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The snow load in Europe and the climate change

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ABSTRACT

It is often assumed that, as a consequence of global warming, a reduction of snow load on the ground should be expected. In reality, snow load is often depending on local orographic situations that can determine an increase of its height, even when the average snow height over the surrounding areas is reduced. Large snow loads on roofs during the winter season of 2005–2006 led to over 200 roof collapses in Central Europe. To proceed with the adaptation of the European standards for important buildings and infrastructures to the implications of climate change, the expected changes in the climatic loading shall be assessed in terms of the Eurocodes concept for characteristic values of variable climatic actions. The paper presents a procedure for derivation of snow load on ground from data on daily temperatures and precipitation. In addition, it allows to derive the characteristic snow loads from climate change projections and thus to evaluate the future trends in variation of snow loading. Analysis of these trends for the Italian territory is performed by comparing the results for several subsequent time periods of thirty years, with those obtained for the reference period 1951–1980. Results presented show a significant increase in the snow loading for the period 1981–2010 in many regions in north and east Italy in comparison with the reference period. It is suggested that a European project on snow load map shall be started, in order to help National Competent Authorities to redraft the national snow load maps for design with the Eurocodes.

1. Introduction

The evidence of climate change is unequivocal and the consequences are increasingly being felt in Europe and worldwide. In particular, the mean global temperature, currently around 0.8 °C above the pre-industrial level, continues to rise, even more evidently in Europe (e.g. European Environment Agency, 2012). Climate change affects all regions of the world by alteration of natural processes, modification of precipitation patterns, melting of glaciers, rise of sea levels, etc. Whatever the warming scenarios and the level of success of mitigation policies, in the coming decades the impact of climate change needs to be considered, taking into account

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Abbreviations: DWL, Design Working Life; ESLRP, European Snow Load Research Project; GCMs, Global Climate Models; GHG, Greenhouse Gases; IPCC, Intergovernmental Panel on Climate Change; LSM, Least Square Method; MC, Monte Carlo (Simulations); PT, Project Team; RCMs, Regional Climate Models; SWE, Water Equivalent of the Snow Pack; RCPs, Representative Concentration Pathways; WRCP, World Climate Research Programmes

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its economic, environmental and social consequences (COM (2013) 216).

The response of the European Union to climate change is an adaption strategy to enhance both the capacity to withstand it, and the readiness to respond to its impacts, particularly in most vulnerable key sectors such as infrastructures for transport of goods or dispatch of energy, and buildings, which are characterised by a long life span and high costs. In this respect, a central role is played by technical standards and by their evolution during the lifetime cycle of the infrastructures and buildings (SWD (2013) 137 final), also considering that the real life span of most structures is much longer than their design working life. Therefore, assessment of the impact of climate change on new and on existing structures is a key aspect in the future evolution of standards, as intended for the second generation of the Eurocodes (Mandate M/515 of the European Commission, 2012), and all other standards relevant to transport infrastructure, energy infrastructure, and buildings/construction (Mandate M/526 of the European Commission, 2014). Moreover, the European Financing Institutions Working Group on Adaptation to Climate Change (2016) highlighted the importance of making projects and investments less sensitive to the effects of climate change, on the basis of emerging experience in implementing adaptation measures that reinforce the climate resilience of goods, people, economies and territories of the beneficiaries. For these reasons, the present study aims to determine the effects of climate change on the snow loads on structures, implementing suitable models and procedures for defining characteristic snow loads on ground from the results of available global and regional climate models.

2. Snowfalls in a changing climate

2.1. Global assessment

Snow is an important part of the climate system, since it increases surface albedo and isolates the atmosphere from the ground. In mountain areas, snow and ice duration, distribution and spatial extent play a key role in the hydrological cycle, are determinant for vegetation and human activities, and, in turn, are important feedback for the climate system (Da Ronco et al., 2016).

A global assessment of climate change trends is presented in the Intergovernmental Panel on Climate Change (IPCC) Report (2013). The assessment considers new evidence of past, present and projected future climate change based on many independent scientific analyses of observations of the climate system, theoretical studies of climate processes, and simulations using climate models.

The future projections of climate change are generally based on a set pf Representative Concentration Pathways – (RCPs) defined according to radiative forcing target level estimated for the year 2100 relative to pre-industrial values (Van Vuuren et al., 2011). RCPs depend on mitigation scenarios and deadlines for the implementation of policies to reduce greenhouse gas emissions, like the Kyoto Protocol. These scenarios show generally further warming and changes in the global water cycle, but, locally, trends can be different or even opposite to the averaged, global ones.

Due to the ongoing climate changes, snow conditions are also expected to change. During the past four decades, the snow extent in the Northern Hemisphere has decreased mostly in spring and summer. In spite of this global trend, the trends in snow conditions have been variable on regional scales (Raisanen and Eklund, 2012). Climate change projections related to greenhouse gases (GHG) concentration in the Northern Hemisphere mid- to high-latitude continents indicate both a strong winter warming and an increase in winter precipitation. The increase in precipitation, if acting alone, would lead to an increase in snowfall and consequently to increased amount of snow on ground. On the other hand, an increase in temperature will reduce the fraction of precipitation that falls as snow and will increase the melting of snow. Whether the snow amount on the ground will be actually reduced or increased depends on the balance between these competing factors (Raisanen, 2008).

General circulation models or global climate models (GCMs) from the World Climate Research Programmes (WRCP) on coupled model inter-comparison project CMIP3 and CMIP5 (Meehl et al., 2007; Taylor et al., 2012) generally agree in predicting a future decrease in snow cover duration and maximum snow water equivalent in central Europe. The IPCC Working Group 1 conclusions state that generally the snow cover extent will be reduced (IPCC, 2013). However, snow cover sensitivity to changes in precipitation and temperature is highly related to topographic features such as elevation, aspect and terrain shading. For example, in the twentieth century snow duration at mid and low altitudes has shown to be very sensitive to temperature increases.

According to Hosaka et al. (2005), in the late 21st century the water equivalent of the snow pack (SWE) is projected to be reduced in most regions and seasons, but SWE will increase from February to April in large parts of Siberia and northernmost North America.

Lemke et al. (2007) found that the regional trends in snow conditions have been variable, although the Northern Hemisphere snow extent has decreased during the past four decades particularly in spring and summer. Where climate is cold enough, midwinter temperatures will remain substantially below zero even after a moderate warming. Thus, at least in the middle of the winter, the phase of precipitation and snowmelt should be quite insensitive to temperature changes. Conversely, where winters are milder, even a modest warming will act to convert part of the snowfall to rainfall and to increase the frequency and intensity of melting episodes. Changes in SWE induced by the expected global warming are thus probably more likely to occur in mild than in cold areas.

Krasting et al. (2013) analysed projections of the Northern Hemisphere snowfall under RCP4.5 in an ensemble of climate model simulations from CMIP5. Their analysis shows that most regions experience decreases in snowfall during the fall and spring, but in some regions, increases in midwinter snowfall are found. In particular, the multi-model ensemble trends show increasing snowfall tendency over Northern Europe and Canada in winter.

2.2. Regional variability

Because of their current state of art coarse horizontal resolution, GCMs could difficulty describe the variation of snow conditions in areas with significant orography or complex land-sea distribution while it is expected to be be better simulated by high-resolution regional climate models (RCMs).

Raisanen and Eklund (2012) analysed changes in snow amount in northern Europe by means of 11 RCMs from the European Union 6th Framework Programme project ENSEMBLES (van der Linden and Mitchell, 2009), under the A1B emission scenario. They found that over the 21st century a large fraction of precipitation falls as rain, and episodes of snowmelt become more common. The amount of snow is generally reduced; however, the regional variability in this change is substantial within northern Europe. By the late 21st century, mildest areas (including Denmark, southern Sweden, southwestern Finland, western parts of the Baltic States and coastal Norway) are projected to lose the greater part of their snow. In some inland areas north of the Arctic Circle and over the Scandinavian mountains snowfall is expected to increase, although less than total precipitation. The largest increase, exceeding 20% in 2070–2099, is predicted in north western Sweden. Furthermore, about a half of the 11 simulations point towards an increase in SWE in northern Swedish Lapland in March.

Lopez-Moreno et al. (2011) simulated changes in intensity and frequency of heavy snowfall events in the Pyrenees using data from the HIRHAM RCM at the end of the 21st century under SRES B2 and A2 emission scenarios. They found that the projected changes in heavy snowfall depended largely on the elevation and the emission scenario considered. Despite the marked decrease in snow accumulation and snow cover duration, heavy snow events will constitute an ongoing risk in many areas. For the highest emission scenario (A2) heavy snowfall intensity and frequency is expected to decrease between 1000 and 1500 m a.s.l. Above 2000 m, the maximum intensity of single and multi-day events is expected to remain stationary, but may increase up to 30% at the higher elevation. For a more moderate emission scenario (B2) at 1500 m and above an upward trend in the maximum intensity and frequency of snowpack is expected, and the frequency of the heavy snowfall events may increase by 20–30% above 2000 m.

2.3. Main trends

As already said, on the basis of IPCC Working Group 1 conclusions (IPCC, 2013) a reduction of snow cover extent could be expected, but snow cover sensitivity to precipitation and temperature changes is highly related to topographic features such as elevation, aspect and terrain shading. In effect, several literature studies based both on GCMs and on RCMs (e.g. Krasting et al., 2013; Raisanen and Eklund, 2012; Lopez-Moreno et al., 2011) show that in some areas of the world (even in Europe), the snowfall is expected to increase. However, the predicted changes are characterised by a small-scale heterogeneous pattern, making the trend of snowfall difficult to predict. Moreover, a reduction of snowfall is not directly linked to a reduction of snow load. In fact, the rain falling on snow can be stored within the snow pack, resulting in an increase in the total snow load (Strasser, 2008).

A strategy for dealing with snow load risks in a changing climate encompassing monitoring and prediction is proposed by Strasser (2008). Modern RCMs are able to provide valuable information at high resolution, which can be used as input for impact models. In particular, climate simulations developed in the framework of the Coordinated Regional Downscaling Experiment initiative over Europe (EURO-CORDEX, Jacob et al., 2014) offer the state-of-art climate projections at the spatial resolution of about 11 km over the whole Europe. Projections at higher resolutions (up to 1 km) would be beneficial for more accurate local analyses and also in the view of developing operational warning systems (Strasser, 2008).

3. Snow load and the climate change

3.1. The European design standards

The publication of the European standards for structural design (the Eurocodes) by the European Committee for Standardization (CEN) in May 2007 marked a major milestone in the European standardisation for construction, since they introduced common technical rules for calculation of the mechanical and fire resistance, and the stability of constructions and construction products. The Structural Eurocodes deal with the design of buildings, infrastructures and civil engineering structures. They are already implemented within most of the CEN Members, as stated in the recent report of the European Commission on the implementation of the Eurocodes (Dimova et al., 2015).

One of the main concepts of the Eurocodes is the design working life (DWL), which is defined as the period for which the structure shall be used with anticipated maintenance but without major repair. The DWL of buildings and other common structures designed with the Eurocodes is 50 years, and the DWL of monumental buildings and bridges is envisaged as 100 years. In this way, structures designed in 2020 shall withstand climatic actions (snow, wind, thermal) and extreme events expected in the period 2020–2070 (as for buildings), and in the period 2020–2120 as regards bridges and monumental buildings, but, as already remarked, most of them are going to last much longer, so being very sensitive to climate change implications. Besides, it must be underlined that climatic data on which the current generation of the Eurocodes is based are mostly 10–15 years old, with some exceptions of recent updates of national data, e.g. the case of the new maps for climatic actions of the Czech Republic.

In 2016 CEN/TC 250 “Structural Eurocodes” started the works on the evolution of the Eurocodes under the Mandate M/515 (2012), and the second generation of the Eurocodes is expected by 2020. According to CEN/TC250 (2013) the standardisation works relevant to the climate change encompass:

- revision and update of EN 1991-1-3 on snow loads, EN 1991-1-4 on wind actions, and EN 1991-1-5 on thermal actions, preparation of background documents;
- conversion of ISO standards on actions from waves and currents, and on atmospheric icing to ISO-EN standards;
- preparing a document with the probabilistic basis for determination of partial safety factors and load combination factors, taking into account the variability and interdependence of climatic actions;
- technical report by Project Team (PT) on SC1.T5 analysing and providing guidance for potential amendments for Eurocodes with regard to structural design addressing relevant impacts of future climate change (general and material specific).

Development of new maps of climatic actions taking into account the implications of climate change is not planned under Mandate M/515.

The Final Report of the Project Team on SC1.T5 “Climate change” (2017) under Mandate M/515 provides advice to the Eurocode writers on how to refer to and implement possible effects from the known future changes in the climate of extremes in Europe. The Report refers to the most recent reports and scientific findings available, as well as to various socio-economic and other summary reports. The report concludes that the science of global climate changes is still not sufficiently developed to identify any substantial methods for quantification of extreme values (with given return periods) for neither temperature, wind, rain, snow nor any combination of these, to be valid for the forecast of changing climate in Europe. It recommends re-examining at regular intervals (no more than 10 years) the weather parameters significant for specification of characteristic values, by using conventional methods (extreme value analyses). However, as regards the bridges and other structures influenced by stresses from extreme temperatures, they should be designed for temperature amplitudes which may be justified using climate projections for the actual region. The report also recommends emphasizing and adjusting the inspections and maintenance schemes for structures approaching their expected life time.

3.2. Definition of the snow load in the European design standards

EN 1991-1-3 “Eurocode 1 – Actions on structures – Part 1–3: General actions – Snow loads” defines the characteristic value of the snow load on ground as the upper value of a random variable with annual probability of exceedance of 2%, so characterized by a “return period” of 50 years around.

In the current version of the Eurocodes, the definition of snow loads on structures is largely based upon the results of the European Snow Load Research Project (ESLRP) (1998) and, in particular, on the European Ground Snow Load Map elaborated within that research. This map was the first snow load map derived at European scale with a strong scientific basis (ESLRP, 1998) and its elaboration started from the analysis of the basic snow data collected across 18 European countries, which at that time were members of CEN. The produced snow load map is incorporated in Annex C to EN 1991-1-3 with the aim to help National Authorities to redraft their national snow maps and to establish harmonised procedures to produce such maps.

By applying extreme value statistics to these observations, the characteristic snow loads were derived corresponding to a given probability of exceedance, considering either exceptional snowfalls or no snowy winters. Basing on the characteristic ground snow loads at weather stations, the research allowed identifying ten major European climatic regions. The corresponding snow maps were elaborated by use of GIS software and, except for Norway and Iceland, where snow load is practically independent of altitude, for each climatic region suitable relationship between the ground snow load and the altitude was derived. It must be also stressed that in ESLRP (1998), exceptional snow loads were considered for the first time at European scale, using the best available scientific approach, which also contributed to dissemination of best practices.

Data series upon which the snow maps given in the Eurocodes are based, generally consist of long-term measurements, usually not less than 40–50 years; these series are suitable for the estimation of the characteristic ground snow load (50 years return period), but they are not enough extended over the time to reflect the effects of the climate change. At present it is therefore necessary to rely on data projections, resulting from appropriate Global or Regional Climate Models.

3.3. Evidence of implications of climate change

As already underlined, one of the conventional remarks about global warming is that as an obvious consequence of it, a reduction of snow load on the ground should be expected. In reality, it should be considered that the snow load on ground often depends on local orographic situations that can determine increases of the height of local snow falls, even in case when the average snow height is reduced considering larger areas. In addition to that, the capacity of the atmosphere to hold moisture increases with the temperature, and this phenomenon may lead to an increase of both, the snow density and the occurrence of extreme snowfalls in regions where temperatures still may happen to be below freezing level during precipitation events.

The above considerations are confirmed by catastrophic collapses of lightweight roof structures caused by snow that occurred in the last 15 years in Europe. Frühwald et al. (2007) consider that insufficient or lacking design with respect to environmental actions was the reason for 11% of the considered 127 failure cases of wooden roofs in Scandinavian countries. Strasser (2008) reports 15 roofs collapses in Germany due to snow load in the period January–February 2006, and describes the case of the roof of an exhibition hall in Katowice/Poland which collapsed after heavy snowfall in January 2006 burying 235 people of which 65 perished. Vasek (2006) reported about 200 collapses of timber and steel roofs in the first months of 2006 in the Czech Republic.

Geis et al. (2012) examined 1029 snow-induced building failure incidents in the United States between 1989 and 2009 and 91 international incidents between 1979 and 2009. The most commonly reported causes of snow-related failures were excessive snow (around 70% of total incidents), rain-on-snow (around 12% of total incidents), and building problems (around 9.0% of total incidents).

Holicky and Sykora (2009) investigated a total of 249 roof collapses mostly in highlands and lowlands in the Czech Republic, taking into account information provided by the Police and the Fire Rescue Service of the Czech Republic. Main observed causes of structural damage were subdivided into human errors in design, execution and use, and insufficient code provisions. By means of probabilistic reliability analysis, Holicky and Sykora (2009) proved that in several cases failure is due to underestimation of actual snow loads, especially when light-weight roof structures are used. In addition, the use of high-quality materials for heat insulation of roofs protected snow from melting and caused its accumulation (often non-uniform). In several cases a significant load due to the combination of snow and ice on roofs, not considered in design codes, was observed. In few cases snow load was also present on roofs with a great angle of pitch. The study points out that further refinement of the consideration of the snow loading in the design standards is needed (Holicky, 2007).

As discussed above, the recent failures of roofs in Europe, which were caused mainly by heavy snow load, naturally call for an estimation of the expected snow load on structures taking into account the implications of the climate change. Only after having such an estimate it will be possible to proceed with further refinement of the definition of the snow loading in the design standards.

4. Data and methods

4.1. Procedure for derivation of snow load from climate change projections

A procedure to derive snow load on ground from data of daily temperatures and precipitation was developed by Croce et al. (2016a) in the framework of a pilot study supported by JRC.

The procedure consisted of the following steps:

- analysis of observed data series to derive conditional probability functions linking snowfall and snow melting conditions with daily data of maximum and minimum temperatures (T_{max} and T_{min}) and precipitation;
- development of a predictive model to evaluate snow loads from water equivalent data and T_{max} and T_{min} using the previously defined functions of conditional probability;
- calibration and validation of the model predictions against observed data series.

In the work of Croce et al. (2016a) data from nine weather stations in Italy were used to seek the conditions of T_{max} and T_{min}, at which snow cover depth increases (in case of precipitation) or decreases (in case of melting or increasing density) and rainfalls are likely to occur. Seven different situations were identified in day n in comparison with day $n-1$:

1. total melting of snow cover present at day $n-1$;
2. partial melting of snow cover present at day $n-1$;
3. constant snow cover depth without precipitation;
4. rainfall in absence of snow cover at day $n-1$;
5. rainfall and total melting of the snow cover present at day $n-1$;
6. precipitation on snow cover with snow depth decreasing;
7. snowfall with increasing of snow cover.

Frequency histograms $Z(T_{min}, T_{max})$ were derived for each of the considered seven situations and converted to continuous surfaces by a mixture model composed by up to three two-dimensional Gaussian functions. Once derived the probability distribution functions for each of the seven situations, the conditional probability functions of snowfall and snow melting for given values of the daily temperatures T_{max} and T_{min} were evaluated. To calculate ground snow load q_{snow} from daily measurements of water equivalent data h_{prec} and T_{max} and T_{min}, a predictive model was developed, using Monte Carlo simulations based on the conditional probability functions. The methodology applied is described in full details in Croce et al. (2016b). The flowchart of the predictive model is illustrated in Fig. 1.

To evaluate the yearly maximum ground snow load q_{max}, Monte Carlo simulations have been repeated for each day of the year. For each year, the process has been iterated 10^4 times as the calibration with up to 10^6 iterations gave nearly indistinguishable results. From the distribution of each series of 10^4 values of q_{max} the median value $\bar{q}_{max}$ has been taken as the best estimate. The characteristic value of the ground snow load q_k associated to 2% annual probability of exceedance has been derived from the set of N yearly simulated maxima $\bar{q}_{max}$ considering Gumbel distribution.

4.2. Evaluation of the model's results against weather station observations

The proposed methodology has been initially tested against the historical data series comparing the outcomes of the method with those obtained elaborating measured data of snow cover depth by the European Snow Loads Research Project (ESLRP, 1998). To test the procedure, the long-time (more than 50 years) series of observed data available for the fifteen Italian weather stations shown in Fig. 2, were used. In the same figure the zonation of the Italian Mediterranean region is shown, according the definition given in the maps included in Annex C of EN 1991-1-3:2004 “Snow Loads”, where the ground snow load at sea level (to which different zones are referred) is increasing from zone n.1 to zone n.4.

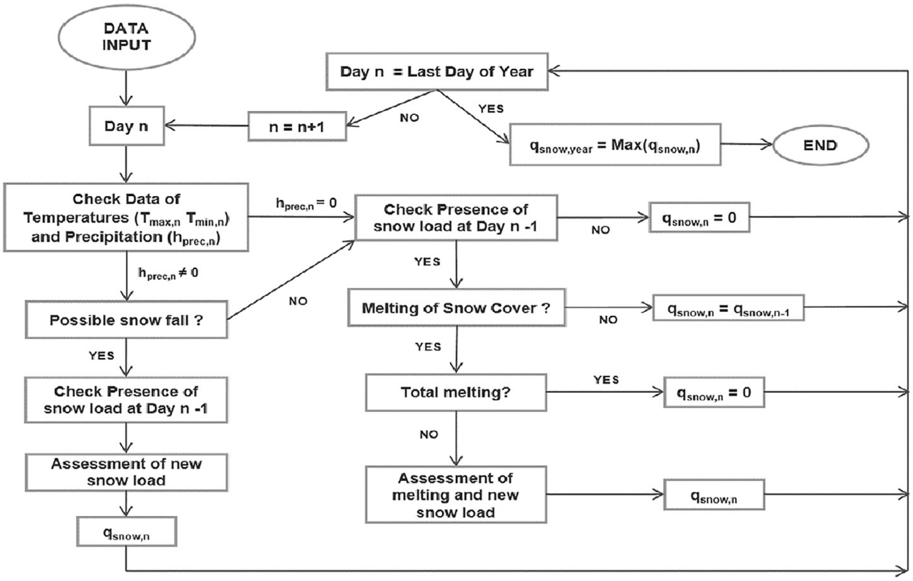
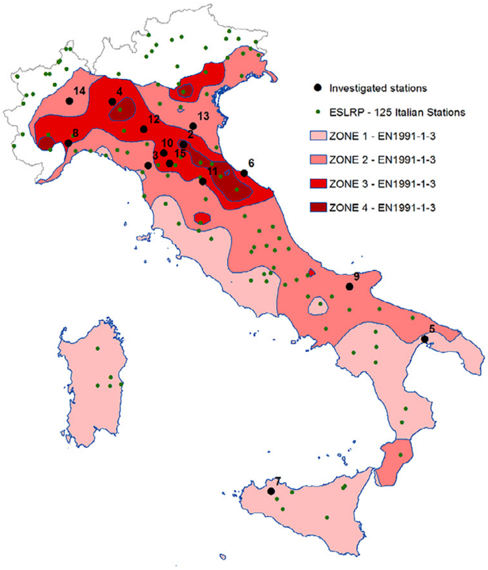


Fig. 1. Flowchart of the predictive model.



Country	N°	Station	LON [°]	LAT [°]	Altitude [m]	q_{kESLRP} [kN/m²]
IT	1	*Ascoli Piceno*	13,56	42,90	136	1,12
IT	2	*Bologna*	11,36	44,50	51	1,67
IT	3	*Castelnuovo Garfagnana*	10,43	44,12	276	1,14
IT	4	*Lodi*	9,51	45,32	80	1,19
IT	5	*Massafra*	17,13	40,58	116	0,54
IT	6	*Pesaro*	12,91	43,92	11	1,07
IT	7	*San Giuseppe Jato*	13,19	37,97	450	0,94
IT	8	*Spigno Monferrato*	8,36	44,55	476	2,40
IT	9	*San Severo*	15,39	41,68	87	0,74
IT	10	*Pavullo*	10,84	44,35	682	3,89
IT	11	*Camaldoli*	11,83	43,80	1111	4,15
IT	12	*Parma*	10,33	44,80	56	1,56
IT	13	*Ferrara*	11,63	44,83	15	1,00
IT	14	*Vercelli*	8,38	45,33	135	1,08
IT	15	*Porretta Terme*	10,99	44,15	349	2,73

Fig. 2. The fifteen Italian weather stations considered in the preliminary study and the zonation of the Italian Mediterranean region according EN 1991-1-3:2004.

The results obtained by the proposed Monte Carlo procedure for the investigated weather stations were then compared to those obtained by the European Snow Load Research Project (ESLRP). Examples of such comparisons for Bologna and Lodi weather stations are reported in the Gumbel probability papers in Fig. 3. In the diagrams, the blue lines, denoted as LSM (MC), are the least square method (LSM) fits for the ground snow load annual maxima obtained by the Monte Carlo simulations, while the green lines, denoted as LSM (ESLRP), represent the ESLRP results.

The differences in the characteristic values of ground snow loads obtained by the European Snow Load Research Project ($q_{k(ESLRP)}$) and by the Monte Carlo procedure ($q_{k(MC)}$) are due to the local disturbances on the measurements of solid precipitation caused by turbulence at the rain gauge mouth, as well as to snow transport phenomena caused by wind (Croce et al., 2016b), as described in details in the following paragraphs. Finally, it was possible to define a correction coefficient, k_{cor},

$$k_{cor} = \frac{q_{k(ESLRP)}}{q_{k(MC)}}, \tag{1}$$

taking into account these systematic effects, and allowing to derive the European Snow Load Research Project results from the results

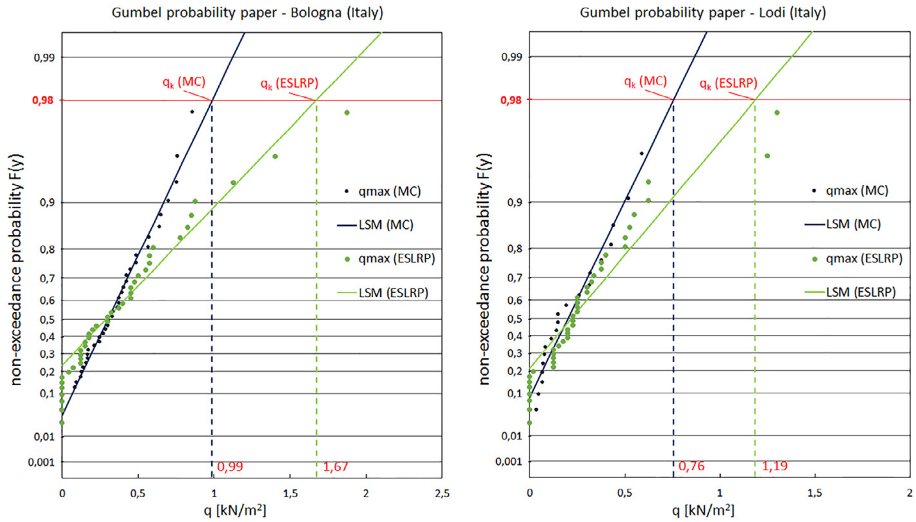


Fig. 3. Comparison of the results obtained by the proposed Monte Carlo procedure (MC) with the results of the European Snow Load Research Project (ESLRP) for the weather stations of Bologna and Lodi.

obtained by the proposed procedure.

Goodison et al. (1998) explained that wind field deformation in the neighbourhood of the gauge orifice could determine systematic errors in solid precipitation measurements, while Mellor (1965) discussed the increase of snow cover depth due to snow accumulation at the observation site due to wind induced transportation phenomena. All these effects justify the differences between the measured height of the snow cover and the one derived on the basis of the water equivalent obtained from gauge measurement (U.S. Department of Commerce National Oceanic and Atmospheric Administration, 2013; Lendvai et al., 2014).

Following the above considerations, Sevruk (1983) proposed the adoption of a suitable correction factor k, usually $k \geq 1.0$, to correct the water equivalent measurements at the rain gauge. Notwithstanding the fact that this factor depends on local conditions, such as the magnitude of the average wind speed during precipitation events, the wind protection of the gauge, etc., the data processing shows that it is possible to assume a nearly constant value for sites with similar conditions, thus confirming the conclusions found in previously recalled studies. This issue is discussed in detail in Croce et al. (2017).

The results in terms of characteristic values of ground snow loads (q_k) and of correction coefficients (k_{cor}) for the investigated stations are reported in Table 1. It must be underlined that k_{cor} is a characteristic of the considered site, and, therefore, it may be considered constant for sites characterized by similar climatological conditions.

4.3. Comparison of the extremes from observed gridded data and observed point data

Before arriving to the definition of future snow maps by applying the illustrated methodology to climate projections, a further

Table 1
Correction coefficients k_{cor} for the Italian weather stations considered in the study.

Country	N°	Station	Characteristic Ground Snow Load		$k_{cor} = \frac{q_{k(ESLRP)}}{q_{k(MC)}}$
			Tested Procedure (MC) $q_{k(MC)}$ [kN/m^2]	ESLRP $q_{k(ESLRP)}$ [kN/m^2]	
IT	1	Ascoli Piceno	0.68	1.12	1.65
IT	2	Bologna	0.99	1.67	1.69
IT	3	Castelnuovo Garfagnana	1.14	1.14	1.00
IT	4	Lodi	0.76	1.19	1.57
IT	5	Massafra	0.16	0.54	3.38
IT	6	Pesaro	0.67	1.07	1.60
IT	7	San Giuseppe Jato	0.50	0.94	1.88
IT	8	Spigno Monferrato	0.88	2.40	2.73
IT	9	San Severo	0.46	0.74	1.61
IT	10	Pavullo	1.45	3.89	2.68
IT	11	Camaldoli	2.37	4.15	1.75
IT	12	Parma	1.08	1.56	1.44
IT	13	Ferrara	0.72	1.00	1.39
IT	14	Vercelli	0.92	1.08	1.17
IT	15	Porretta Terme	1.87	2.73	1.46

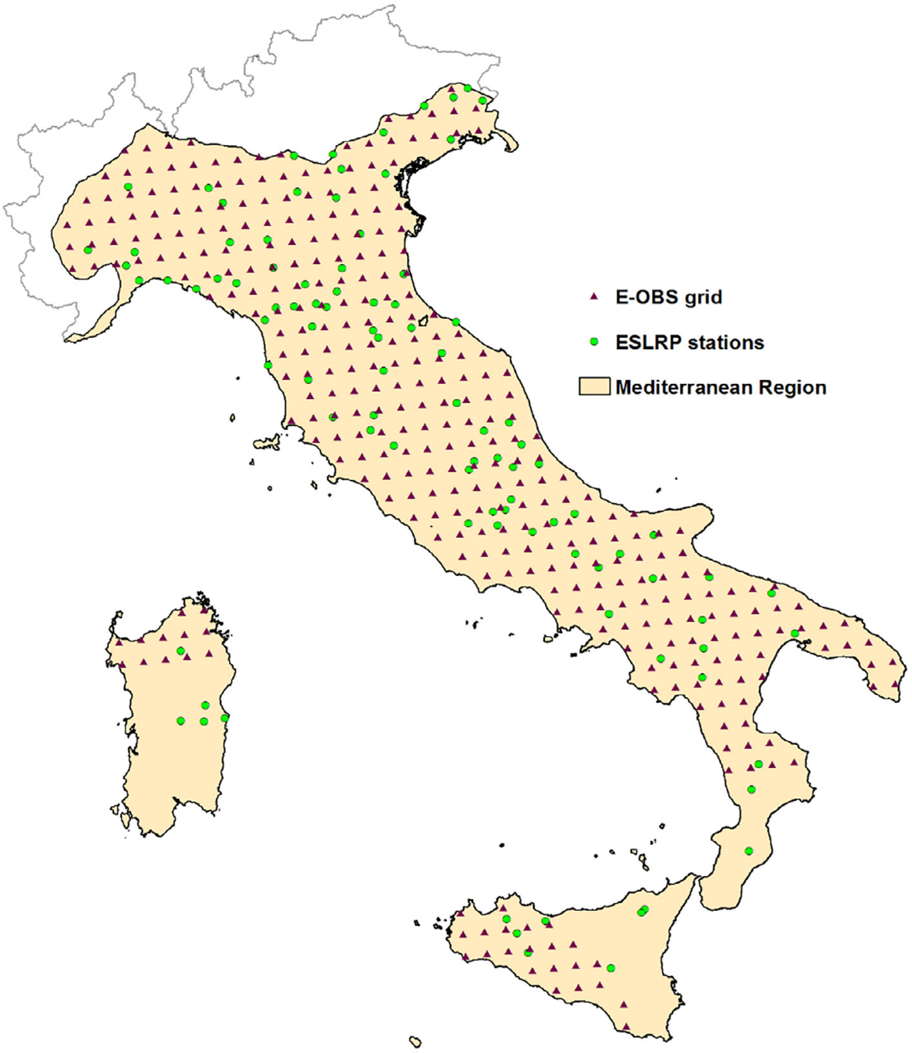


Fig. 4. E-OBS – grid cells and ESLRP weather stations for Italian Mediterranean region.

calibration is needed. Indeed, climate projections are provided for cells of about 12 × 12 km (EUR11 – 0.11° on a rotated grid) and are generally agreed to represent area averaged data, rather than point process data, especially for precipitation data. Therefore, the analysis of gridded precipitation data can lead to an underestimation of extremes. This issue has been analysed for the Italian Mediterranean region, as defined in the Annex C to EN 1991-1-3:2004, by comparing characteristic ground snow loads derived using grid cell data provided by E-OBS dataset (Haylock et al., 2008) with those derived in the ESLRP as point estimates, as shown in Fig. 4.

The results confirm that, for the Italian Mediterranean Region, the characteristic values computed by the analysis of the gridded data (E-OBS dataset for the period 1951–1990) are typically lower than the values obtained by point-data. In fact, indicating with q_{kESLRP} the snow load estimated using ESLRP data and with q_{kEOBS} the snow load estimated using E-OBS gridded data, the Δq_k*–altitude* diagrams presented in Fig. 5a, and the q_{kESLRP}/q_{kEOBS} *–altitude* diagrams presented in Fig. 5b clearly show that Δq_k and q_{kESLRP}/q_{kEOBS} both increase with the site altitude.

Starting from these results, the relationship between the difference of characteristic values (Δq_k) and altitude has been estimated for each of the four climatic zones defined by EN 1991-1-3 for the Italian Mediterranean Region. The results are presented in Figs. 6a–6d, respectively.

As recommended by EN 1991-1-3:2004, only site's altitudes lower than 1500 m are considered, as for higher altitudes influence of local conditions becomes predominant.

Once having estimated these relationships, it is possible not only to draw the snow load map on the ground obtained by the analysis of gridded data, but also to correct it in order to take into account also local orography. This correction is particularly relevant because it allows an immediate comparison between estimates of characteristic ground snow loads obtained from projected data, with current code's prescriptions (Croce et al., 2016b).

In Fig. 7 the Italian Mediterranean Region snow load maps at the effective site altitude derived from EN 1991-1-3:2004 and from

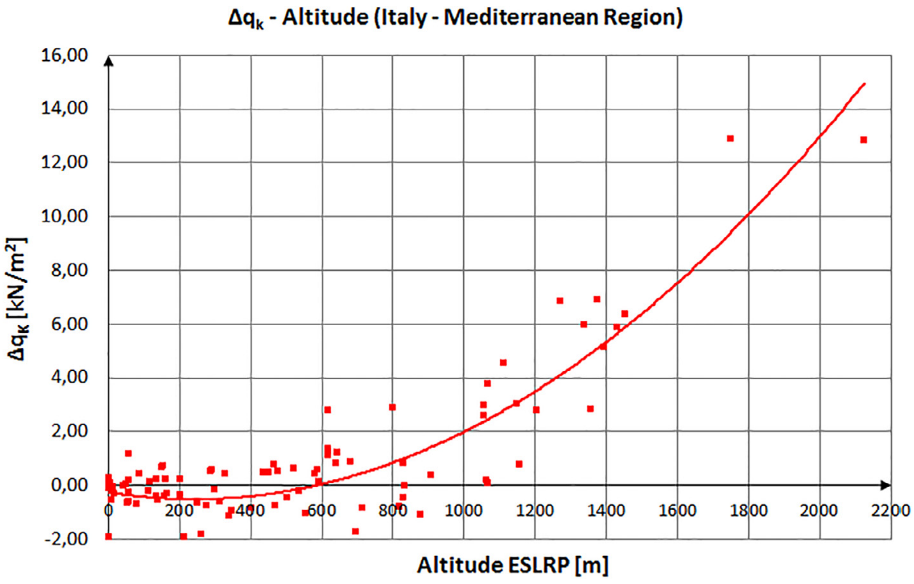


Fig. 5a. Δq_k – altitude plot (Italy Mediterranean Region).

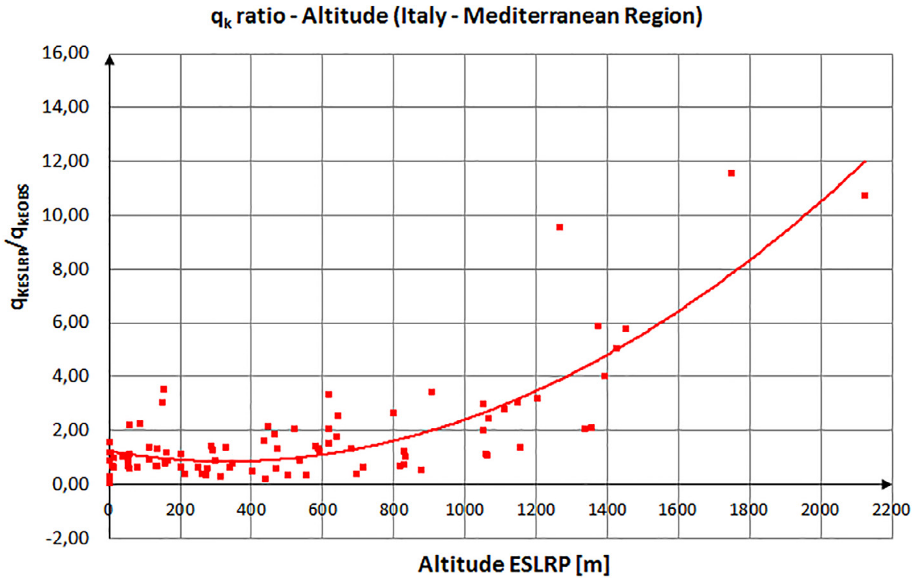


Fig. 5b. q_{kESLRP}/q_{kEOBS} – altitude plot (Italy Mediterranean Region).

the E-OBS dataset are illustrated, together with their difference before applying the altitude correction laws to $q_{k,E\text{-}OBS}$ results. In Fig. 8, the same comparison is shown referring to $q_{k,E\text{-}OBS}$ values, corrected by the above mentioned altitude relationships. As already observed, sites whose altitude is above 1500 m are excluded from the analysis, because extremely influenced by local parameters.

5. Selected results

The pilot study is being expanded now to take into account a larger number of weather stations spread all over Italy, in order to assess the snow load based on the predicted data of daily maximum and minimum temperature and precipitation in terms of water equivalent data, provided by the EURO-CORDEX initiative and to arrive to refined and updated snow map on the ground for Italy. The on-going activities of the pilot study on implication of climate change on snow load map for structural design incorporate the following tasks:

- Comparing results obtained by observed point-source data (weather stations) and by observed gridded data provided in the E-OBS dataset (Haylock et al., 2008), in order to set up a refined methodology to analyse gridded data (like those provided by climate

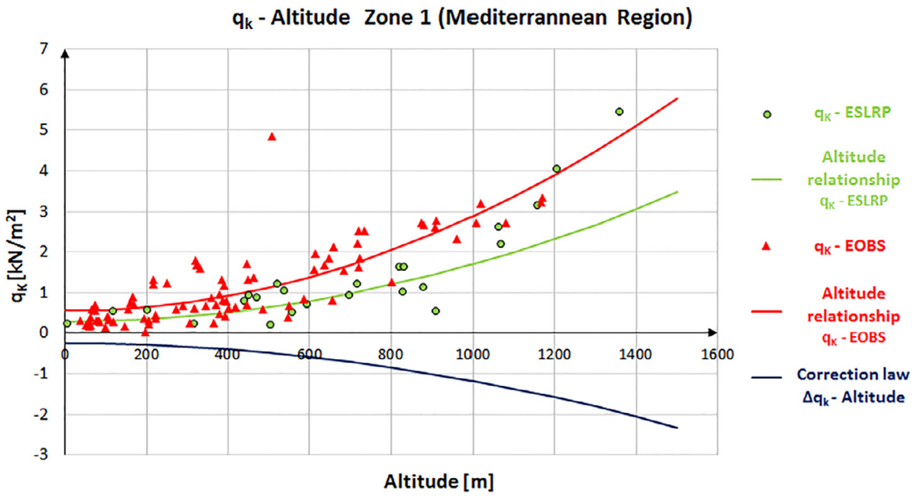


Fig. 6a. q_k – altitude plots for Italy Mediterranean Region – Zone 1.

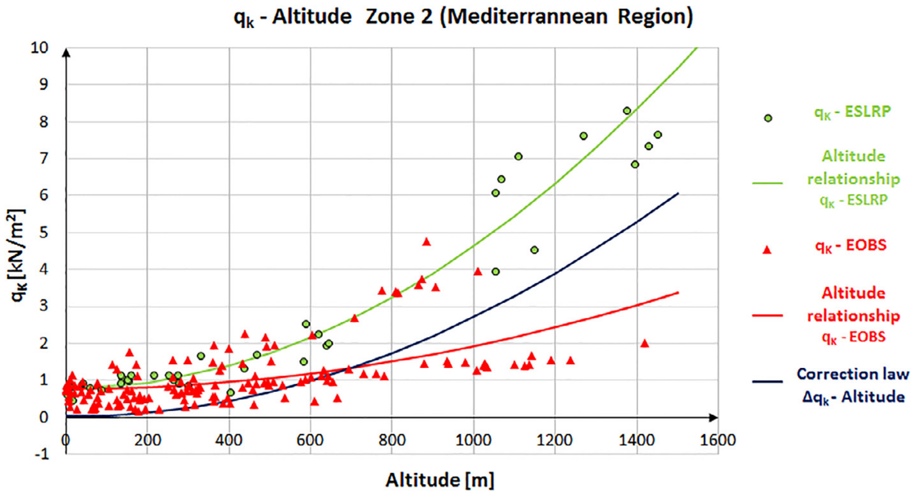


Fig. 6b. q_k – altitude plots for Italy Mediterranean Region – Zone 2.

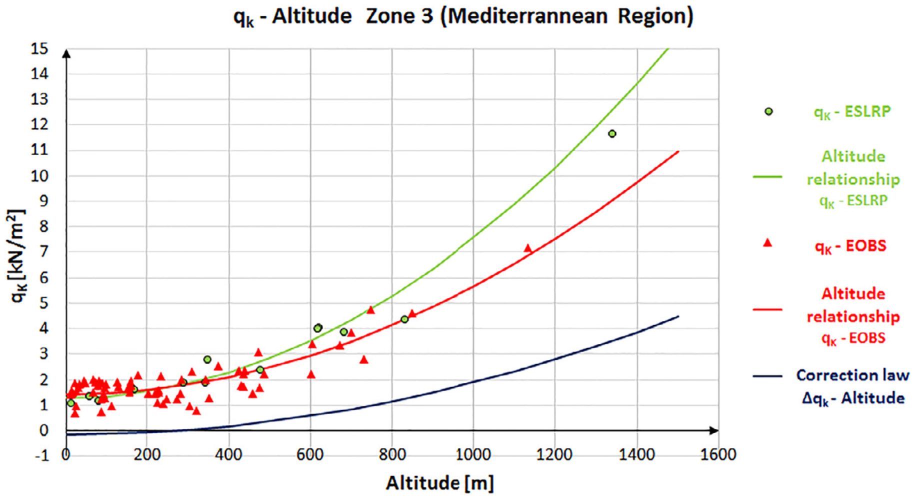


Fig. 6c. q_k – altitude plots for Italy Mediterranean Region – Zone 3.

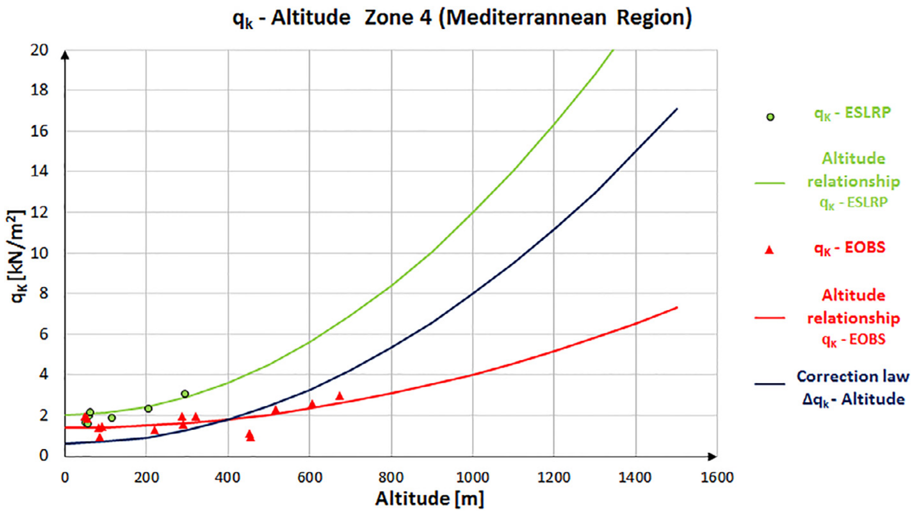


Fig. 6d. q_k – altitude plots for different zones Italy Mediterranean Region – Zone 4.

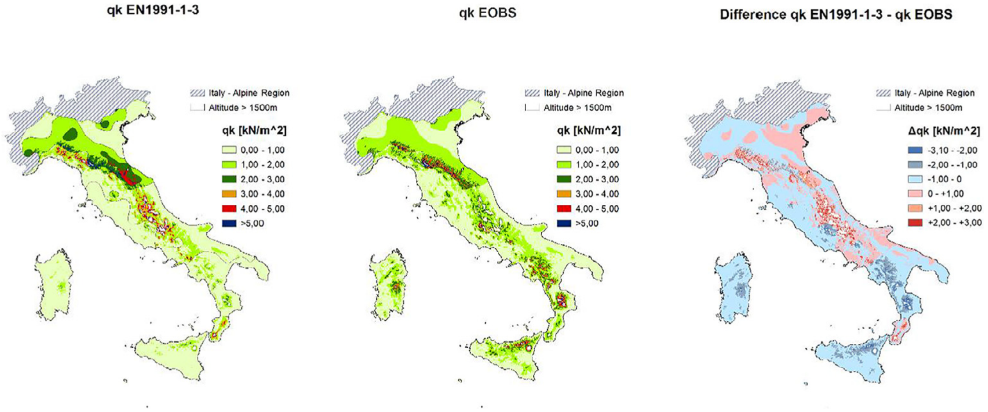


Fig. 7. Comparison of snow loads at effective site altitude in Italy – Mediterranean Region (before application of altitude correction laws to $q_{k,E\text{-}OBS}$).

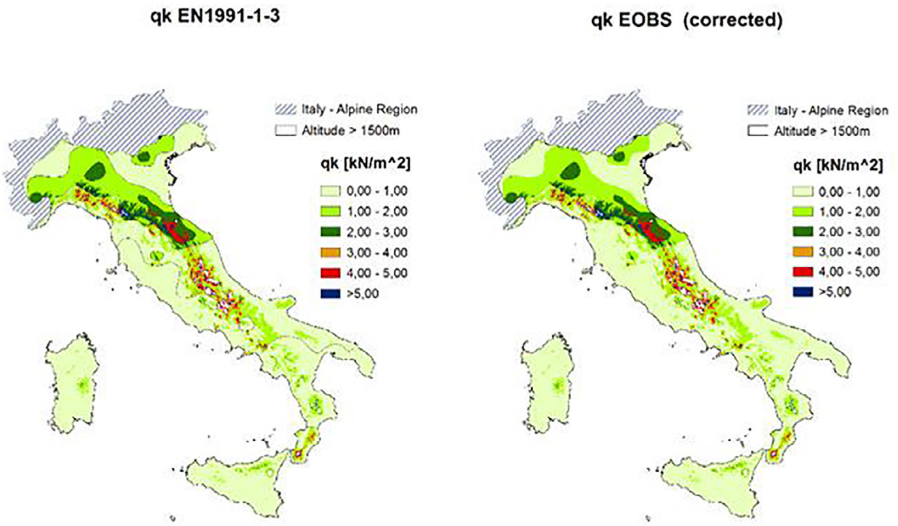


Fig. 8. Comparison of snow loads at effective site altitude in Italy – Mediterranean Region (after application of altitude correction laws to $q_{k,E\text{-}OBS}$).

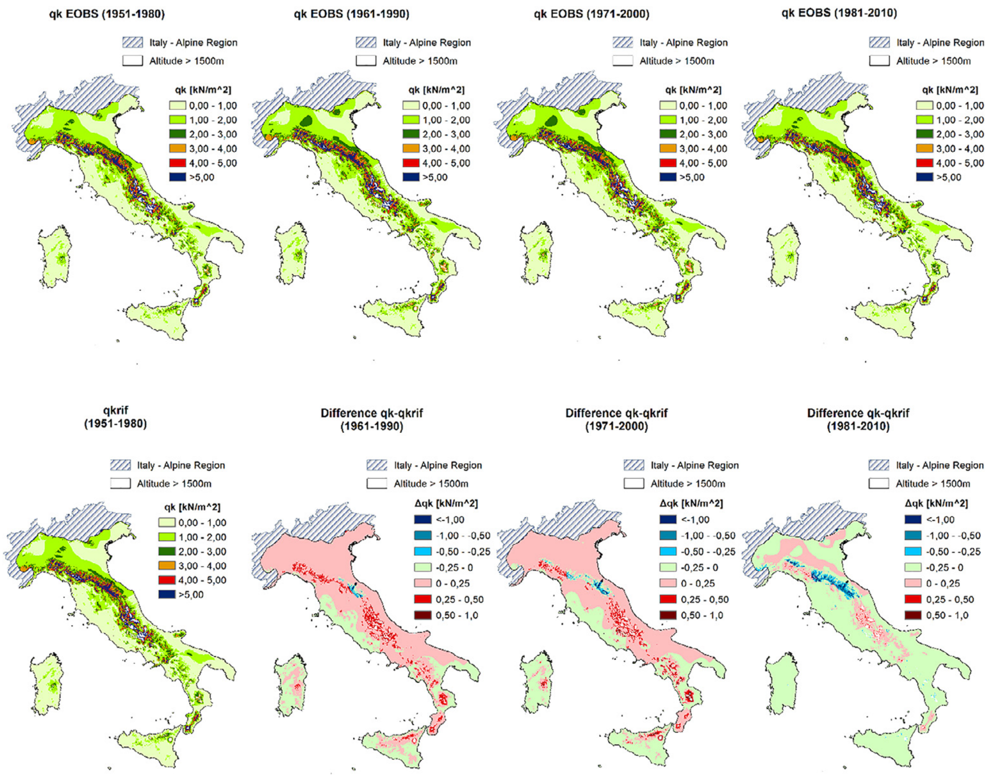


Fig. 9. Comparison of snow load obtained using different periods of E-OBS data in terms of ($q_{k,E\text{-}OBS}$-$q_{k,rif}$).

models) able to take into account the effects of area average on the extreme values;

- Analysing observed gridded data for Italy (E-OBS dataset for the period 1951–2010) in subsequent time periods of thirty years, shifted ten years by ten years, to estimate actual trend of variation of characteristic ground snow loads, if any;
- Extending the analysis to different global climate models (GCMs), regional climate models (RCMs) in different representative concentration pathways (RCPs) scenarios, to take into account the variability of climate projections;
- Extending the coverage of the elaboration in order to study other European countries.

Some of the results obtained until now are illustrated in the following paragraphs.

5.1. Actual trend of variation from the analysis of E-OBS dataset

Outcomes of elaboration of E-OBS gridded data ($q_{k,E\text{-}OBS}$) obtained according the methodology described in the previous section have been analysed and discussed for Italian regions. In particular, the outcomes derived considering several consecutive time periods of thirty years, shifted ten years by ten years (1961–1990, 1971–2000 and 1981–2010), have been compared with those obtained for the reference period 1951–1980 ($q_{k,rif}$) in order to estimate both, the actual trend of variation of characteristic ground snow loads and its dependence on the time period (Croce et al., 2016b).

For each subsequent time period analysed, the results are illustrated in Fig. 9 in terms of differences ($q_{k,E\text{-}OBS}$-$q_{k,rif}$) and in Fig. 10, in terms of percentage difference ($q_{k,E\text{-}OBS}$-$q_{k,rif}$)/$q_{k,rif}$.

When examining these maps, it appears clearly that trends are different depending on the region. However in several northern and eastern Italian regions snow loads are generally increasing, while in western and southern Italian regions they tend to decrease.

Further study will encompass analysis of projected data, provided by different climate models, in order to derive maps of future trends of characteristic ground snow loads.

5.2. Preliminary results from the analysis of climate projections

The implementation of the procedure illustrated in the previous Section 4 has been extended to the analysis of different climate models and scenarios, again for the fifteen Italian weather stations already listed (see Table 1 and Fig. 2). Available projected data of EURO-CORDEX initiative (Jacob et al., 2014; Kotlarsky et al., 2014), for the nearest grid cell to each weather station, have been used considering different regional climate models (RCMs), DMI-HIRHAM5, including bias correction, as suggested by Dosio and Paruolo (2011), CNRM-ALADIN5.3 and KNMI-RACMO22E, driven by global climate models (GCMs) under two representative concentration

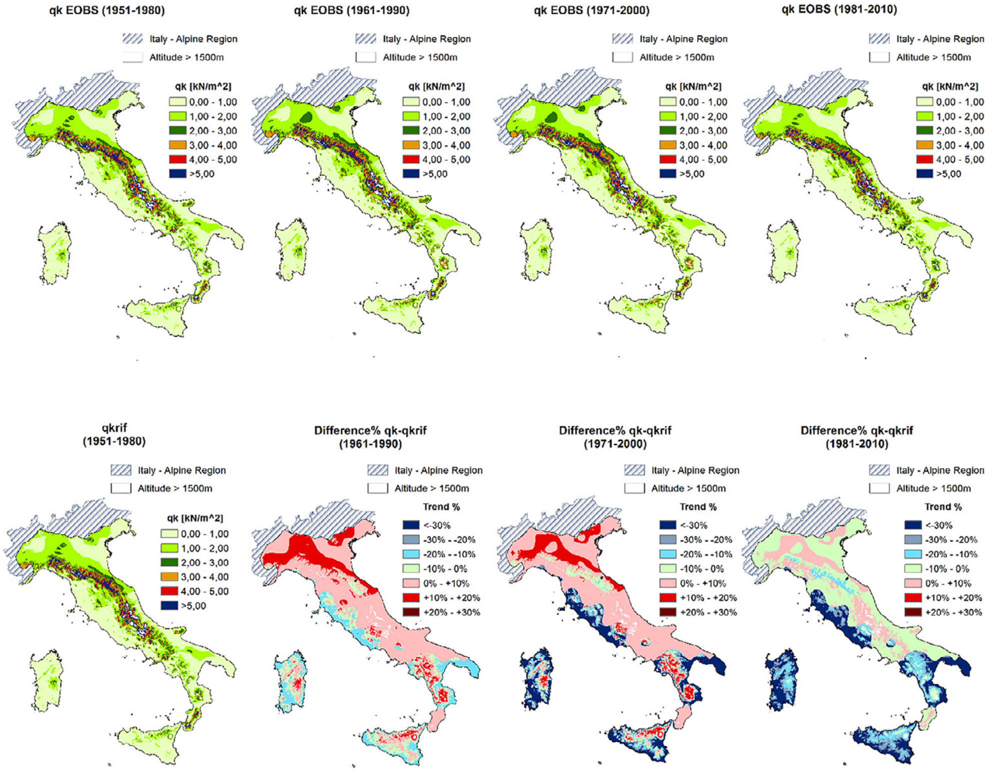


Fig. 10. Comparison of snow load obtained using different periods of E-OBS data in terms of $(q_{k,E\text{-}OBS}\text{-}q_{k,rif})/q_{k,rif}$.

pathways, RCP4.5 and RCP8.5, as illustrated in Table 2.

The analysis has been carried out for subsequent time periods of forty years. The characteristic ground snow loads obtained for each GCM in seven of the fifteen considered weather stations considering RCP8.5 and RCP4.5 scenarios, $q_{kRCP8.5}$ and $q_{kRCP4.5}$, respectively, and their ratio are reported in the diagrams in Figs. 11a–11g.

The results presented on the left side diagrams of Figs. 11a–11g show that in some cases significant local increases can be detected for some time intervals, even if the characteristic values of ground snow load in the investigated weather stations are characterized by a generally decreasing trend for almost all analysed climate models and scenarios.

The decreasing trend is distinct for all models and scenarios in Ascoli Piceno, Lodi and Pesaro, Nevertheless, it is interesting to notice that the ratio $q_{kRCP8.5}/q_{kRCP4.5}$, represented on the right side plots of Figs. 11a–11g, varies significantly over time depending on the considered climate model. In many cases the ratio $q_{kRCP8.5}/q_{kRCP4.5}$ is larger than one and sometimes even larger than two, like the predicted, for example, by DMI-HIRHAM5 in Bologna or by KNMI-RACMO22E in Pesaro, thus clearly demonstrating that increases of GHG emissions do not necessarily imply a decrease of snow loads, in spite of common sense expectations.

Furthermore, by increasing the number of weather stations considered in the study, combining the results obtained in each of them with different climate models and using an approach similar to that presented in the previous paragraph for the observed E-OBS data, it will be possible not only to evaluate percentage changes in the characteristic ground snow loads, but also to derive snow load

Table 2
Climate models and scenarios considered.

RCM	Resolution	Driving GCM	Driving experiment/scenario	Period
DMI-HIRHAM5	EUR11 (0.11°/12.5 km)	EC-EARTH	Historical (bias correction)	1981–2005
			RCP4.5 (bias correction)	2006–2100
			Historical	1981–2005
			RCP4.5	2006–2100
			RCP8.5	2006–2100
CNRM-ALADIN5.3	EUR11 (0.11°/12.5 km)	CNRM-CM5	Historical	1981–2005
			RCP4.5	2006–2100
			RCP8.5	2006–2100
KNMI-RACMO22E	EUR11 (0.11°/12.5 km)	HadGEM2-ES	Historical	1981–2005
			RCP4.5	2006–2090
			RCP8.5	2006–2100

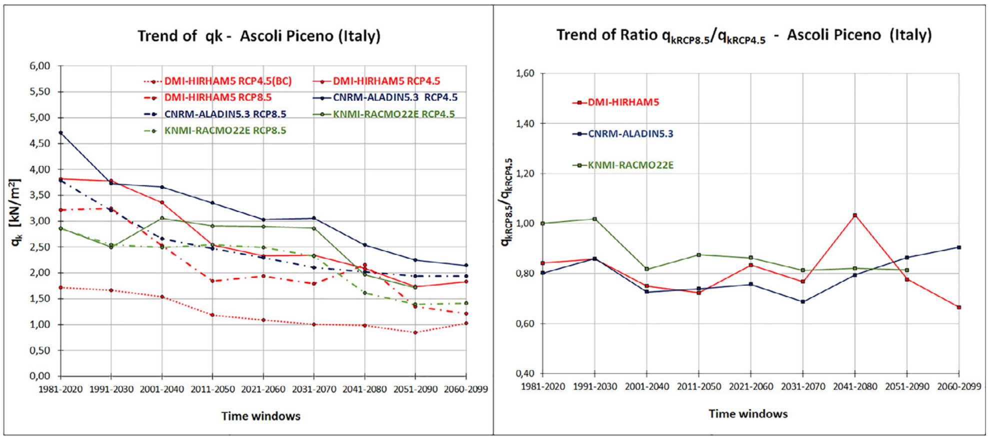


Fig. 11a. Trends of q_k [kN/m^2] for different RCMs and RCPs for Ascoli Piceno weather station.

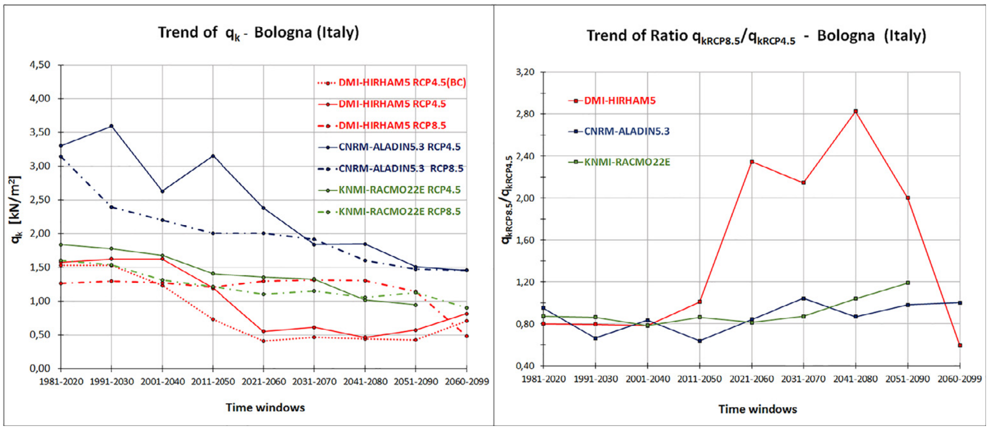


Fig. 11b. Trends of q_k [kN/m^2] for different RCMs and RCPs for Bologna weather station.

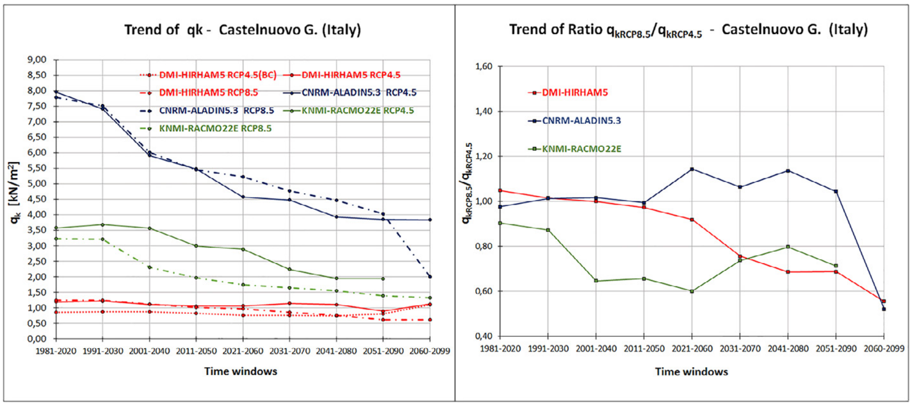


Fig. 11c. Trends of q_k [kN/m^2] for different RCMs and RCPs for Castelnuovo Garfagnana weather station.

maps for subsequent time windows.

Finally, the proposed methodology should allow to achieve a comprehensive overview of the impact of climate change on extreme snow loads according different emission scenarios, thus providing guidance for potential amendments of the current version of snow load maps in technical standards.

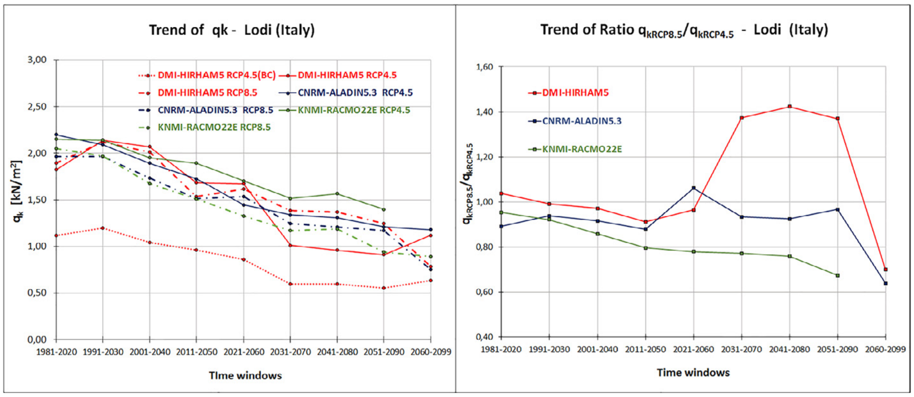


Fig. 11d. Trends of q_k [kN/m^2] for different RCMs and RCPs for Lodi weather station.

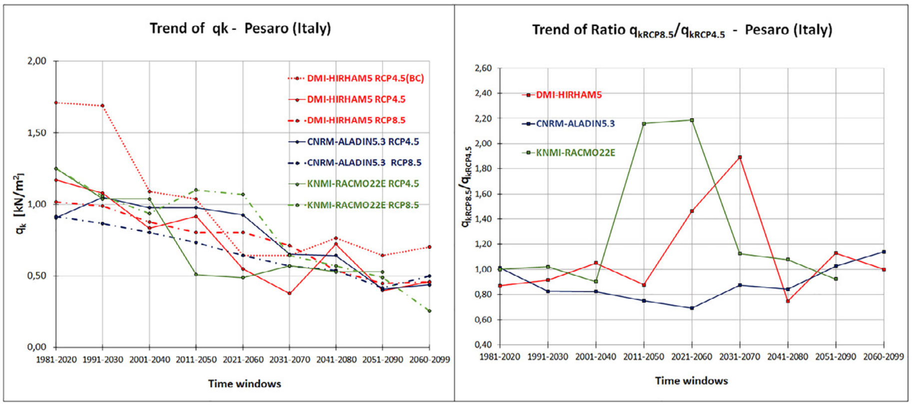


Fig. 11e. Trends of q_k [kN/m^2] for different RCMs and RCPs for Pesaro weather station.

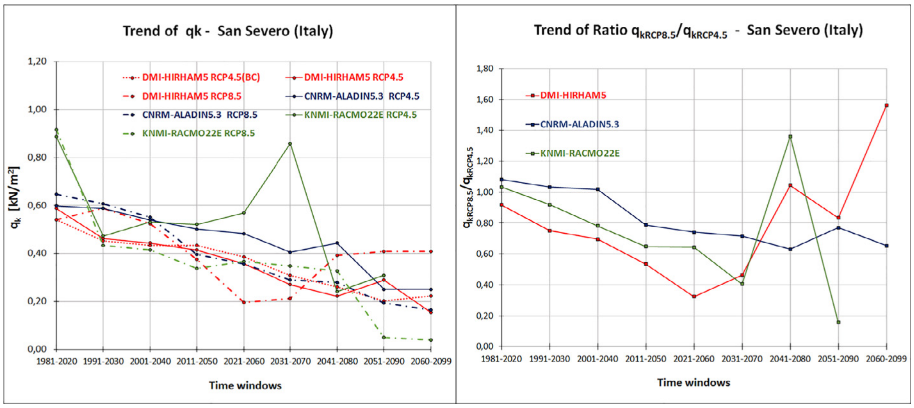


Fig. 11f. Trends of q_k [kN/m^2] for different RCMs and RCPs for San Severo weather station.

6. Conclusions

Recent failures of roofs in Europe, which were mainly caused by considerable snow loads, naturally call to estimate the snow load on structures taking into account the implications of the climate change. Such an estimate is a prerequisite to proceed with further refinement of the definition of the snow loading in the design standards.

A European project on snow load map shall be started as soon as possible, in order to update the existing snow load maps in Annex C of EN 1991-1-3 and to help National Authorities to redraft their National snow load maps. The established in the project procedure for definition of snow load from climate change projections will allow producing new National snow maps in a harmonised way by using the best available knowledge, and thus will contribute to the reduction of the inconsistencies at border between neighbouring

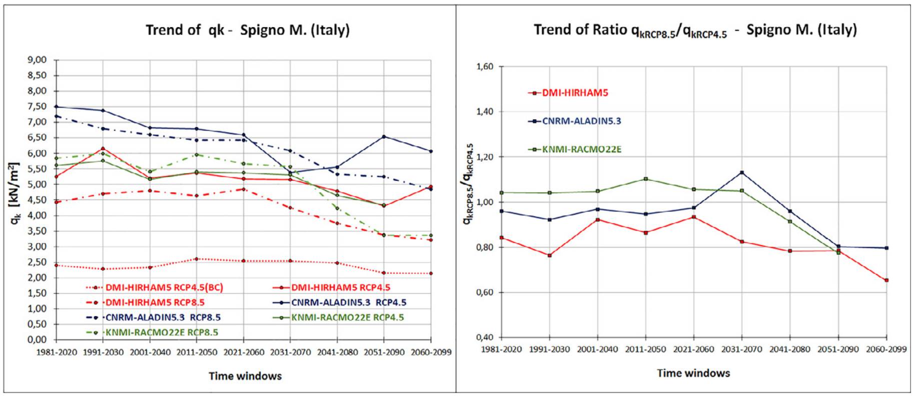


Fig. 11g. Trends of q_k [kN/m^2] for different RCMs and RCPs for Spigno Monferrato weather station.

countries. The estimate of the expected snow loading will not only enhance the structural reliability, but will also help to couple the thermal efficiency retrofitting of the roofs with their safety by providing basis for better definition of the resulting snow load on the roofs themselves.

The procedure developed in the pilot study on snow load provides a strong scientific basis for creation of snow load maps taking into account the climate change implications, since it allows to estimate characteristic ground snow load on the basis of daily data for the minimum and maximum temperature and precipitation, which are typically available as outputs of climate change projections for all possible scenarios.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.crm.2018.03.001.

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