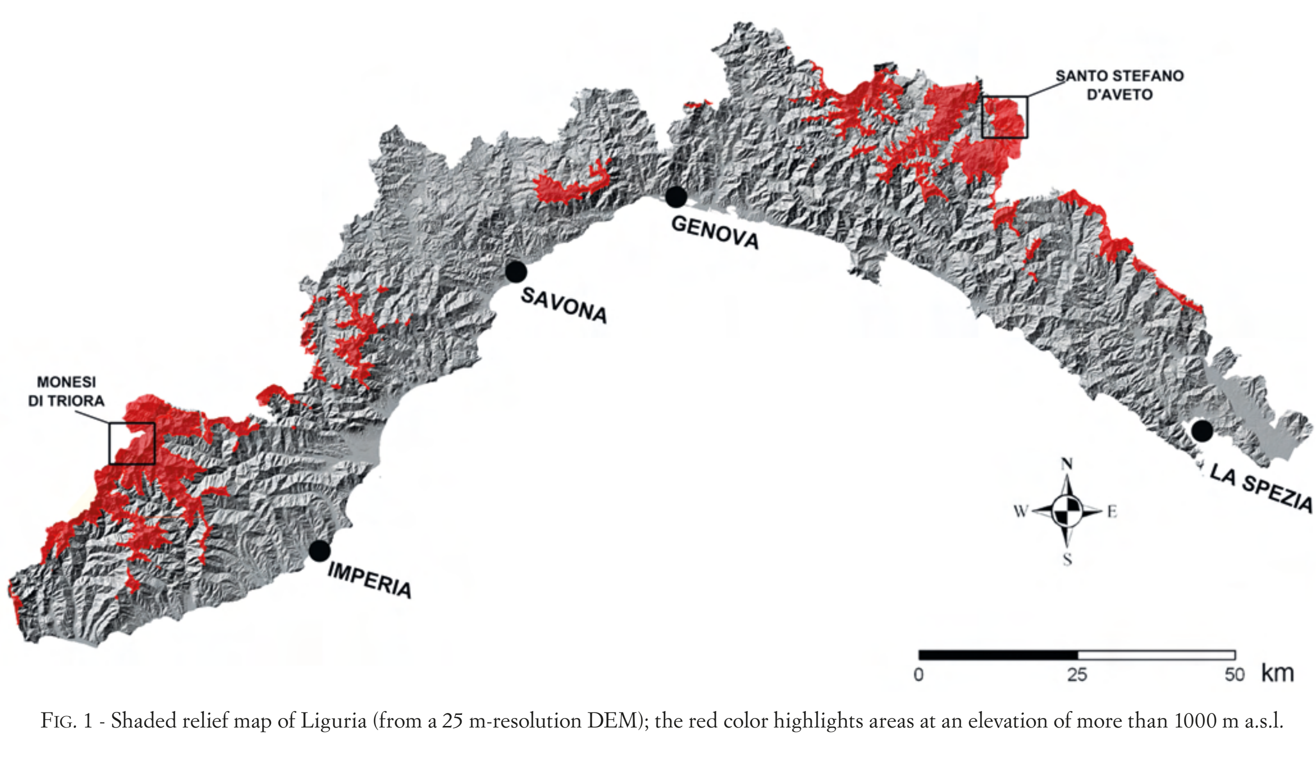

FIG. 1 - Shaded relief map of Liguria (from a 25 m-resolution DEM); the red color highlights areas at an elevation of more than 1000 m a.s.l.

(1255 m a.s.l., starting point of the lifts) were developed. From Rocca d'Aveto a Nordic ski trail about 20 km long also starts, branching along the slopes of the southern and western Mt. Maggiorasca and Mt. Tomarlo.

The ski area of Monesi di Triora was realized in the mid-1950s, with the construction of a chairlift and of four ski lifts on the northern slopes of Mt. Saccarello (2201 m) as well as with the development of different ski slopes with a total length of about 15 km. In the nearby resort of Upega, there is also a 5 km-long oval track for Nordic ski.

Both ski resorts have proved to be popular tourist attractions in the 1960s and in the 1970s, followed by a period of tourist decline (mid-1980s). Repeated seasons of small snow accumulation which led to the economic crisis of the companies owning the facilities, has forced their default in the early 1990s.

From the 2008/2009 winter season, thanks to investments aimed at the development of mountain tourism in the Liguria Region to boost both summer and especially winter tourism, the ski resorts of Santo Stefano d'Aveto and Monesi were reopened with the construction of two new chairlifts, replacing the old and obsolete facilities.

MATERIAL AND METHODS

Climatological data

Manual snow and weather observations provided by the Meteomont Service (Snow and Avalanche Forecast National Service, State Forestry Corp) have been used to determinate the average climatological characteristics and snow precipitation regime in the two nivo-meteorological stations (29 years, period 1986-2014). Daily maximum and minimum temperatures, snow height and snowfalls measurements recorded in the nivo-meteorological stations of Santo Stefano d'Aveto (1175 m a.s.l. coordinate UTM 4933160 N / 537300 E) and Monesi di Triora (1360 m a.s.l., coordinate UTM 4880937 N / 399737 E) sites have been considered.

Avalanche data

Data on snow avalanches having affected the two study areas have been acquired from the CFS inventory, now a digital database, automatically fed by the patrols in the area. It contains a record of the occurred events from 1955 to present. Each record includes: event date and type; location on map; data on the characteristics of the event and of the release, track and deposition zones (geology, geomorphology, vegetation, length, width, thickness, volume); surveyed effects (damage, casualties, and rescue procedures); snow release conditions; photographic documentation and any other relevant document or report drawn up after the event (verbal assignment cutting, newspaper articles, reports on relief efforts, etc.).

To boost data provided by the State Forestry Department, municipal archives of Santo Stefano d'Aveto and Monesi di Triora have been analyzed for updating snow avalanche inventory with interviews to local residents and operators of ski resorts.

Terrain analysis

A quali-quantitative method for evaluating the geomorphological setting of the two study areas, focused on terrain analysis, has been used to locate the most critical areas where avalanches might release. It is a really simple GIS mapping procedure, based on the overlap of 4 different layers of morphological attributes: land use, plan curvature, aspect and slope angle. For this study we used the freeware GRASS GIS software (Shapiro & *alii*, 1993).

Every attribute layer maps (except the land use one) have been elaborated on a 5 m resolution DEM (kindly provided by Regione Liguria). This DEM was chosen because of its best balance between resolution and representativeness of the territory for described parameters. The land use map was chosen for the relatively high resolution (1:10.000 scale), and because it was the most updated map (2012) available for the study area.

Based on existing literature, attributes have been classified by values ("weight"), the highest for the most favorable condition for avalanche release (tab. 1). For each parameters the maximum weight was set to 10.

Slope angle was classified into 6 classes, considering the class 37-40° the most favorable to release. The weights to the other classes were given according to the slope angle frequency distribution of avalanches reported by Schweizer and Jamieson (2001).

Land cover was divided into 4 classes and the relative weights were set according to the work of Julián & Chueca (2012), given that grassland is the most favourable class for avalanche release.

TABLE 1 - Key factors classes and related ratings (R) utilized for snow-avalanche susceptibility map.

Slope (deg)	R	Land cover	R	Curvature	R	Aspect	R	Snow-avalanche susceptibility	R
37-40	10	high density forest	0	concave	10	North	2	high	29-40
34-37 and 40-43	5	low density forest/schrubs	2.5	plan	6	East	5	medium	17-28
31-34 and 43-46	3	bare rocks	7.5	convex	3	West	5	low	5-16
46-52 and 28-31	2	grassland	10			South	10		
25-28 and 52-55	1								
< 25 and > 55	0								

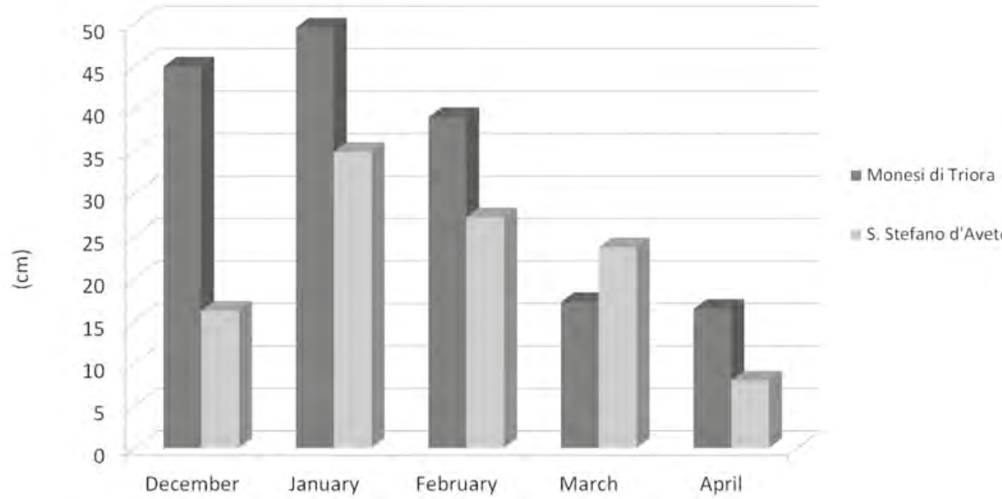

FIG. 2 - Seasonal distribution of snow precipitation.

Plan curvature was classified into three classes: concave, plan and convex, being concave the worst case for avalanche release (Gleason, 1995; McClung, 2001; Schweizer & *alii*, 2003).

The aspect was classified into four classes. From historical data, Southern aspects are the most prone to avalanche release in the two study areas, therefore this class was assigned a weight of 10.

An overlap of the resulting weighted layers has been performed by summing "weights" of the 4 attributes, thus generating the final susceptibility map, where each pixel is classified according to three geomorphological susceptibility levels: "high", "medium", or "low". The minimum possible value is 5 and the maximum 40.

RESULTS

Climate in the area

The analysis of the historical record brought to the results shown in figg. 2-4. Snow rate is unimodal, with a winter maximum in January. Comparable snow amounts occur in December and February at Monesi di Triora (40 cm) and in February and March at Santo Stefano d'Aveto (20-25 cm) (fig. 2). These results are in agreement with the studies made by Terzago et al. (2010, 2012): measurements from stations in the south-western Alps indicate the mean monthly snow accumulation in January at the highest, at elevations between 800 and 1600 m a.s.l.

The average seasonal temperature (from December to April) is -3 °C for the minimum temperature series and 6 °C for the maximum ones; values at Santo Stefano d'Aveto are respectively -2 °C and 6 °C (fig. 3). The lowest temperature (-15 °C) was recorded on February 7th and 8th, 2001; the highest temperature is 23 °C, temperature recorded on March 28th, 1989.

At Monesi di Triora weather station, the coldest month is December (T min -4 °C and T max 4 °C). In April we detected a slight rise in temperature values compared to March (-1 °C, 10 °C), due to the persisting of snow cover.

For Santo Stefano d'Aveto the lowest temperature values are recorded in February (T min: -4 °C; T max: 5 °C). The lowest temperature (-19 °C), was recorded on March 1st, 2005; the highest (23 °C) on April 9th, 2011.

The dataset shows a general high variability of temperature measures, even within the same month; for example, recorded values at Monesi di Triora range from -15 ºC to 22 ºC in February.

The median of the seasonal snow height for Monesi di Triora is 41 cm and shows a high variability ranging, from 0 cm to 177 cm (95 °percentile). Higher mean snow height values are recorded in February (53 cm). Santo Stefano d'Aveto presents lower snow height values at the seasonal scale and also a large variability range, with values reaching 87 cm in February at the monthly scale (fig. 4).

Historical snow avalanches

The recorded snow avalanches, all through the period of data availability (1986-2014), are 56 in the Monesi di Triora area, and 27 in the Santo Stefano d'Aveto one. Here below their main characteristics are presented, highlighting that the fewer events of the Upper Aveto Valley make the related analyses less consistant.

During the analyzed period, snow avalanche types having affected Monesi di Triora area were mainly full-depth slab avalanches or surface loose-snow avalanches, and only sporadically surface slab-avalanches or full-depth loose snow avalanches (fig. 5). For the most part, small and medium-sized wet or slush avalanches are registered, mainly caused by temperature rise and only seldom by new snow amounts.

On average, the total snow accumulation in the avalanche days was 107 cm, with a snowpack density of 171 kg/m^3; the daily mean air temperature was 3.1 °C, with a minimum of -2.0 °C and a maximum of 5.8 °C. Concerning the weather condition in the avalanche days, the mean air temperature did not show any positive or negative trend, while the maximum air temperature resulted higher in the last

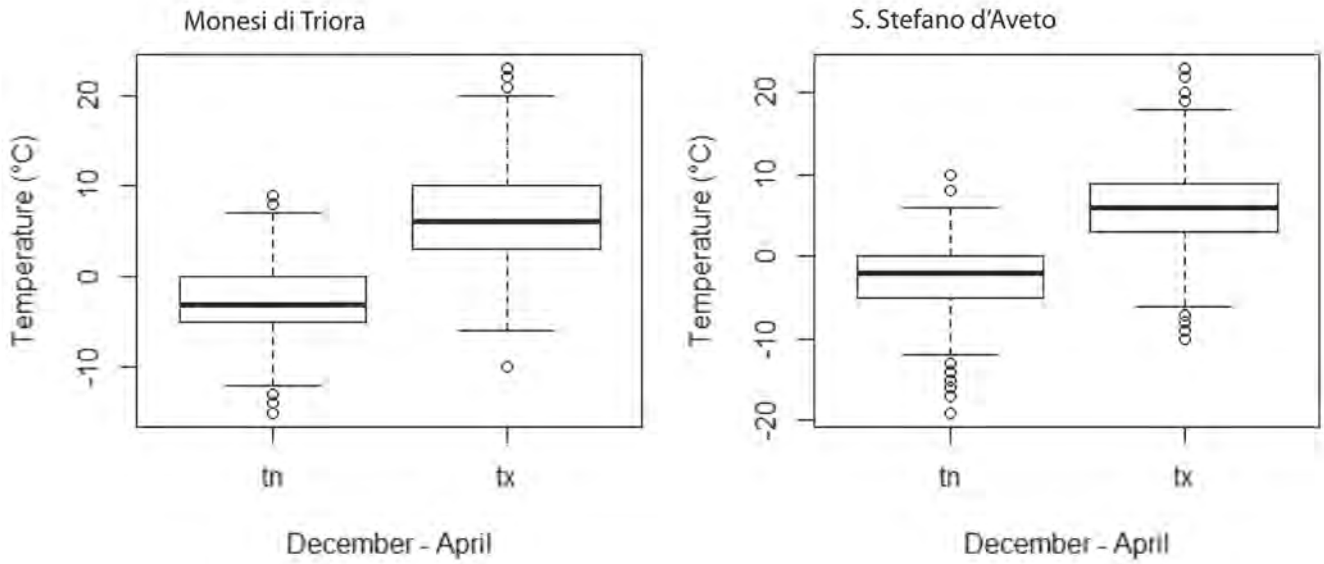

FIG. 3 - Statistics of the December-April minimum (Tn) and maximum temperatures (Tx) over the period 1986-2014 for Monesi di Triora (left) and S. Stefano d'Aveto (right). For each box the lower hinge, the median, the upper hinge correspond to the 1st, 2nd, 3rd quartiles respectively, the lower and upper hyphen represent the minimum (5° percentile) and the maximum (95° percentile) of the sample. The period December-April represents the entire season.

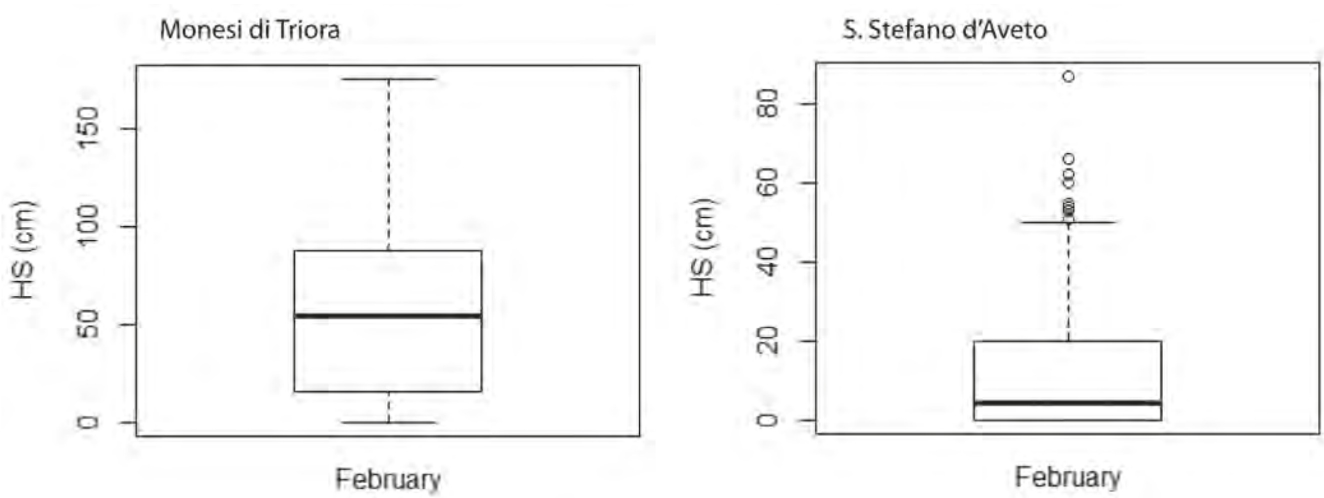

FIG. 4 - Statistics of the February snow height over the period 1986-2014 for Monesi di Triora (left) and S. Stefano d'Aveto (right). The lower hinge, the median, the upper hinge correspond to the 1st, 2nd, 3rd quartiles respectively, the lower and upper hyphen represent the minimum (5° percentile) and the maximum (95° percentile) of the sample.

decade with the presence of more frequent extreme values.

By analyzing the more continuous avalanche dataset from 2010 to 2014, it resulted that most of the events occurred on grassland (70%), but a significant percentage (23%) occurred within forested areas.

During the analyzed period, the type of avalanches having affected Santo Stefano d'Aveto area were mainly surface loose-snow avalanches of small/medium dimension on southern aspects. On average, the total snow accumulation in the avalanche days was 27 cm, with a snowpack density of 87 kg/m^3; the daily mean air temperature was -0.8 °C, with a minimum of -5.9 °C and a maximum of 4.3 °C. Concerning the weather condition in the avalanche days, the maximum air temperature showed a positive trend, while an opposite tendency occurred for the minimum temperature, resulting then in a larger daily temperature range. The frequency of snow avalanche events increased in the last decade, as well as the width of thermal excursion. In fact, starting from the 2003-04 ski season, also the maximum air temperature resulted higher, with more frequent extreme values, if compared to the 1986-2000 period (fig. 6).

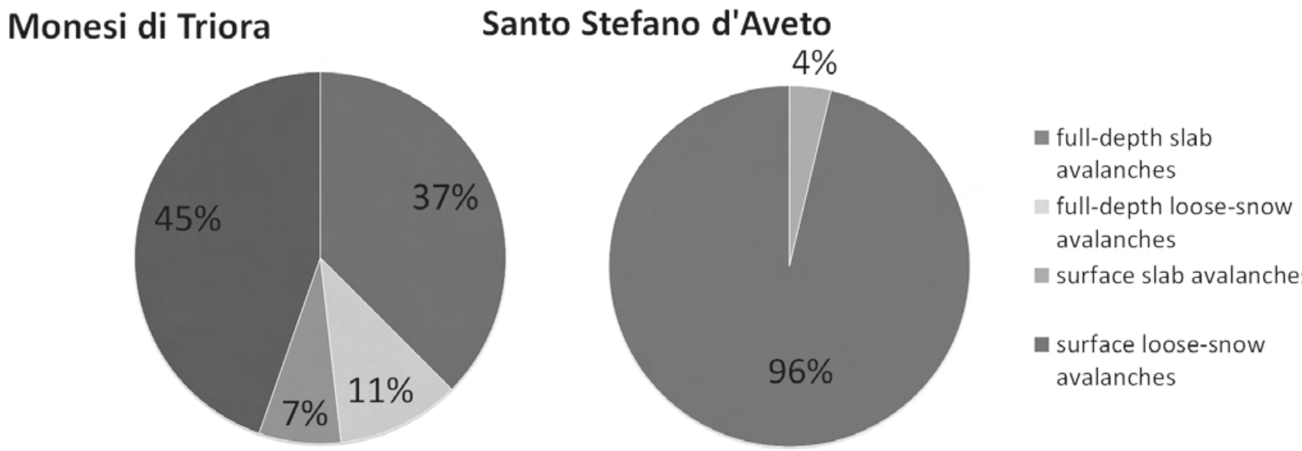

FIG. 5 - Snow-avalanche types for Monesi di Triora and Santo Stefano d'Aveto ski resort areas.

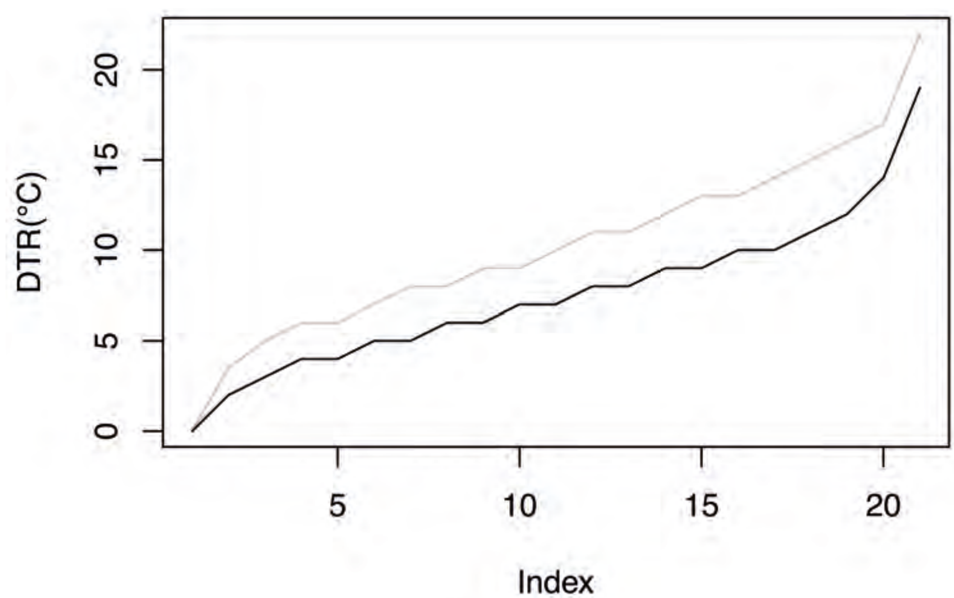

FIG. 6 - Comparison between temperature indexes within 2 time intervals at the Santo Stefano d'Aveto series (grey line: 2001-2014; black line: 1986-2000). In X axis, index of percentiles, from 1 = 0 percentile to 20 =100 percentile. In Y axis, DTR, thermal excursion between Tmax and Tmin.

Snow avalanche accidents

As mentioned above, both ski districts have been affected by several snow avalanches. Among the approximately 100 events recorded within the Snow Avalanche Inventory, we highlighted those occurred in 1971 at Monesi di Triora and in 2011 at Santo Stefano d'Aveto, both having caused the loss of human lives.

The March 20th, 1971 event occurred between 13:45 and 14:00 hour: a spontaneous snow slab avalanche released in the valley of the Rio Raggioso, located between Monesi and Colle di Nava. The release zone was located at around 1550 m a.s.l.: a fracture width of about 400-500 m, along a slope angle of 40-45° with a NE aspect. The avalanche track was characterized by a shrubby gully along a clear cut over a wooded slope. The avalanche reached the main road SP 1 between Monesi and Colle di Nava and stopped at about 1300 m a.s.l., forming a 80 m long deposit.

The day before the event (March 19) weather conditions were characterized by snow precipitation of about 20 cm and temperatures between 1 and 7 °C (max), while March 20th was characterized by a heavy rain (40 mm) and temperatures between 4 and 8 °C. The avalanche released after a heavy snowfall followed by an increase in temperatures with heavy rainfall. The avalanche caused victims, two motorists who were driving on the main road.

The January 30th, 2011 event occurred at around 13:00 hour: a spontaneous snow slab avalanche released along the slope between the Mt. Bue and the Prato della Cipolla wetland. The release area, with a fracture width of about 30 m, was located around 1720 m a.s.l. and presented a slope angle of 30-35°with a SW aspect. The avalanche track was characterized by an open slope, with herbaceous vegetation, and converged in a small watershed at about 1640 m a.s.l., where the avalanche stopped. The avalanche deposit

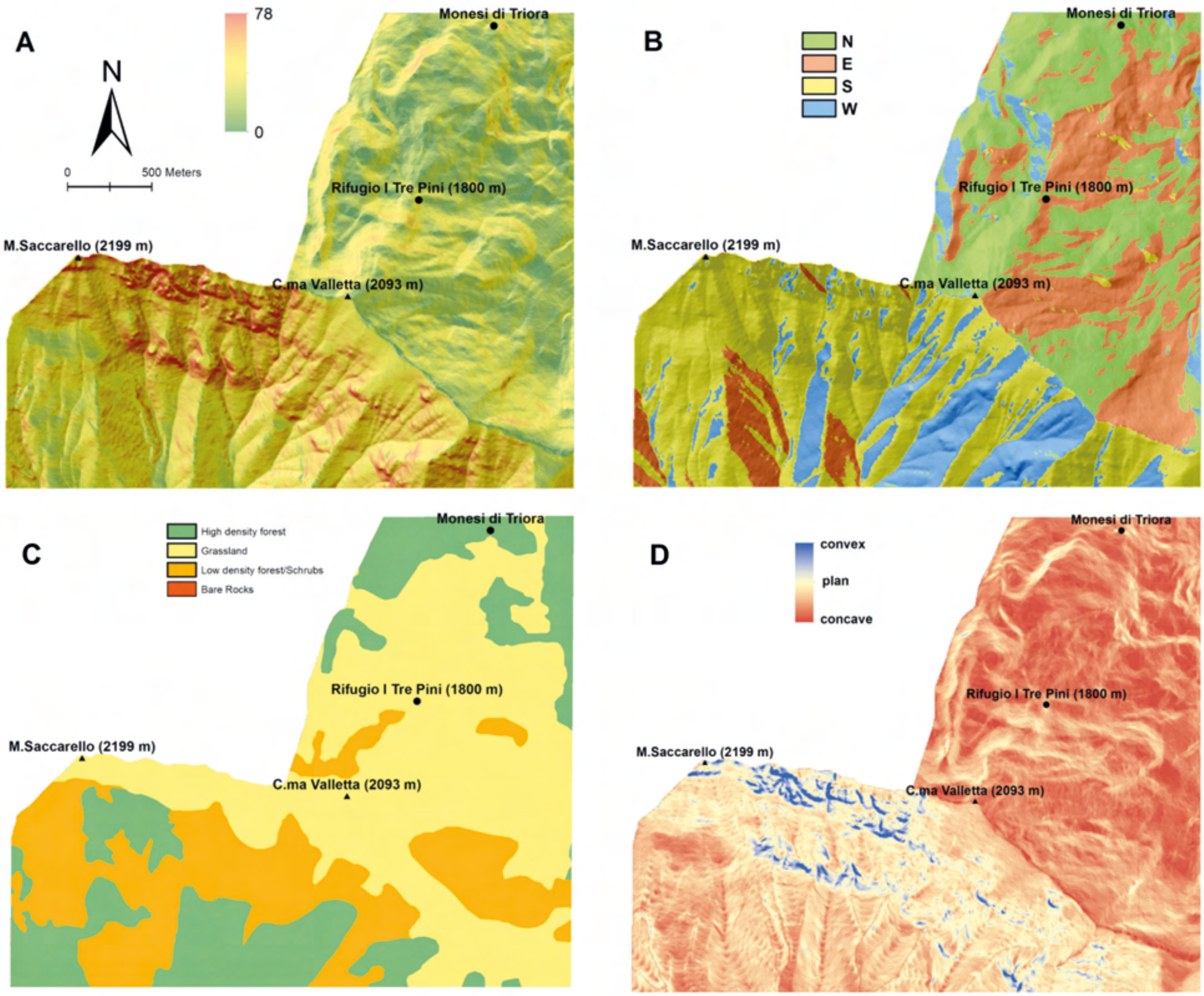

FIG. 7 - Slope angle (A), aspect (B), land use (C) and plan curvature (D) maps for the study area of Monesi di Triora.

was about 20 m long, 15 m wide, up to 2 m thick, and had an estimated volume of 300 m^3. During the motion the snow avalanche caught an off-track skier, who died.

The weeks before the event were characterized by a succession of snowfalls, with daily average air temperatures between -1 and -3 °C, and rainfalls, with daily average air temperatures between 2 and 6 °C. Thus the avalanche was triggered after heavy snowfalls occurred the previous days, which were deposited on a layer of compacted snow.

Morphological susceptibility to avalanches

According to our geomorphological analysis, in both study areas a large extent of the terrain is potentially prone to avalanches. Figure 9 shows the results of the GIS analysis for the two study areas.

The greatest part of the area, where both the ski-resorts are located, has been classified within the "low" (16% of total area for Monesi di Triora and 43% for Santo Stefano d'Aveto) and "medium" (72% for Monesi di Triora and 50% for Santo Stefano d'Aveto) susceptibility classes. The "high"susceptibility class (12% for Monesi di Triora and 7% for Santo Stefano d'Aveto) covers neighboring areas to the ski resorts, where off-piste, ski-touring, back-country skiing and snow-shoeing is a common practice.

In Monesi di Triora, where most events occurred in the off track areas, the historical avalanches overlap well with the high-susceptibility area. In particular, the well-know avalanche path located along the ski lift line (NE sector of fig. 9) has been recognized and classified as high/medium susceptibility. Along this path several avalanches occurred between 1986 and 1996. Instead, a special attention deserves the case of the first two avalanches shown on the left side of Fig. 9, where the GIs procedure did not performed well. They are well-known avalanche path with release area covered by dense and sparce forest. In the GIS procedure, the low weight given to this land cover classes (see Tab. 1) is enough to classify this areas as "low susceptibility", even though the slope angle is similar to the adiacent areas classified with a higher susceptibility. This arises the issue of the avalanche release

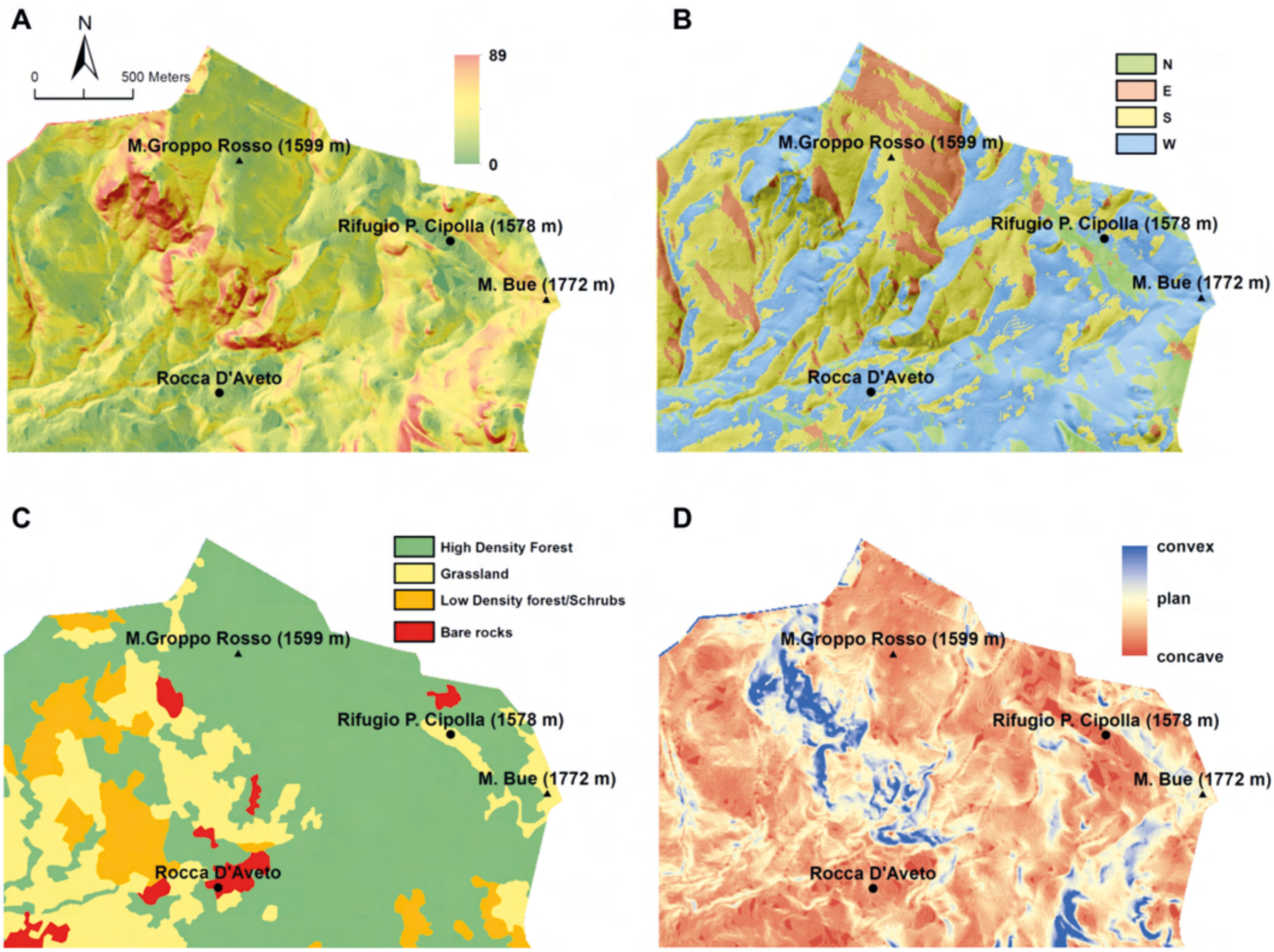

FIG. 8 - Slope angle (A), aspect (B), land use (C) and plan curvature (D) maps for the study area of Santo Stefano d'Aveto.

within forested areas, which, to have a protective role, must have specific characteristics. A field based characterization would be necessary to assess the forest composition, structure and coverage, which are the most important features to be considered for this issue (Bebi & *alii*, 2009; Viglietti & *alii*, 2010; Teich & *alii*, 2012; Viglietti & *alii*, 2013).

DISCUSSION AND CONCLUSIONS

Analysis of historical avalanches, review of climate conditions, study of geomorphological characteristics and land use allowed the preliminary assessment of avalanche susceptibility in two ski areas of the Liguria Region. Several parameters have been taken into account, such as hazard key factors of slopes, meteorological data, snow conditions related to avalanche events, and the interactions with human activities and infrastructures. Based on this dataset, relevant issues for a better avalanche hazard assessment can be discussed.

The application of a snow avalanche susceptibility model based on the terrain parameters revealed to be a useful tool for the identification of potential avalanche areas, as the results of the procedure were in acceptable agreement with the limited amount of historical data. In fact, either the most recent snow avalanches at Santo Stefano d'Aveto (2011) or the largest event occurred in Monesi di Triora (1971) fall within the highest susceptibility class.

Focusing on Santo Stefano d'Aveto, the most recent (1986-2014) recorded events are small size surface avalanches (less than 500 m^2); therefore a possible improvement for the susceptibility map might be achieved by using a more detailed digital elevation model.

Moreover the evaluation of the GIS procedure could be improved by the inclusion of other avalanche-predisposing factors (such as for ex. terrain roughness), as well as a balancing of the weights assigned to the different parameters. These improvements could be also achieved through a statistical approach based on the back analysis of other case studies, collected in a georeferenced database.

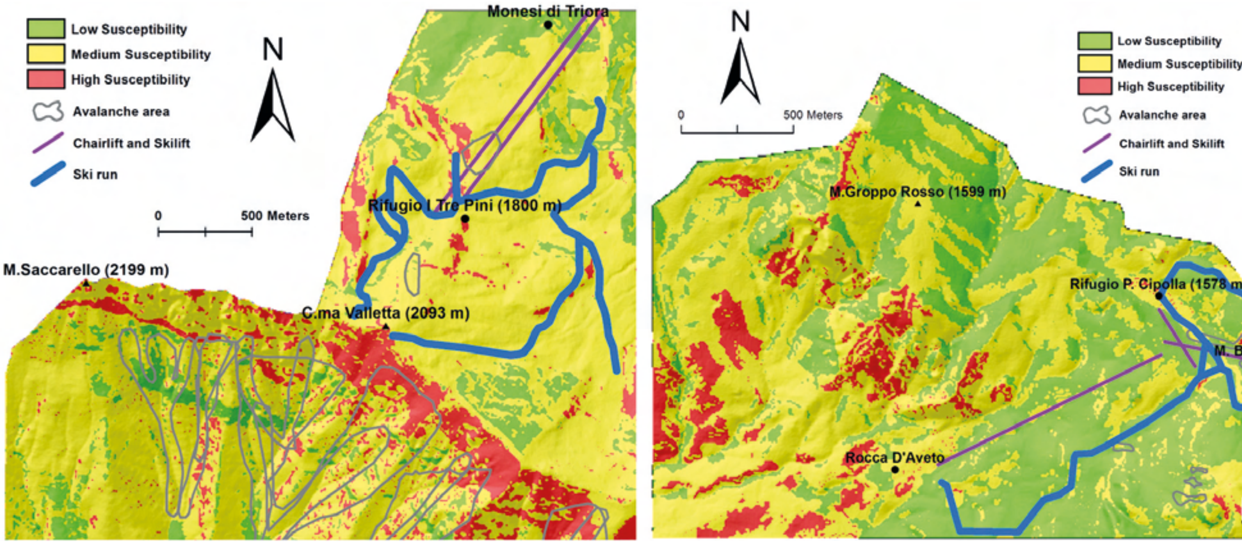

FIG. 9 - Snow-avalanche susceptibility maps based on morphological and land-use factors for Monesi di Triora (left) and Santo Stefano d'Aveto (right) ski resorts. One of the main snow avalanche area of Monesi di Triora described in text is located long the skilift lines.

In relation to weather and snow conditions, the analyzed meteorological series evidence a significant increase of the maximum temperatures compared to the minimum ones during the last 15 years: this implies an increase of daily thermal excursion, which might favor snow avalanche triggered by diurnal thermal rise, as shown by a slight rise of recorded events.

This is in agreement with data recorded in other mountain sites, such as in the North-Western Italian Alps, where a statistical significance positive trend for the maximum and minimum air temperatures has been observed in the period 1961-2010 (Terzago & *alii*, 2010, 2012; Acquaotta & *alii*, 2013, 2015). The greatest changes for the maximum air temperatures were recorded in March and January, while the greatest changes for the minimum air temperatures were recorded in June. The analysis of maximum temperatures highlights an increasing trend in winter between 2000 m and 1600 m a.s.l.

The temperature increase at the mid altitudes could adversely affect the tourist exploitation of the mountain region. The rising of air temperatures will be accompanied by snow losses for the winter tourism and skiing season causing impacts on the socio-economic structures of the populations that live in the mountains (Fazzini & *alii*, 2004). Also a retrospective analyses by Fratianni & *alii* (2015) of data from automatic and manual snow and weather stations of the North-western Italian Alps outlined a significant decrease of the snow depth over the seasonal time scale in the 1951-2010 period. As a matter of fact, the main contribution to this negative trend comes from spring, when the snow-depth decrease is comparable to the one registered over the complete season (Terzago & *alii*, 2013).

In this context of climate change, the frequency of full-depth wet avalanches (including the gliding ones) might increase (Lazar & Williams, 2008) and deserves more attention, due to the fact that they are extremely difficult to predict and with high destructive power. In particular, a glide snow avalanche is a specific full-depth avalanche, which generates from the intense gliding of the entire snowpack (Höller, 2014). Especially the study area of Monesi di Triora is characterized by large areas classified as grassland with a southern aspect: a combination of factors very favorable to glide-snow avalanche formation (Maggioni & *alii*, 2016). In fact, a snowpack on southern aspects can accumulate intense solar radiation which can eventually generate water percolating down to the bottom of the snowpack and decrease the friction on the ground, increasing the gliding process. Or, the soil can retain a lot of the heat gained in summer and generate a wet film at the snow/soil interface which decrease the snowpack basal friction (e.g. Ceaglio & *alii*, 2016; Jones, 2004; Mitterer & Schweizer, 2012; Frigo & *alii*, 2014).

The overview of the snow avalanche situation in the Santo Stefano d'Aveto and Monesi di Triora ski resorts, highlighted their peculiar characteristics in relation to avalanche activity, weather and snow conditions, due to the specific climatic conditions of the Liguria and the established trends in the Alpine climate.

Considering the increased flow of tourists into mountain areas and the poor perception of the associated risks, particularly in those regions dominated by "marine" leisure activities, the study offered some relevant contributions for the observation and better assessment of avalanche hazards. Nevertheless, discussion revealed some open issues concerning survey methodologies and susceptibility models of snow avalanches, which should be more investigated not only in Liguria, but also in other mountain areas.

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