The summer 2021 Switzerland hailstorms: weather situation, major impacts and unique observational data

Jérôme Kopp[1], Katharina Schröer[2,3,4], Cornelia Schwierz[3], Alessandro Hering[5], Urs Germann[5] and Olivia Martius[1]

[1]*Oeschger Centre for Climate Change Research and Institute of Geography, University of Bern, Switzerland*
[2]*Institute for Environmental Decisions, ETH Zurich, Switzerland*
[3]*Federal Office of Meteorology and Climatology MeteoSwiss, Zurich, Switzerland*
[4]*Faculty of Environment and Natural Resources, University of Freiburg, Germany*
[5]*Federal Office of Meteorology and Climatology MeteoSwiss, Locarno-Monti, Switzerland*

Introduction

Between 18 June and 31 July 2021, a series of exceptionally widespread and intense hailstorms occurred over Switzerland, causing major damage to buildings, cars and crop fields. Hail-related loss estimates from insurance companies suggest that these events were among the most expensive in recent decades, as the storms affected densely populated areas, such as the cities of Lucerne and Zurich (see Figure 1), and also large areas of farmland.

The Swiss private insurance company La Mobilière (founded in 1826) reported 20 000 damage claims for vehicles related to the hailstorm of 28 June 2021 – a record for the company for a single hail event (La Mobilière, 2021). The building insurance company for the region of Lucerne (GVL) reported 18 000 damage claims, which is six times the average yearly number of claims (GVL, 2021), and estimated losses of Swiss Francs (CHF) 400 million (~USD 430 million), related to hail and floods. More than 15% of all buildings in the region were affected (GVL, 2021), with 12 000 buildings damaged by hail on 28 June 2021 alone. The Swiss Hail Insurance Company (Schweizer Hagel, founded in 1880), which offers insurance coverage for agricultural crops in Switzerland since 1880, received almost 14 000 damage reports in 2021. Almost one in two insured farms by Schweizer Hagel declared a loss, with the estimated insured crop compensation exceeding CHF 110 million (~USD 117 million) (Schweizer Hagel, 2021). For both GVL and Schweizer Hagel, 2021 was the costliest year in the companies' history.

While the events in 2021 caused major impacts, they also present a unique research opportunity because several measuring platforms were capturing the hailstorms. The measuring platforms include: (i) a newly set-up network of automatic hail sensors (project 'The Swiss Hail Network') that report the size and kinetic energy of individual hailstones with very high temporal and size resolution (Löffler-Mang *et al.*, 2011; Wetzel, 2018), (ii) the crowdsourcing function of the MeteoSwiss app (Barras *et al.*, 2019) and (iii) two operational hail products of the Swiss weather radar network (Germann *et al.*, 2022): the probability of hail (POH) at the ground (Waldvogel *et al.*, 1979) and the maximum expected severe hailstone size (MESHS; Foote *et al.*, 2005).

Using the data captured by those complementary hail-dedicated observing systems, we review the hail activity in Switzerland during the period of interest (18 June to 31 July) and investigate two particularly intense hail days: 28 June and 8 July. In addition, the 20-year (2002–2021) radar-based Swiss hail climatology (NCCS, 2021) was used to classify the observed events. It was launched in May 2021 just before the summer of extreme hail events.

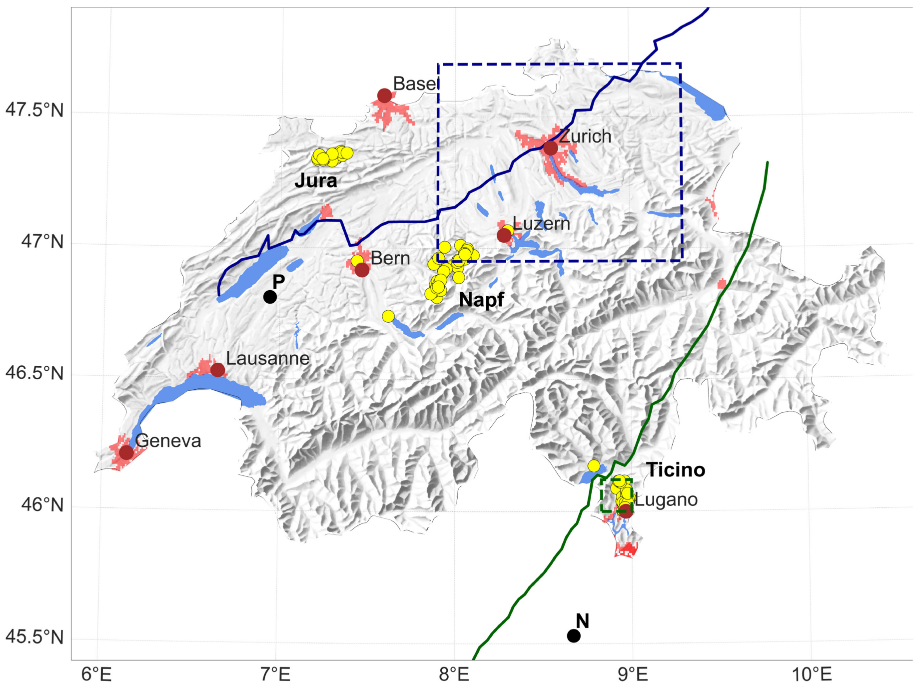

Figure 1. Map of Switzerland. Red patches show urban areas; yellow dots denote automatic hail sensor locations in the three hail-prone regions (Jura, Napf and Ticino); the blue and green tracks show the path of the centroid of the longest living storms of 28 June and 8 July 2021, respectively, as derived from radar observations (the storm centroid being the geometrical centre of the polygon representing the storm as a continuous area exceeding a minimum radar reflectivity threshold); the dashed blue and green rectangles delimit the subareas shown in Figure 11(a) and (b), respectively; locations of the Payerne (P) and the Novara Cameri (N) soundings displayed in Figure 9 are also shown.

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Figure 2. Left: An automatic hail sensor installed in the project 'Swiss Hail Network' (© Manu Friederich). Right: Zoom on the sensor Makrolon disc as a golf ball is falling (La Mobilière/Sascha Moetsch).

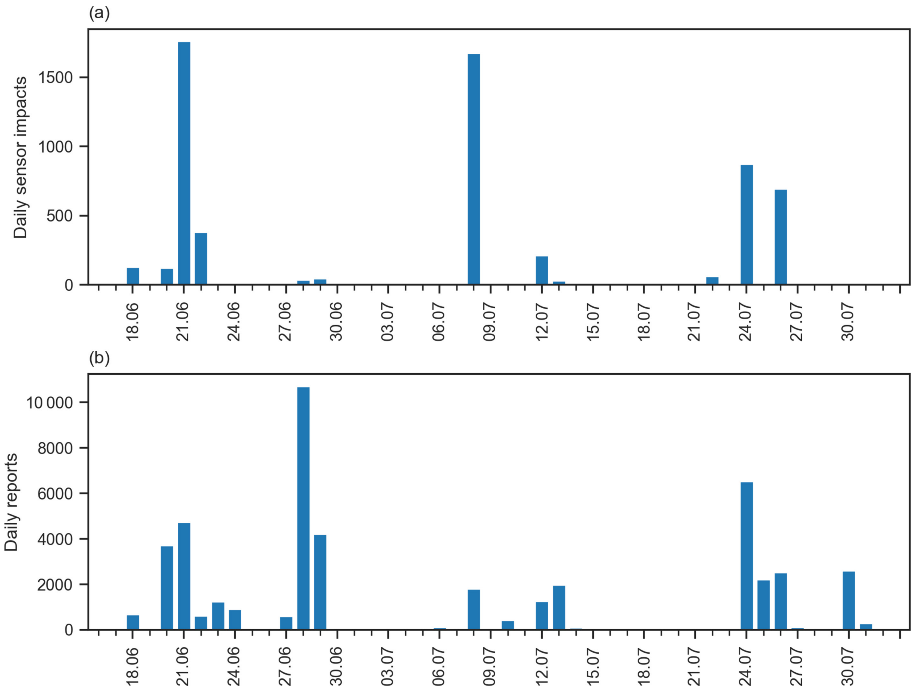

Figure 3. Daily number of (a) sensor impacts (all sensors) and (b) crowdsourced reports between 18 June 2021 and 31 July 2021.

The purposes of this study are: (i) to describe the synoptic-scale situation, the mesoscale environment, the storm tracks and the hail activity of 28 June and 8 July in detail, (ii) to present the new automatic hail sensors and their capabilities, (iii) to demonstrate the exceptional character of the hailstorms from a climatological perspective and (iv) to touch upon the new research avenues opened by the hail observation systems and the hail climatology.

Information on the large-scale weather situation stems from ERA5 reanalysis (Hersbach *et al*., 2020) interpolated to a 0.5° grid. Information on the local atmospheric situation over Switzerland stems from the COSMO2E analysis over a 1km grid (COSMO, 2021).

Hail observations

In the 'Swiss Hail Network' project, 80 automatic hail sensors were installed between June 2018 and July 2020 in the three most hail-prone regions according to the climatology (Nisi *et al*., 2016, 2018; NCCS, 2021): the Jura, Napf Region and southern Ticino (Figure 1). This project is a public–private partnership between La Mobilière, MeteoSwiss, inNET Monitoring AG and the University of Bern.

Each hail sensor consists of a Makrolon (thermoplastic) disc with a diameter of 50cm (Figure 2). The disc begins to oscillate upon the impact of a hailstone and the oscillations are recorded by a highly sensitive microphone. This sound signal is then converted to hail kinetic energy using a log-linear calibration curve. The hailstone diameter is calculated from the kinetic energy, assuming spherical hailstones with constant drag coefficient. The related uncertainty is about 0.5mm (Löffler-Mang *et al*., 2011; Wetzel, 2018).

Compared to traditional hailpads, automatic sensors have the advantage of recording the exact timing of hailstone impacts, they are easier to maintain because they require less human intervention and are less subject to impact saturation during high concentration events.

The crowdsourcing function of the MeteoSwiss app allows users to report the hail size category, time and location using their smartphone. Detailed information on the crowdsourcing function and applied plausibility filters is available in Barras *et al*. (2019). From autumn 2021, users can also upload photographs together with a hail report; however, this functionality was not yet active during the June/July 2021 events.

The radar-based products POH and MESHS are derived by combining the freezing-level height from the analysis of the numerical weather prediction model COSMO with the maximum height at which radar reflectivity reaches at least 45dBZ for POH and 50dBZ for MESHS (for details, see Nisi *et al*., 2016, 2018). POH describes the probability of hail occurrence, ranging from 0 to 100%, and MESHS estimates the largest expected hail diameter, starting at 2cm.

Both the number of crowdsourced reports and the number of impacts recorded by the sensors during June and July 2021 exceeded previous monthly maxima in their respective periods of record. Approximately 48 000 crowdsourced reports and 6400 sensor impacts were recorded (Figure 3). This corresponds to 48% of all the filtered reports received since the function was added to the MeteoSwiss app in May 2015, and to 47% of all the valid impacts measured since the first sensor was installed (June 2018).

More than 10 000 reports were sent on 28 June alone, representing the highest daily number on record (Figure 3b). The fact that the storms produced large hailstones and occurred over densely populated areas explains this high number of reports. The sensors recorded around 1700 impacts on 21 June and 8 July, also their largest daily number on record (Figure 3a), as hailstorms happened directly over areas where sensors were located.

Climatological evaluation

We assess the climatological extremeness of the hail events by ranking their spatial extent and intensity, considering three domains covered by the Swiss radar network: the Swiss territory (CH), North of Alps (NoA) and South of Alps (SoA) (cf. Barras *et al*., 2021). NoA extends into Germany and France in the north and northwest, while SoA also covers parts of Italy in the south and east (Figure 4).

We consider the number of hail days defined as days with at least 100km² of POH ≥ 80% (NCCS, 2021). A 'severe' hail day occurs if at least 100km² of MESHS ≥ 4cm are observed. The impact intensity is separated accordingly into 'severe hail' from 4cm MESHS and 'extreme hail' from 6cm MESHS.

In Switzerland, the 2021 hail season had 27 hail days, which is close to the long-term average of 32.35 (±8.4) hail days. However, 15 days were severe hail days, which clearly exceeds the expected annual number of severe hail days of 10.95 (±4.0) days.

The long-term ranks of the hail area and the impact intensity for five of the most extreme hail days in 2021 are summarized in Table 1. On 28 June, the largest areas for severe and extreme hail and the second-largest hail-affected area (hail likely) were recorded for Switzerland since 2002. In the NoA domain, the event ranked as the second-largest area for severe and extreme hail. On 8 July, the SoA domain set a new record in hail-affected area across all intensities. Overall, more top-ten ranks are present for the severe and extreme hail areas (4 and 5 top-ten ranks, respectively) than for the hail-affected areas (3 top-ten ranks), indicating that the events of 2021 were unusually intense.

The daily MESHS values reached 9.2cm on 28 June and 6.3cm on 8 July (Table 1a). In some areas, these values correspond to return periods well in excess of 70–100 years (Figure 5). Return periods are estimated based on 3000 synthetic years calculated with an environmentally constrained stochastic resampling approach[1] (Schroeer *et al*., 2022).

From the hail observations and the climatological evaluation, the 28 June and

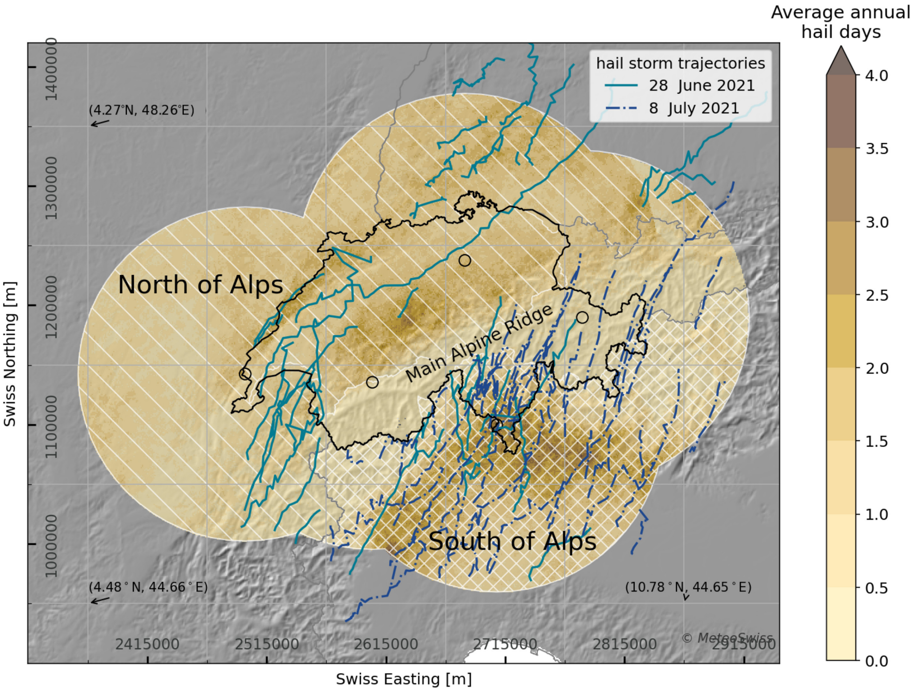

Figure 4. Swiss radar domain and regions North of Alps (white hatched) and South of Alps (white squared) and Switzerland (black contour). The background colourscale indicates the climatological frequency of hail days within 140km of the five Swiss radar stations (black circles); hailstorm tracks (from 2cm maximum expected severe hailstone size) are shown in light blue for 28 June 2021 and dashed blue for 8 July 2021.

[1]The resampling approach builds on 40 000 high-resolution MESHS hailstorm footprints extracted from the 20-year record of the Swiss weather radar network. Storm objects are resampled in daily resolution, conditional on the large-scale weather situation and topographic region. Maximum hail stone sizes within storm footprints are resampled through fitted probability mass functions of observed MESHS within similar storm type groups. Return values are finally estimated using Weibull's formula based on the obtained synthetic time series of the resampling years.

Table 1

Daily maximum expected severe hail stone size (MESHS) and areas of the five most intense 2021 hail events for Switzerland (CH), North of Alps (NoA) and South of Alps (SoA). The rank is given in brackets, top-ten ranks are shown in bold. Ranks are given relative to all 3660 potential hail days of the hail seasons 1 April–30 September 2002–2021, of which 645 had hail areas ≥100km².

	Region	*20 June 2021*	*21 June 2021*	*28 June 2021*	*8 July 2021*	*24 July 2021*
(a) MESHS in event (cm)						
	CH	8.2	7.2	9.2	6.3	6.9
	NoA	8.2	7.2	9.2	2.3	6.9
	SoA	6.8	3.7	7.4	8.8	8.1
(b) Event area (000 km²) – number of radar pixels (1km²) with values above the threshold						
Hail likely (POH ≥ 80)	CH	4.4 (34)	3.8 (43)	**8.8 (2)**	2.5 (83)	**8.0 (5)**
	NoA	9.9 (26)	13.9 (11)	13.7 (12)	0.06 (951)	1.1 (19)
	SoA	1.3 (270)	0.4 (598)	2.4 (134)	**15.4 (1)**	3.4 (76)
Severe hail (MESHS ≥ 4cm)	CH	**19 (7)**	1.0 (23)	**4.4 (1)**	0.5 (68)	1.0 (25)
	NoA	2.7 (18)	3.4 (11)	**5.9 (2)**	0 (1593)	1.1 (66)
	SoA	0.14 (297)	0 (1557)	0.4 (136)	**4.8 (1)**	1.2 (34)
Extreme hail (MESHS ≥ 6cm)	CH	**0.8 (3)**	0.05 (70)	**1.1 (1)**	0.008 (169)	0.07 (57)
	NoA	**0.9 (6)**	0.16 (67)	**1.5 (2)**	0 (1337)	0.06 (121)
	SoA	0.02 (238)	0 (1368)	0.03 (219)	**1.1 (1)**	0.3 (22)

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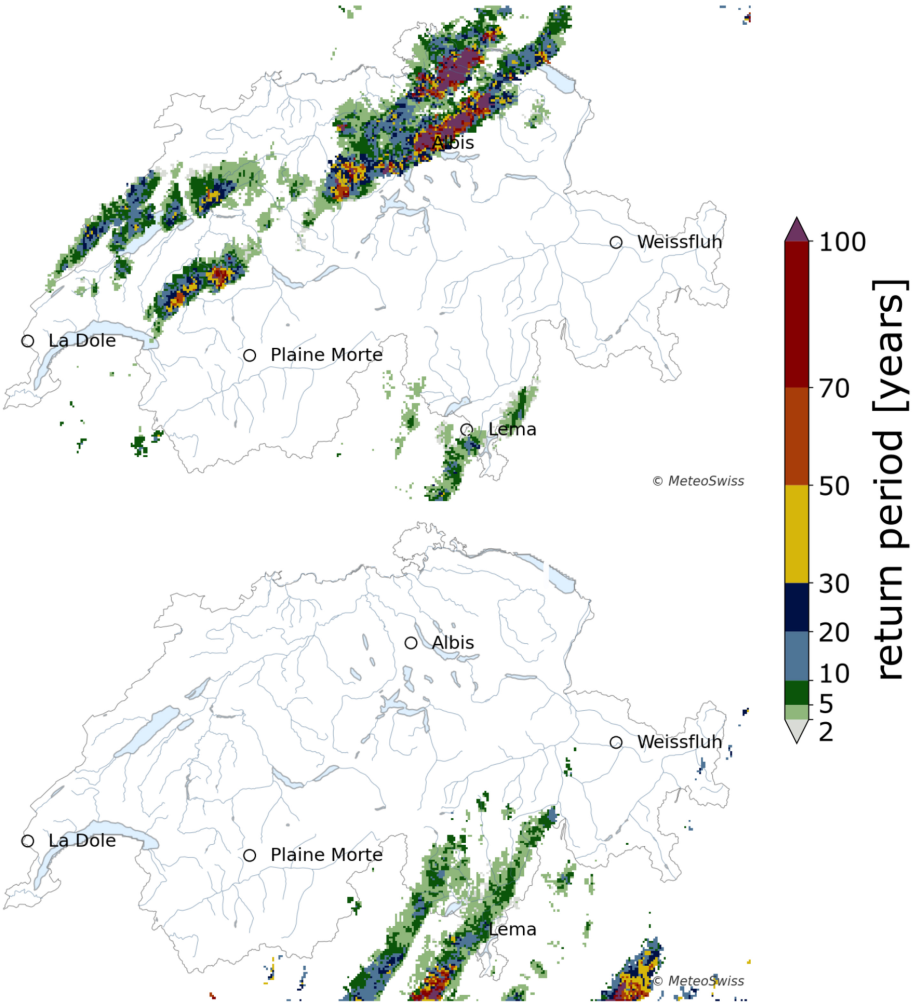

Figure 5. Local return period estimates for 28 June (top) and 8 July 2021 (bottom). Estimates refer to the frequency of expected annual maximum expected severe hailstone size per radar pixel (1km²).

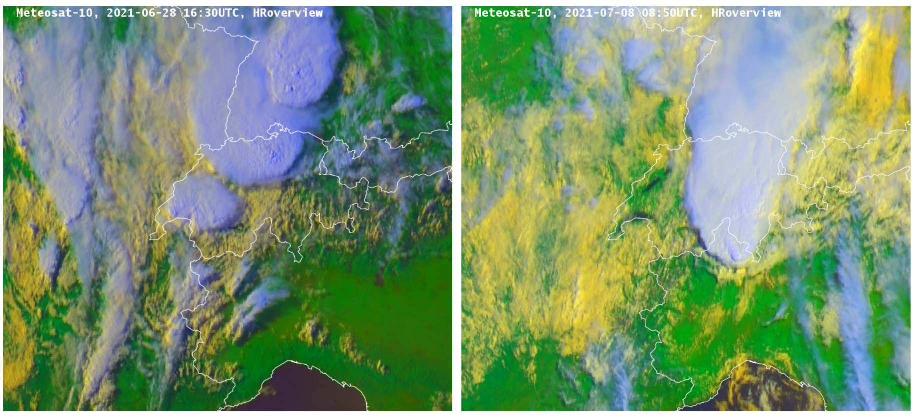

Figure 6. Satellite images of Switzerland showing clouds on 28 June 1630 UTC (left) and 8 July 2021 0850 UTC (right) (EUMETSAT MSG HRoverview composite channels, 3-km resolution).

8 July 2021 emerged as particularly interesting days and we therefore present a short description of the weather situation and hail activity on these days.

Weather situation on 28 June and 8 July

On 28 June, the storms originated in western Switzerland around 1400 UTC and then moved along the northern flank of the Swiss Alps following southwest to northeast tracks (cf. Figure 4). On 8 July, the storms formed in northern Italy around 0700 UTC and moved over southern Switzerland (Ticino) following south to north tracks (cf. Figure 4).

Several supercells were identified on both days with one storm evolving in a mesoscale convective system on 28 June (blue track in Figure 1). The longest living supercell of 8 July is marked by the green track in Figure 1. For both days, satellite pictures show the large extent of the storms and the presence of overshooting tops (Figure 6).

The advection of moist and unstable air into Switzerland from the southwest was important for the formation of previous severe hailstorms in Switzerland (cf. Peyraud, 2013; Trefalt *et al*., 2018) and was also present on 28 June.

On 28 June, the large-scale flow over central Europe was characterised by a positive potential vorticity (PV) anomaly (upper-level cut-off) over western France and a ridge downstream (Figure 7a). The cut-off was associated with moist south/southwesterly flow (Figure 7c) and quasigeostrophic lifting (i.e. Q-vector convergence) over Switzerland (Figure 7a).

All the ingredients for severe convection (instability, shear and high moisture levels) were present (Doswell *et al*., 1996) over Switzerland. An elevated mixed layer (EML) is visible in the sounding of 28 June (steep lapse rate between 780 and 620hPa) (Figure 9a). EMLs are relevant for significant hail events as they contribute to the formation of high CAPE (Ribeiro and Bosart, 2018).

CAPE was indeed high (>1500Jkg^{-1}; Trefalt, 2017) (Figure 8g) and the integrated moisture content of the atmosphere over northern Switzerland was around 30mm (Figure 7c). The bulk shear between the surface and 500hPa exceeded 18ms^{-1} over northwestern Switzerland. There was also directional shear (Figure 8e), with 4–6ms^{-1} northerly surface winds (Figure 8a) and 22–26ms^{-1} southwesterly wind at 500hPa (Figure 8c). The 1200 UTC sounding at Payerne (Figure 1) confirms the high values of CAPE and bulk shear for that day (Figure 9a).

On 8 July, an elongated PV trough was located over western Europe, extending southward to the Iberian Peninsula (Figure 7b). In this case, the downstream flank of the trough was located slightly more to the east compared to the PV cut-off of 28 June. The associated flow was southerly over southern Switzerland, and quasigeostrophic lifting was present over the south flank of the Alps (Figure 7b).

CAPE over southern Switzerland reached values above 1500Jkg^{-1} (Figure 8h) and the integrated moisture content of the atmosphere was around 32mm (Figure 7d). The bulk shear between the surface and 500hPa exceeded 25ms^{-1} over southern Switzerland (Figure 8f). The 1200 UTC sounding at Novara Cameri (Figure 1) confirms the high values of CAPE and bulk shear for that day (Figure 9b).

Hail footprints and hail size measurements

Figure 10(a) and (b) shows the radar hail footprints, the crowdsourced reports and the measurements of the automatic hail sensors for 28 June and 8 July, respectively.

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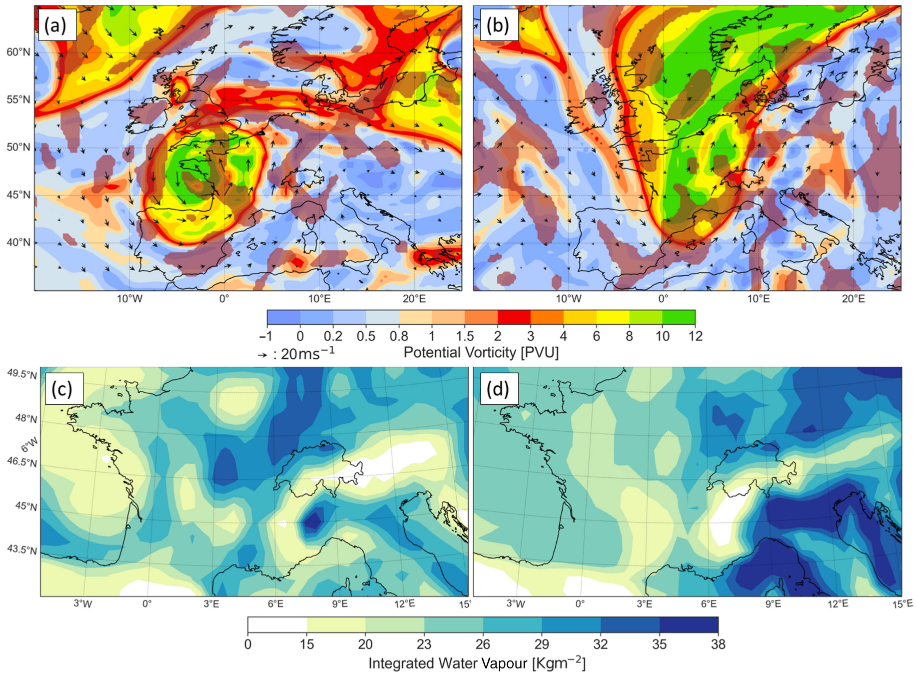

Figure 7. (a,b) ERA5 PV on the 330K isentrope (PV units, colour shading), horizontal wind field at the same level in ms^{-1} (arrows) and Q-vector convergence ≥5 × 10^{-18}ms^{-1}kg^{-1} (brown shading); (c,d) ERA5 Integrated Water Vapor; on 1200 UTC 28 June 2021 (left) and 0600 UTC 8 July 2021 (right).

On 28 June, hailstorms occurred over densely populated areas (Figures 1 and 10a), partially explaining the high number of crowdsourced reports; however, only one sensor measured few impacts and therefore the sensor data for 28 June are not discussed. A closer inspection of the region where the storms were most intense (Figure 11a) reveals that the largest hailstones (reference object 'tennis ball') were reported in areas where MESHS values were also the highest (>6cm). The coherence of the radar and crowdsourced data is confirmed by several photographs from local people showing hailstone sizes of up to 9cm in diameter, for example, hailstones A (Figure 12a) and B (Figure 12c). Hailstones of this size have local return periods of 50–100 years (NCCS, 2021; Figure 5), also explaining the historical damage reported by insurance companies (Figure 12b).

On 8 July, hailstorms passed over southern Switzerland (Ticino; Figures 1 and 10b), where several of the installed sensors captured hail impacts (Figure 11b). Four sensors recorded more than 200 impacts (Figure 13a). Most hailstones recorded by the sensors had a diameter between 0.75 and 1.25cm, with only a few hailstones exceeding 2cm, which is the lowest value for which MESHS is defined. However, MESHS is defined as the largest hailstone size over 1km^2, and the area covered by a single sensor is roughly six orders of magnitude lower (7.85 × 10^{-7}km^2). Hence, the probability that the largest expected hailstone hits the sensor is low.

The largest crowdsourced hail size reports (golf ball: 3.7–5.5cm) are also slightly smaller than the MESHS values. The size range takes into account that standard golf balls are 4.3cm and that visual observations may tend to overestimate the size. People are asked to report the largest hailstone they see, but usually the vicinity is also much smaller than 1km^2. Pictures taken on site (Figure 12d and e) show hailstones ranging from 2 to 4cm. The event on 8 July thus confirms earlier studies that MESHS values are on average larger than crowdsourced reports (Barras *et al.*, 2019). However, for the event on 28 June, the MESHS of 9.2cm and maximum reported diameters of hailstones of 8–10cm indicate that this bias is not systematic for all storm types.

Automatic hail sensors record the precise timing of hailstone impacts. Figure 13(b) shows the corresponding time series of the diameters measured by the four sensors shown in Figure 13(a). We can estimate that the hailstorms remained no more than 6min over the sensor location, considering that the impacts seem to occur in two separate bursts between 0941–0943 UTC and 0944–0946 UTC. The hail impacts recorded by the sensor at Bironico occurred between 094330 UTC and 094600 UTC.

Summary and outlook

On 28 June and 8 July 2021, all the ingredients for severe convection were present and resulted in severe hailstorms over Switzerland, causing historical damages, as recorded by several insurance companies. The new Swiss hail climatology allowed us for the first time to estimate the return periods for those events and to confirm that they were exceptional in terms of spatial extent and intensity. The areas affected by hail were among the largest ever observed and MESHS return periods locally exceeded 70–100 years. A comparison of those events with hail observation time series extending further back in time than 2002, such as for example the hail damage reports collected by the Swiss Hail Insurance Company (Willemse, 1995), could potentially reduce the uncertainty in the quantification of the return periods. However, the available damage reports and historical documentations are highly inhomogeneous in both time and space and thus make systematic comparisons challenging.

The combination of the automatic sensors of the Swiss Hail Network, the polarimetric weather radar network and the hail reporting function in the MeteoSwiss app with more than a million users every day is unique. We showed that those observing systems give a coherent and comprehensive picture of both the hail footprint and hailstones diameters. The automatic hail sensors make it possible to capture the local duration of a hailstorm and to precisely record the timing of hailstone impacts.

The data collected by those observing systems during the summer 2021 hail events are numerous and remain to be fully exploited in further studies. Not only radar-derived POH and MESHS data but also the polarimetric radar-based hydrometeor classification presented in Besic *et al.* (2016) could be validated and verified against ground observations and potentially improved by systematically comparing them with sensor impacts and crowdsourced reports.

One of the most promising research avenues is to investigate hailstone size distributions and temporal evolution using the sensor data, as this would enhance our general understanding of hail and could help to improve hail parameterization schemes in weather and climate models.

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Correspondence to: J. Kopp

jerome.kopp@giub.unibe.ch

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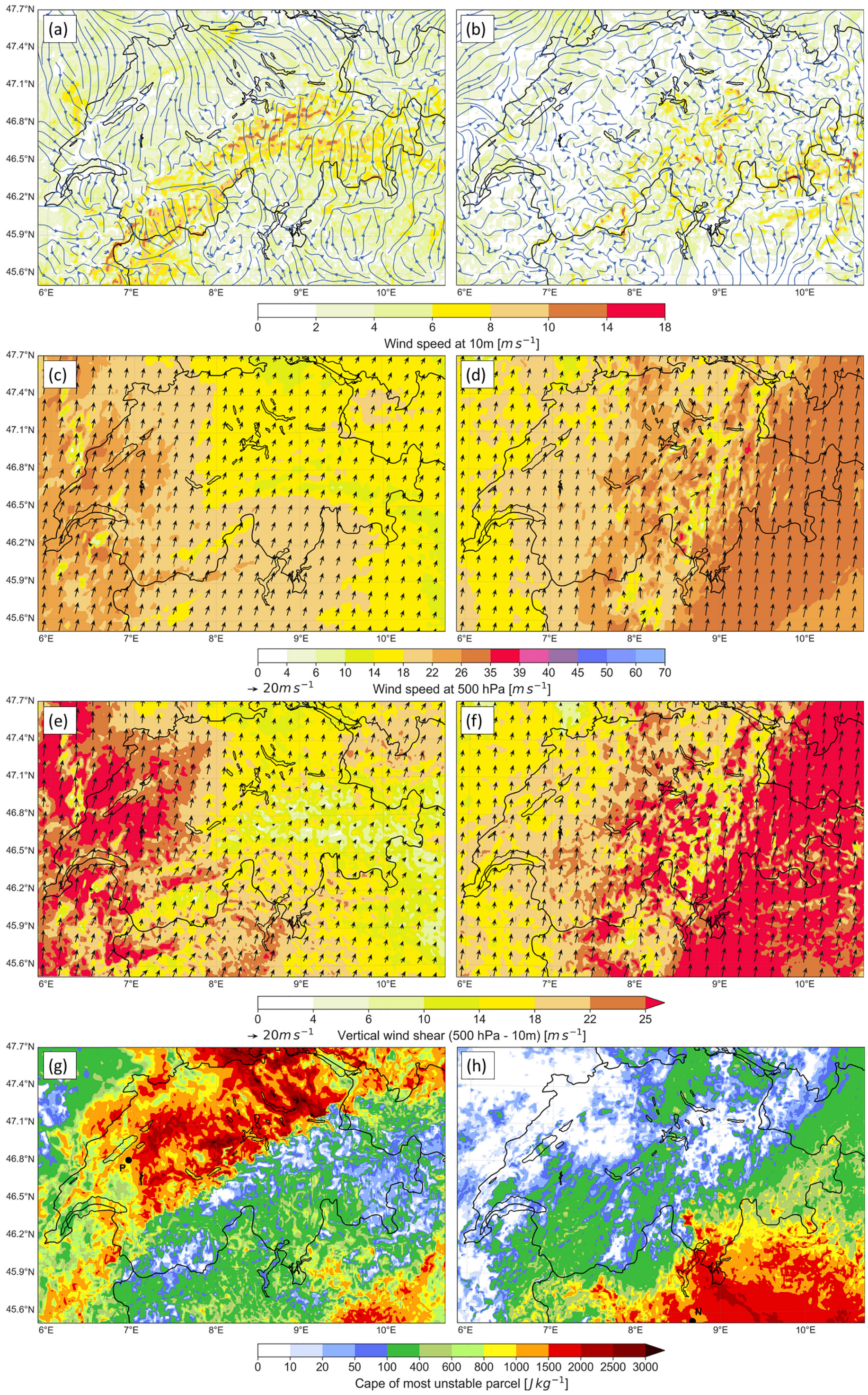

Figure 8. (a and b) COSMO2E 10-m surface wind magnitude (colour shading) and direction (streamlines); (c and d) COSMO2E 500-hPa wind magnitude (colour shading) and direction (vectors); (e and f) COSMO2E vertical wind shear (difference between 500-hPa and 10-m wind) magnitude (colour shading) and direction (vectors); (g and h) COSMO2E CAPE of most unstable parcel with location of Payerne (g) and Novara Cameri (h); on 1300 UTC 28 June 2021 (left) and 0800 UTC 8 July 2021 (right).

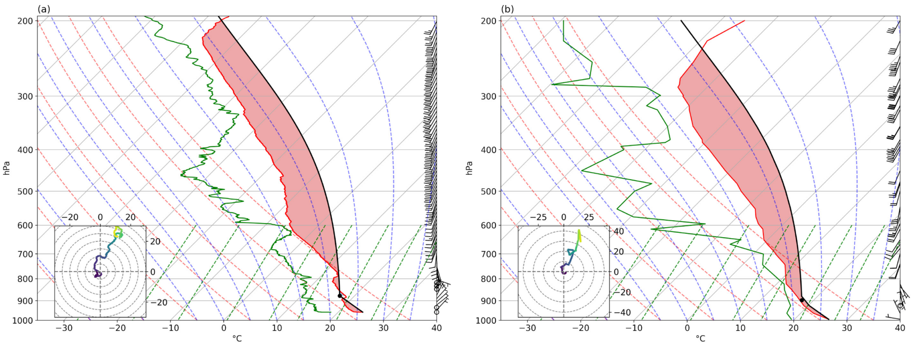

Figure 9. Soundings of (a) Payerne and (b) Novara Cameri stations.

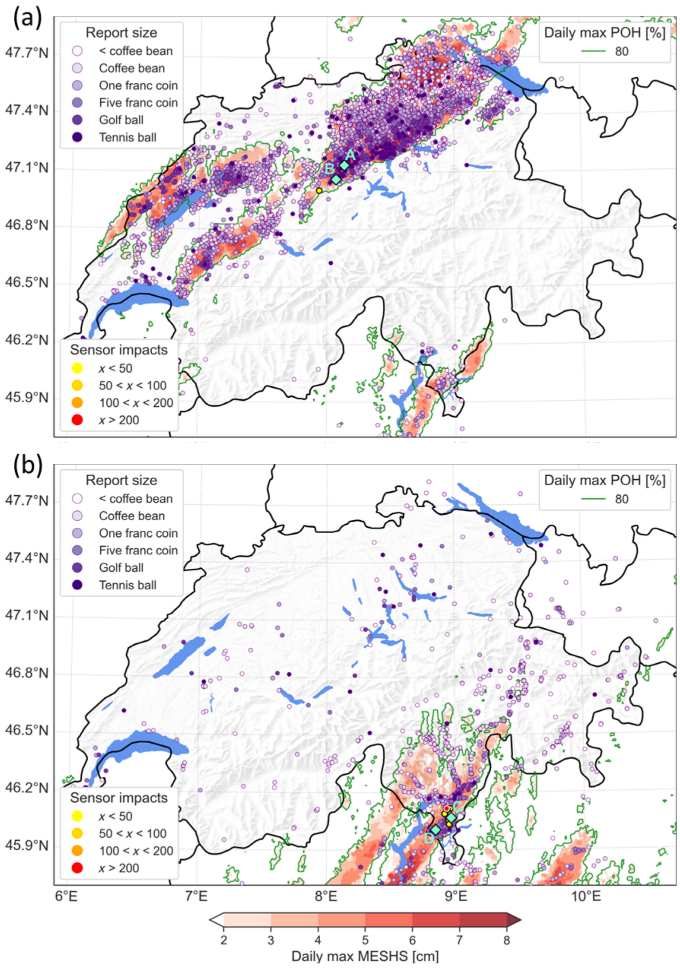

Figure 10. Hail observations: probability of hail (POH) ≥ 80% areas (green contours), daily maximum expected severe hailstone size (MESHS) (red colour scale), location of crowdsourced reports (purple dots, largest sizes are darker), sensor impacts (yellow to red dots), location of hailstone pictures with their respective letters (blue diamonds, see Figure 12); (a) 28 June 2021 and (b) 8 July 2021.

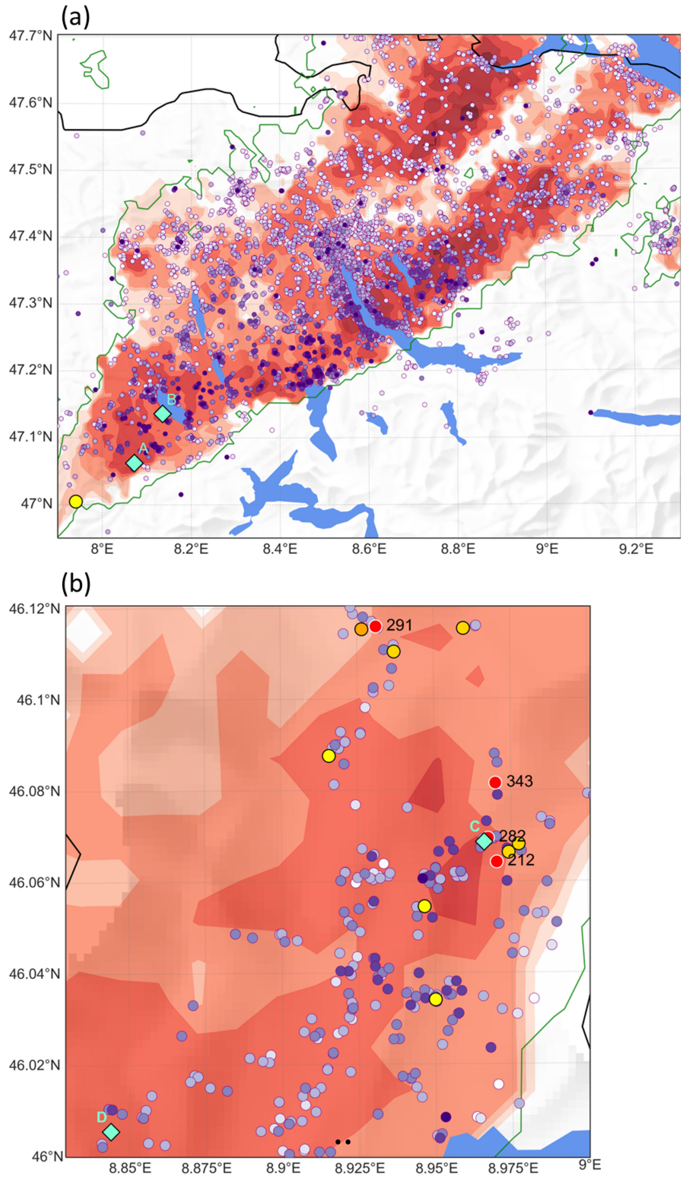

Figure 11. Zoom into the subareas shown in Figure 1 on (a) 28 June and (b) 8 July 2021. Legend follows Figure 10.

Figure 12. (a) Hailstone A. Picture source: Sturmarchiv Schweiz/(www.sturmarchiv.ch, © M. Kost, Wolhusen via SRF. (b) Hail damages in Wolhusen (location of hailstone A). Picture source: Sturmarchiv Schweiz/www.sturmarchiv.ch, © Whatsapp, Urheber unbekannt. (c) Hailstone B. Picture source: Sturmarchiv Schweiz/www.sturmarchiv.ch, © Roland Müller, Nottwil via SRF. (d) Hailstones C. Picture source: SRF Meteo/https://twitter.com/srfmeteo/status/1413086126026461184, © C. Brechbühl. (e) Hailstone D. Picture source: same as (d).

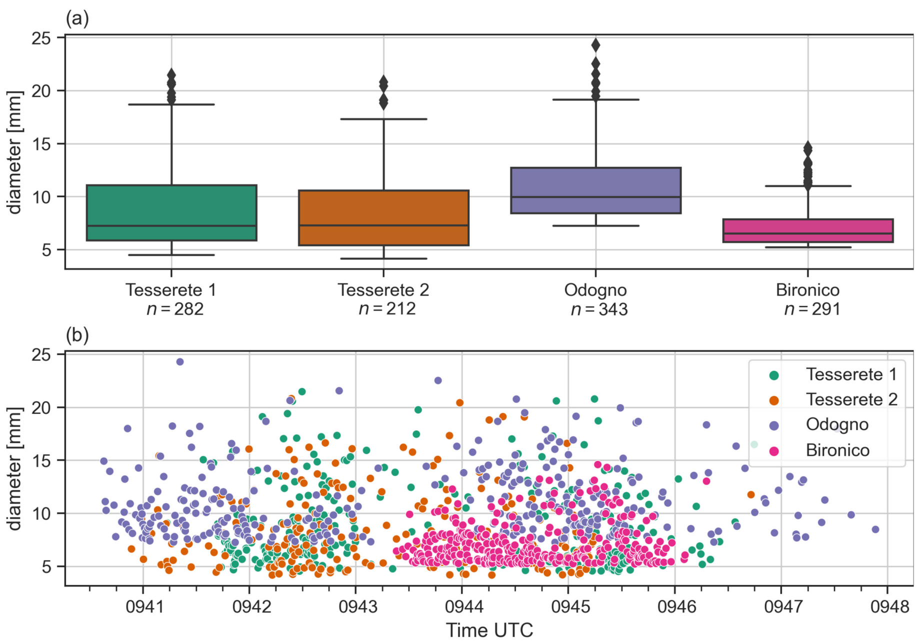

Figure 13. Hail sensor measurements by diameters (mm) for sensors with more than 200 impacts on 8 July. (a) Boxplots and (b) time series. Boxes extend from the first (Q1) to the third (Q3) quartile values of the data, with a line at the median. The position of the whiskers is 1.5 × (Q3 – Q1) from the edges of the box. Outlier points past the end of the whiskers are shown with black diamonds.