High-resolution hail monitoring in an alpine fruit-growing region

Emanuele Eccel[1], Fabio Zottele[2]*

Abstract: *The hail monitoring network in Trentino has been uninterruptedly run since 1974. It consists of 271 impactometric measurement sites, arranged according to a 2-km regular grid. Recorded data allow an estimation of the kinetic energy of the hailstorm. To investigate the acknowledged correlation between electric activity of thunderstorm cells and the amount of hail fallen during hail, in this study consideration is given to two aspects: i) the relationship between ground lightning measures and hail indices; ii) some spatial and altitudinal features of hail climatology. Hail data were aggregated in one hail season per year, from May to September. The correlation of hail indices with elevation is clear, yet it cannot fully explain the inhomogeneous distribution in some areas, where local features significantly affect hail occurrence. The statistical link between annual hail values and the total measured number of lightning flashes is also good; for some indices it is highly significant (p<0.01) after the removal of respective time trends. This allows to propose the use of the number of lightning flashes over a hail season as a good indicator of hail fallen in the same period.*
Keywords: *hailstorms, Trentino, lightning, spatial interpolation.*

Riassunto: *La rete di monitoraggio grandine in Trentino è operativa continuativamente dal 1974. Essa consiste in 271 siti di rilievo impattometrici disposti secondo una griglia di lato approssimativo 2 km. Il rilievo consente di stimare l'energia cinetica della grandinata. Per investigare la nota correlazione tra l'attività elettrica delle celle temporalesche e la quantità di grandine caduta durante gli eventi grandigeni, in questo studio sono esaminati due aspetti: i) la relazione tra misure di fulmini al suolo e gli indici di grandine; ii) alcune caratteristiche spaziali ed altitudinali della climatologia della grandine. I dati di grandine sono stati aggregati su base annuale (in un'unica stagione, da maggio a settembre). La correlazione degli indici di grandine con la quota è chiara; essa però non può spiegare da sola la distribuzione non omogenea in alcune aree, dove effetti locali influenzano significativamente l'occorrenza della grandine. Anche la relazione trovata tra i valori annuali di grandine e il totale di fulmini rilevati è buona per la maggior parte degli indici, per alcuni di essi altamente significativa (p<0.01) dopo aver rimosso i rispettivi trend temporali. Ciò consente di proporre la misura dei fulmini registrati, a livello stagionale, come un buon indicatore della grandine caduta nella medesima stagione.*
Parole chiave: *grandinate, Trentino, fulmini, spazializzazione.*

1. INTRODUCTION

There is a general agreement on the observed increase in climatic extremes, like floods, heat waves and hailstorms in the last decades, in Europe as well as in other regions of the world (Munich Re., 1999; Brunetti *et al.*, 2002; Coleman, 2003; Meehl *et al.*, 2007). This is one likely consequence of the ongoing climate change, although a major role may have been played by an increase in vulnerability in the demographic and urban settlement structure in many parts of the world. In the Alpine area storms, among the meteorological adversities encompassing all kinds of intense activity connected to severe weather conditions, represent the second major cause of economic damages and the first cause of insured damages related to natural hazards. Hail is responsible for extreme, though localized, damages, becoming an outstanding source of economic loss even for goods other than crops. Historical hailstorms highlight the relevant potential risk in Europe; in 1984 an ominous event in Munich, Germany, caused around 1.5 billion € damage, of which about 750 million € was insured (SwissRe, 2006).

In Italy, the northern regions are particularly affected by hail (Berz and Siebert, 2000). In the Alpine region of Trentino, hail alone represents by far the most important meteorological adversity to its valuable crop production. The harm is not only due to the loss of the harvest itself, in case of very severe events, but also to the economical depreciation of the crop, when the damage is not so severe to destroy the harvest. In this region, agricultural damages, almost entirely referred to apple and grapevine, ranged, in the

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period 2003 – 2008, from 3.6% (2004) to 16.6% (2008) of the insured capital, with an average of 10.0% (A. Berti, pers. comm.). An analysis of the hail climatology by Eccel *et al.* (2012) for Trentino shows that in the last decades this phenomenon has remained mostly unchanged in its average features (like the number of episodes or the hit surface), whereas its more extreme aspects have undergone a remarkable increase.

Hail measurement is a time-consuming activity. The simple recording of the hail event in terms of "present weather" – currently done by all the Global Telecommunication System (GTS) stations around the world – results in too coarse a resolution for a proper sampling of the effects of deep-convection. Due to its large variability in space, its short duration (minutes to a score of minutes) and the extremely local scale of the phenomenon ("hail streaks" have dimensions of a few km by a few hundreds of meters), a thorough hail monitoring over a territory requires a high-resolution network, typically made up of hundreds of hailpads. Hence, dense hail networks in the Alpine region (not differently from other areas in the world) are scarce and they are far from covering all the potentially affected territory. Even when they exist, their coverage focuses in general on the most sensitive areas, namely cropland, neglecting the others. For example, networks are operated in the Alpine regions of Styria, Trentino, Friuli and Slovenia, as well as in Spain and in France, just to mention European countries.

The increasing use of advanced radar techniques (particularly, the dual polarisation facilities allow the identification of hail in cumulonimbus cells – Sugier and Tabary, 2006), the development of hailpad networks has apparently eased off, owing to complexity and cost issues for its maintenance, and interest in hail measurement has turned to alternative methods. Probably also because of such restrictions, the number of climate studies based on impactometric data is relatively small (Dessens and Fraile, 1994; Sànchez *et al.*, 1996; Eccel and Ferrari, 1997; Vinet, 2001; Fraile *et al.*, 2003; Giaiotti *et al.*, 2003, Berthet *et al.*, 2010; Eccel *et al.*, 2012; Manzato, 2012).

This is not the place to review the state of the art of the investigation on radar skill in hail detection and measurement; the datasets created by this technique have, of course, an extremely high resolution in both time and space, but also large inhomogeneities. Another easily measurable physical quantity of thunderstorm cells is their electric activity. There have been a number of studies on this subject, mostly focussing on the physics of the phenomena (like one very recent from Emersic *et al.*, 2011), generally investigating the relationships between lightning and hail at the atmospheric cell level. In the USA, Changnon (1992) reported that lightning activity is strongly associated with hail occurrence, even if the areas of most severe hail damage do not coincide with those of most intense flash records. In Switzerland, Hohl and Schiesser (2001) found an excellent relation (r=0.95) of hail kinetic energy with negative cloud-to-ground lightning flashes (the majority of them), but not for the positive ones, and suggest the use of this indicator as nowcasting predictor for intense hailstorms. The same scale of investigation (cloud cell) yielded different results in southern France (Soula *et al.*, 2004): the highest number of lightning flashes was associated to no-hail-bearing thunderstorms, even if the authors state that often positive flashes were observed in such cases, depressing their negative proportion.

Far from trying to add a contribution to the physical comprehension of the phenomenon, the present work aims at checking a very simple technique - cloud-to-ground lightning survey - for thunderstorm detection. The statistical correlation with hail activity makes it suitable for climate purposes, rather than for operational nowcasting applications. The discussion is enriched by the analysis of some spatial interpolation of basic hail quantities, allowed by the high-resolution quantitative measurements from the local hailpad network.

2. STUDY AREA, DATA, AND METHODOLOGY

The geographic and climatic context

Trentino (central-eastern Italian Alps – Fig. 1) is a system of major valleys, among which the longest is 'Val d'Adige'. The cropland is mostly devoted to apple and grapevine growing. In general, climate in Trentino can be ascribed to the humid, temperate, oceanic type, particularly in the pre-alpine areas, more open towards the Po Plain and the Adriatic See. Some areas show features of transition to a more continental-alpine climate, cooler and often drier, more typical of the inner mountain valleys. Albeit precipitation amounts are mostly distributed over two maxima (autumn and spring), in some mountain areas rainfall peaks in summer (Eccel and Saibanti, 2007). The higher and inner areas receive an important supply of rainfall from summer thunderstorms, thanks to orography-induced mechanisms of convective instability triggering. For this reason, like in many other

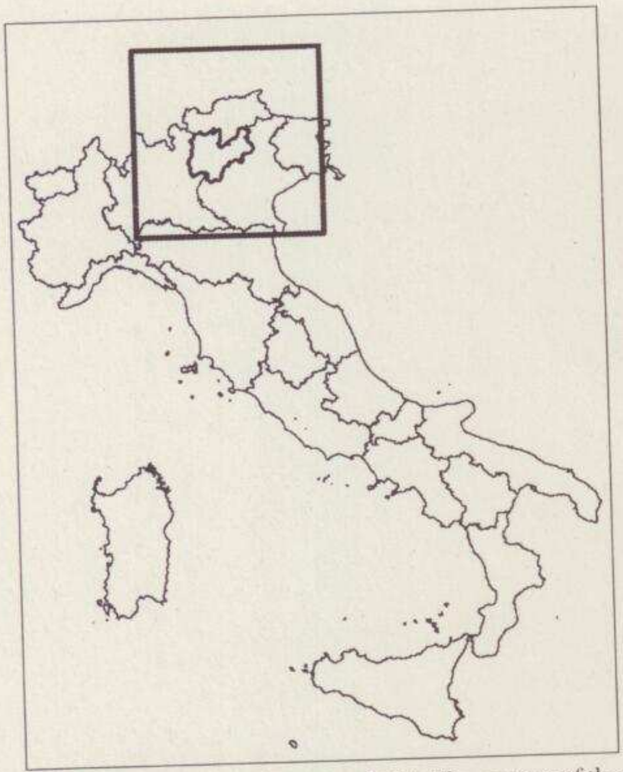

Fig. 1 - The study area (Trentino, Italy). The contour of the province is in bold.
Fig. 1 - L'area di studio (Trentino). Il contorno della provincia è in grassetto.

regions of the Alps, hailstorms are more frequent and more intense in elevated areas.

The hail monitoring network

The measurements are performed by "Schleusener"-type, 15 cm x 15 cm polystyrene hailpads, covered with a 0.135 mm thick aluminium sheet (Schleusener and Jennings, 1960). The pad is mounted horizontally on a bearing fixed at 1 m from the ground. Each hailstone leaves a dent on the aluminium sheet, whose depth (and hence its horizontal dimension) is proportional to its kinetic energy. After inking, the dents are counted and measured.

The hail monitoring network in Trentino, established in 1974 and since then continuously operated, covers the main agricultural areas, with roughly square grids of 2 km's side, as regular as possible. It ranges from an elevation of 70 m to 1260 m a.s.l., with 271 sites altogether (Fig. 2 – the mapped hail indices are discussed in section 3). The cropland is mostly devoted to apple and grapevine growing. Only minor changes in the network (expiry of sites and addition of new ones) occurred over the years. The measurement season starts on 1st May and ends on 30th September, only exceptionally

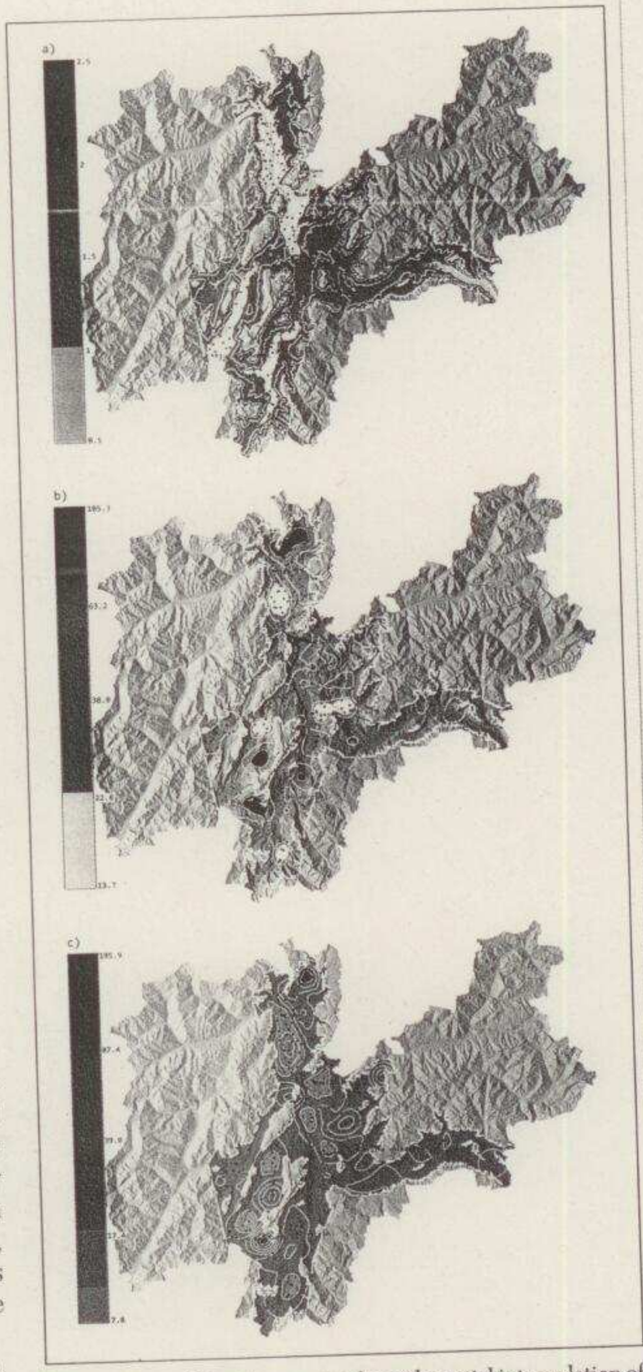

Fig. 2 - Map of Trentino orography with spatial interpolation of three hail indices. a) mean nr. of hail occurrences per hailpad. b) kinetic energy, average over all reports (m.en_rep, see Appendix) (J m^{-2} - log scale). c) mean annual cumulated kinetic energy (m_tot_en, see Appendix) (J m^{-2} - log scale). Spatial interpolation carried out with kriging with external drift (height), 40-m resolution.
Fig. 2 - Mappa del Trentino con la spazializzazione di tre indici di grandine: a) numero medio di occorrenze di grandine per grelimetro. b) energia cinetica media (J m^{-2} – scala logaritmica). c) media annua dell'energia cinetica cumulata (J m^{-2} – scala logaritmica). Spazializzazione realizzata con kriging con forzante esterna (altitudine), risoluzione 40 m.

earlier or later, if important events occur before or after this standard season.
Data are gathered after each hailstorm. Each hailpad reading yields one hail "report", which is the survey unit of the hail network. One "event" is made up from all the reports recorded on the same date. Of course, there are a few cases of events occurring around midnight that are ascribed to two different days, according to the time of occurrence. The opposite case is when two separate events occur at different times in the same day, and are counted as one. Given the small number of cases, and considering that the first case (overestimation of events) acts in the opposite way of the second (underestimation of events), the error was neglected, also because in this work hail data were aggregated over the seasons.
Volunteer observers substitute each hailpad after it is impacted and fill in a report with ancillary information on the hailstorm. Hailpads are sent to the agency that operates the network (GIS Unit of E. Mach Foundation – FEM - http://meteo.iasma.it/meteo/), where they are inked and interpreted (hailpad reading protocol and calibration in Montefinale *et al.*, 1982). Each dent is assigned to one diameter class (there are seven), each identifying a specific kinetic energy. The total energy comes from the product of the number of hailstones in each class by the specific kinetic energy for the class itself.
Only the vertical component of kinetic energy was considered. From dent counting and measurement, given the proportionality of both hailstone diameter (d) and its terminal velocity to the dent, the kinetic energy Ek of each hailstone is (details in Eccel *et al.*, 2012)

$$Ek \propto d^4$$

Lightning measurements
As lightning is an indicator of thunderstorm, its measurement was used to compare hail indicators to the total thunderstorm activity in the period 1996-2009. Lightning flashes were retrieved from the Italian lightning monitoring network (CESI – SIRF: http://sirf.cesi.it). The network is formed by 16 sensors positioned on the Italian territory. Ten more sensors are used as well, located beyond the Italian border, to enhance the network sensitivity. Each sensor is connected by a dedicated line to CESI's operational centre in Milan.
All the sensors use IMPACT technology (Global Atmospherics Inc.), and make use of broadband electromagnetic antennas, with GPS synchronization, Time Of Arrival (TOA) and Magnetic Direction Finding (MDF) calculation methods. They detect the electromagnetic field emitted by each cloud-ground lightning, providing raw data (electromagnetic field vector, time, etc.). Each sensor is able to discriminate a lightning signal from the background noise. Being the electro-magnetic field disturbance very quickly and clearly detected by the network, the time resolution is very high (fractions of second). The space resolution allows to locate the falling site of a lightning stroke in the range of about 500 m from the exact point. In general, both time and space resolution of the SIRF (Sistema Italiano Rilevamento Fulmini) network are higher than the corresponding resolutions of the hail network.
The data were aggregated over the territory of Trentino by CESI-SIRF and summed yearly for the period May – September, the same as for the hail monitoring. Both the whole administrative region (province of Trento) and the area restricted to the impactometric network domain were considered for the spatial aggregation of lightning data.

Data processing
Measuring and collecting hail data with the detail of each single class of hailstone diameter provide a huge amount of information. In this work, data processing for hail climatology was rather trivial: values were processed as single reports (for example, to extract maxima), and reports were aggregated by event (each identified by one single day) and by season (one hail season per year). Extreme values were investigated as both absolute maxima and 90th percentiles. An explanation of all hail indices is given in the Appendix. The analysis of the link of hail indices with the electric activity consisted of the assessment of the correlation between each couple of seasonally-aggregated hail index vs. lightning flash count.
The spatial interpolation of three basic hail indices (nr. of hail days, mean kinetic energy, accumulated kinetic energy) was carried out by kriging with external drift (elevation), implemented in the open-source R code, library "gstat" (R Developing Core Team, 2011) and graphically represented by the open-source GIS GRASS (GRASS Development Team, 2010). The resolution of the spatial interpolation was 40 m. In order to avoid extrapolation of data in non-monitored areas, the analysis was restricted to the area of Trentino that falls within the limits of the hail network and lies below 1200 m a.s.l. (Fig. 2)

3. RESULTS AND DISCUSSION

Correlation with lightning totals
From the visual assessment of the time series of the total number of lightning flashes per year (NLF)

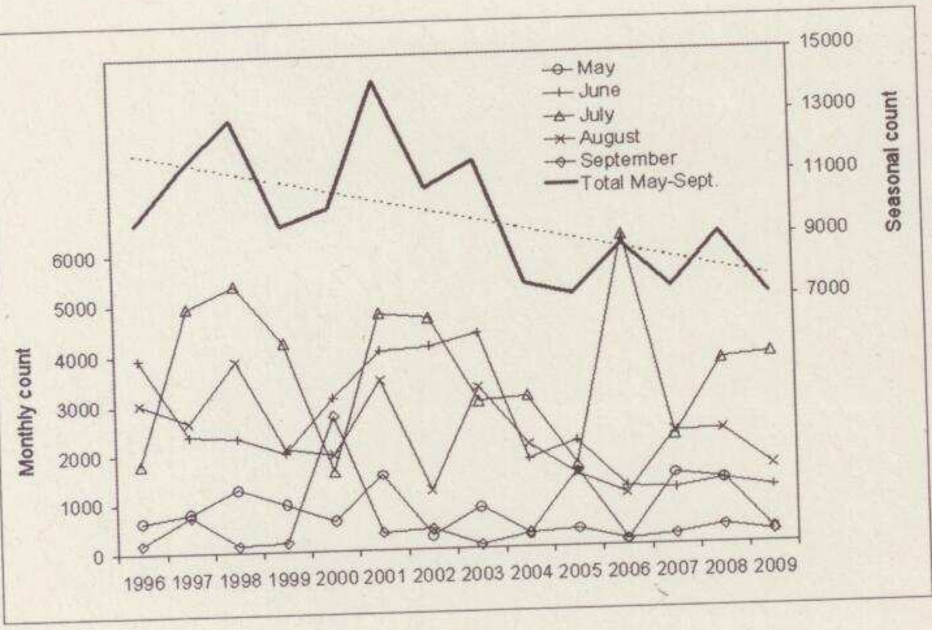

Fig. 3 - Number of lightning strokes (NLS) for the whole Trentino area, in the five months of the hail-monitoring season. Thin lines: monthly counts. Thick line (and dashed linear interpolation line): total seasonal count. Data obtained from CESI-SIRF.

Fig. 3 - Numero di fulmini (NLS) per l'intera area trentina, nei cinque mesi della stagione di monitoraggio grandine. Linee sottili: conteggio mensile. Linea spessa (e linea tratteggiata interpolante): conteggio stagionale totale. Dati rilevati da CESI-SIRF.

over the area covered by the hailpad network in Trentino, there has been a general decrease in the period 1996-2009 (Fig. 3), significant with $p<0.05$. More precisely, it can be seen that every hail season in the series from 2004 to 2009 had lower values than any others in the 1996-2003 period. This trend results from the sum of single months: a significantly ($p<0.05$) decrease can be found for the month of June, but not for the other months. Similar results were obtained when considering the whole region (Trentino).

The correlation between hail indices and NLF can be calculated using both raw or time-detrended series to discard the effects of independent time trends for both phenomena. The coefficients of determination R^2 are reported in Tab.1 and the scatterplots of the annual series in Fig. 4 and Fig. 5. It could be argued that, while seasonal NLF decreases over the period, many hail indices, namely those that express kinetic energy –especially of intense episodes - are increasing (Eccel *et al.*, 2012), suggesting an opposite time trend for hail in the same observational period. Because the two phenomena are aspects of the same atmospheric

Hail index	whole region		hail network area	
	raw	detrended	raw	detrended
cum_hit_surf_dens	NS	0.362	0.305	0.384
hail_days	NS	NS	NS	NS
m_surf_ev	0.349	0.349	0.287	NS
cum_en_dens	NS	**0.454**	NS	0.339
m.en_rep	NS	0.349	NS	NS
sd_en	NS	0.372	NS	NS
m_ev_en	NS	NS	NS	NS
m_tot_en	0.288	**0.490**	NS	NS
max_en_rep	NS	0.405	NS	NS
extr_en_rep	NS	0.303	NS	NS
tot_en_max_ev	0.363	**0.475**	NS	NS
tot_en_extr_ev	NS	0.303	NS	NS

Tab. 1 - Coefficients of determination R2 of hail indices and total number of cloud–to-ground lightning flashes (NLF) over whole Trentino region and over the impactometric network area. Only figures with $p<0.05$ are reported. In bold if $p<0.01$. NS: non-significant. See Appendix for acronyms.

Tab. 1 - Coefficienti di determinazione R2 tra indici di grandine e numero totale di fulmini nube – suolo (NLF) sull'intero territorio trentino e sulla sola area coperta dalla rete impattometrica. Sono riportati solo i casi con $p<0.05$. In grassetto se $p<0.01$. NS: non significativo. Consultare "Appendix" per i dettagli sugli acronimi.

agent – the cumulonimbus activity –a negative link between them is hardly explainable. For this reason, to discard the effects of independent mechanisms that lead to either decrease or increase of single variables, the pairs of hail indices – NLF were detrended, to isolate and highlight the statistical relationship.

Indeed, there is a general increase in the correlation (and significance) between hail indices and NLF after detrending, with some pairs significant at $p<0.01$ (panels b), f), and i) in Fig. 4); the latter represent: accumulated energy density (cum_en_dens), mean total energy (m_tot_en), and total kinetic energy for the maximum annual event (tot_en_max_ev). While the link between total amount of lightning in a hail season and the corresponding accumulated hail measures is quite natural, it is interesting to comment the high statistical link between the most severe seasonal event(s) (also the 90th quantile event – tot_en_extr_ev, Fig. 4d - shows a significant statistical link with NLF) and total season lightning. This result is a consequence of the strong link between the most severe event and the total kinetic energy accumulated over the whole season: the most important event is on average responsible for – roughly – the half of the total kinetic energy of the hail season (Eccel and Ferrari, 1997). The number of events (hail_days, Fig. 4e), and consequently their mean energy (m.en_rep), are poorly "explained" by the NLF alone, if this is considered a "predictor". None of these two

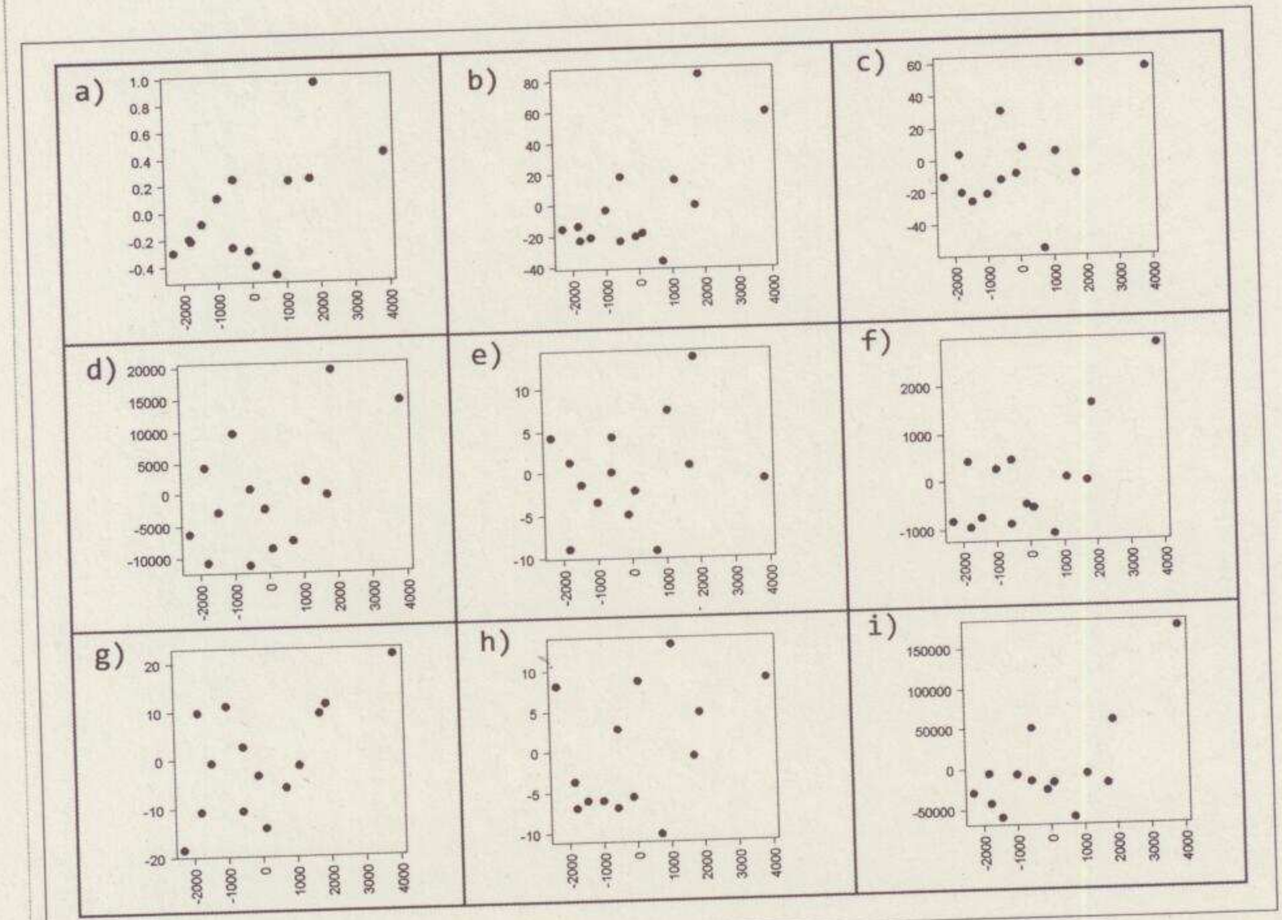

Fig. 4 - Detrended scatterplots of anomalies of hail indices vs. NLS (seasonal number of strokes) over Trentino. Period: 1996-2009. a) cum_hit_surf_dens b) cum_en_dens c) extr_en_rep d) extr_tot_en_ev e) hail_days f) m_tot_en g) m_surf_ev h) m_ev_en i) tot_en_max_ev (see Appendix for key). See also Tab.1 for numeric values of the coefficients of determination and their significance.

Fig. 4 - Grafici a dispersione delle serie detrendizzate delle anomalie degli indici di grandine vs. NLS (numero stagionale di fulmini) sul Trentino. Periodo: 1996-2009. a) cum_hit_surf_dens b) cum_en_dens c) extr_en_rep d) extr_tot_en_ev e) hail_days f) m_tot_en g) m_surf_ev h) m_ev_en i) tot_en_max_ev (consultare "Appendix" per il significato). Vedere anche la Tab.1 per i valori numerici dei coefficienti di determinazione e la loro significatività.

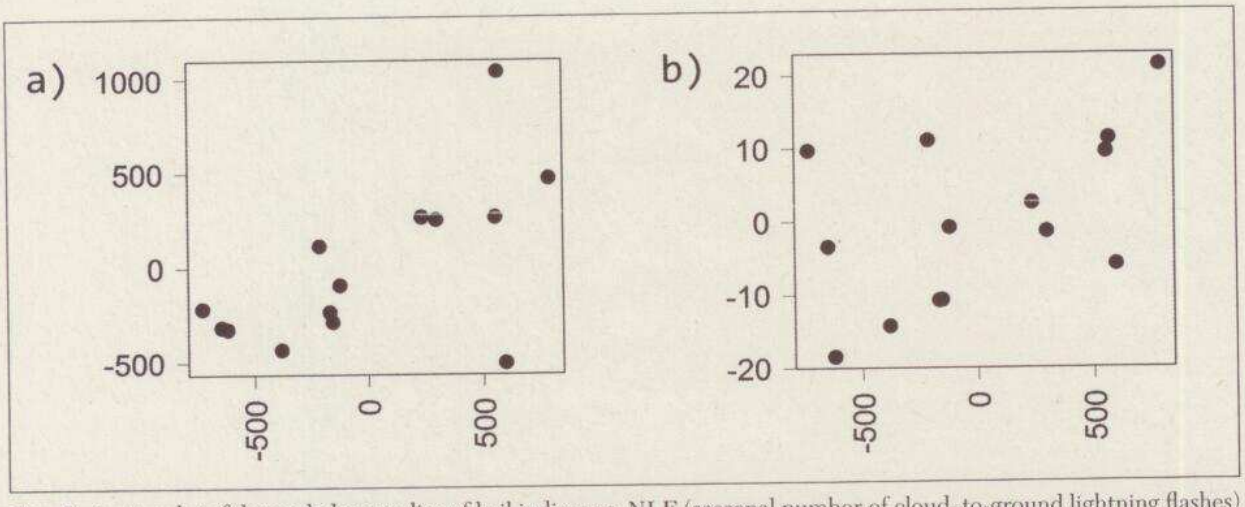

Fig. 5 - Scatterplot of detrended anomalies of hail indices vs. NLF (seasonal number of cloud–to-ground lightning flashes) over the area covered by the impactometric network in Trentino. Period: 1996-2009. a) cum_hit_surf_dens. b) cum_en_dens (see Appendix for key). See also Tab.1 for numeric values of the coefficients of determination and their significance.
Fig. 5 - Grafici a dispersione delle serie detrendizzate delle anomalie degli indici di grandine vs. NLF (numero stagionale di fulmini nube - suolo) sull'area coperta dalla rete impattometrica trentina. Periodo: 1996-2009. a) cum_hit_surf_dens b) cum_en_dens (consultare "Appendix" per il significato). Vedere anche la Tab.1 per i valori numerici dei coefficienti di determinazione e la loro significatività.

indices refer directly to the total kinetic energy for season, which is the most important index, being strongly correlated to the real hail damage to crops and goods.
The coefficients (not shown) are always positive: the more lightning, the more hail. Indeed, if one considers the period 1996-2009, there is no hail index that shows a significant time trend at $p<0.05$; some of them (the mean surface for event, m_surf_ev, or the maximum total energy for event, tot_en_max_ev) display a negative time trend, even if with a very low significance (data not shown).
When the spatial domain of lightning measurement is restricted to the area actually covered by the hail monitoring network, and not to the whole administrative region (province of Trento), the correlation between lightning activity and hail decreases. This issue deserves some attention. In general, in the case of "restricted area", detrending does not increment correlations in such an evident way as it does when the whole region is considered for lightning measurement. However, the two most important hail indices (the accumulated hit surface density, cum_hit_surf_dens, and the total kinetic energy density, cum_en_dens) do show good links with the electric activity in the hail season (table 1). An explanation for the displacement of hail with respect to lightning would require a thunderstorm-cell-scale analysis. Changnon (1992) reported, for the USA, a general space and time gap between maximum flash rate and hail. There are important differences when dealing with single events. In the same work by Changnon, it is stated that the number of flashes was well related to hail severity, but also that 75% of the lightning centres were not associated with hail. However, in this study, as already stated, the issue has not bee tackled at the event scale. Further comments on the difference in the most frequent locations of lightning and hail are given at the end of next section.
It can be concluded that both lightning and hailstorm activities may show their own time trends, but, when the latter are removed from the series, the correlation between the two phenomena become clearer. This was not an unexpected result, keeping in mind that both lightning and hail are measurable effects of thunderstorm cell activity. The good correlation between some hail indices and lightning activities suggests its use as a proxy for hail incidence in an area, at least from a climatic point of view.

Spatial and altitudinal patterns of hail

Spatial interpolation of hail data (Fig. 2) was restricted to a narrow region that extends from the hail network domain to cover the main agricultural valleys of Trentino. It is a limited area, nevertheless it comprises the majority of the grapevine and apple production farms in the region. This analysis encompassed all data recorded for the period 1974-2008.
With the exception of mean kinetic energy, all indices

(number of events, accumulated kinetic energy, maximum recorded energy) exhibit a significant positive correlation with altitude (Tab. 2). However, interesting geographic patterns appear when the data are reported on the map (Fig. 2). The mean annual number of occurrences at the most hail-prone site is 3.6 times higher than at the less-prone one (Fig. 2a). In general, elevated sites are more prone to hail occurrence, but the relationship is uneven, with the highest frequency occurring in the central-eastern part, not equalled by other mountain areas. More interesting hints come from the analysis of kinetic energy maps (Fig. 2b). Mean energy (per report) shows a polycentric pattern, with single spots exceeding the general average. This index expresses the mean kinetic energy, irrespective of the average number of events occurring at the site. More useful is the map of accumulated kinetic energy (Fig. 2c), which is the index most strongly linked to the crop damage. The spatial pattern is more even: mean energy peaks are smoothed, due to the co-occurrence of a lower number of episodes recorded in such areas. However, even in a relatively small region like the agricultural area of Trentino, there is an evident heterogeneity, not always explainable by altitude only. For example, in the 'Val di Non' there is a clear gradient in hail severity moving from SW to NE, namely from the right to the left of the Noce river valley. The other two "hot spots" (the 'Val di Gresta' and the area between the 'Val di Cembra' and the 'Altipiano di Piné') are both influenced by the presence of single high-elevation hailpad sites (see Fig. 2c).

Another aspect can add insight to the issue of hail displacement with respect to lightning. Fig. 6 shows the total number of lightning flashes in the period 1996-2010 over the area corresponding to the hail network coverage, at the resolution of 1 x 1 km². The survey period only partially overlaps with that of Fig. 2, but some features can be recognized from both sources, namely the maximum in the "central" area, south and north of Trento (compare Fig. 6 with Fig. 2b – kinetic energy, m.en_rep). There is no evidence of a general lightning increase with elevation. Even if based on qualitative inference, this observation is consistent with the higher correlation between hail activity and lightning measurement, when the monitoring domain is extended to a larger, regional area.

4. CONCLUSIONS

This work highlighted a possible application of the processing of quantitative, impactometric high-resolution hail data collected in Trentino. The spatial analysis allowed to highlight geographic hail distribution. Even though a general increase of hail with elevation is evident (both as event occurrences and energetic intensity), altitude is not the only driver of hail, even in a small region like Trentino, where different areas show different degrees of exposure to hailstorms.

The other issue considered, the climatic link with lightning flashes recorded over the area (NLF), yielded a significant relationship between hail and electric activity of thunderstorm cells. In this case, too, there were differences between hail indices, each of them showing different statistical links with lightning. A good correlation was found between total accumulated energy (and its density, i.e., related to the covered area) and NLF. Being these indices the most useful in assessing the hail impact over an area, and being NLF easily measurable by the CESI-SIRF facility, we deem that NLF can be considered a good indicator of hail presence over a season. More careful inference should be used to investigate single episodes, as discussed in Section 1, owing to the time and space displacement of hail with respect to the lightning, and also to the different correlations with hail according to stroke polarity. However, this issue remains beyond the aims of this study. Since impactometric networks in the Alpine area risk to suffer a policy of dismantlement (or not implementing new ones), lightning recording seems a good candidate to become a proxy for hail amount. Of course, for a validation of the approach a wider area should be investigated than the one considered in this study. Another potentially interesting aspect to be investigated in detail is the correlation between lightning activity and hail recorded at smaller scales. A validation of the findings of the quoted works would allow an extension of the results

Hail index	Trend / 100 m height
cum_hit_surf [km²]	0.4
m_tot_en [J m⁻²]	8.3
m.en_rep [J m⁻²]	2.6
max_en_rep (annual mean) [J m⁻²]	5.7

Tab. 2 - Correlations of hail indices (each referred to single hailpads) with measurement heights (trends expressed over 100 m height). All values significant with $p<0.001$. See Appendix for details.

Tab. 2 - Correlazioni degli indici di grandine (ognuno riferito a singoli grelimetri) con le quote dei siti di misura (trend su 100 m di altitudine). Tutti i valori sono significativi con p<0.001. Consultare "Appendix" per i dettagli sugli acronimi.

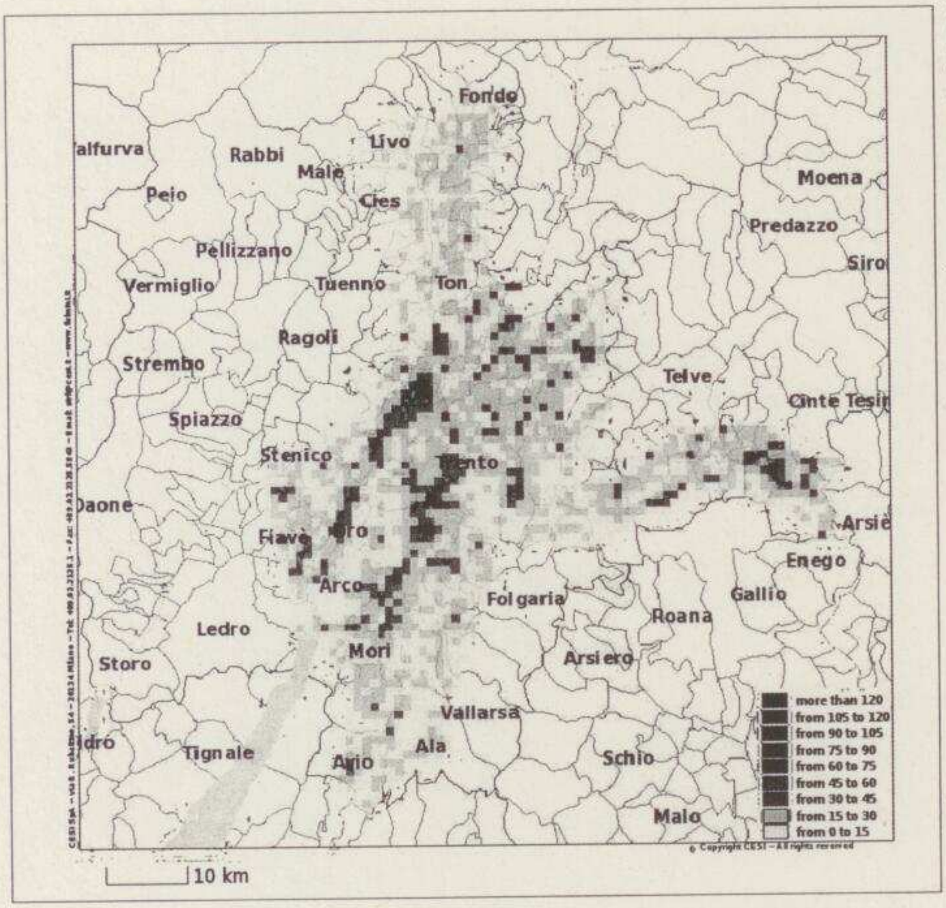

Fig. 6 - Total number of lightning flashes in the area corresponding to the coverage of the hail impactometric network (courtesy of CESI). Darker pixels correspond to higher flash rates.

Fig. 6 - Numero totale di fulmini nell'area coperta dalla rete impattometrica trentina (per gentile concessione di CESI). La tassellatura più scura corrisponde a valori più elevati di fulmini registrati.

down to the event scale. Positive results would make lightning survey, in association with other measurement devices (meteorological radar and raingauges), a feasible approach to indirect hail assessment.

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APPENDIX – Hail indices and units

cum_hit_surf_dens = accumulated hit surface density (=cum_hit_surf / total monitored surface) (-)
hail_days = nr. of hail days (or events: one event ≡ one hail day) (-)
m_surf_ev = mean surface for event (km^2)
cum_en_dens = density of accumulated kinetic energy ($J\ m^{-2}$)
m.en_rep = mean energy per report (one report ≡ one event at one site) ($J\ m^{-2}$)
sd_en = standard deviation of kinetic energy (per report) (J)
m_ev_en = spatial mean kinetic energy for event ($J\ m^{-2}$)
m_tot_en = total kinetic energy per season (MJ)
max_en_rep = max kinetic energy for report ($J\ m^{-2}$)
extr_en_rep = extreme (90^{th} percentile) kinetic energy for report ($J\ m^{-2}$)
extr_tot_en_ev = total kinetic energy for extreme (90^{th} percentile) annual event (MJ)
tot_en_max_ev = total kinetic energy for maximum annual event (MJ)
tot_en_extr_ev = total kinetic energy for extreme (90^{th} percentile) event (MJ)

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