Hail events in Germany, rare or frequent natural hazards?

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Abstract. Hail represents a natural hazard in Germany with potentially substantial economic and environmental impacts, but it often receives less attention than other weather phenomena. This, combined with the very local nature of hail, results in a lack of observations and further analysis. This study investigates hail characteristics, across Germany using crowdsourced observations since 2000 and weather radar data over a six year period. A study with 3D printed hailstones provided insights into human perception of hail sizes, revealing that collective crowd estimates closely approximate actual measurements, though individual estimations can vary significantly. By deriving hail proxies out of radar data we analyzed hail frequency, spatial distribution, and size variations. Our research reveals a gradient in hail occurrence, with southern Germany experiencing substantially higher hail probabilities compared to northern regions. Mountainous areas demonstrated increased hail frequency relative to lower-elevation territories. June emerged as the peak month for hail events, characterized by both highest frequency and largest hail sizes. This research contributes to a better understanding of hail as a natural hazard in Germany, providing valuable insights for risk assessment, insurance purposes, and public awareness.

1 Introduction

Hail is a major natural hazard that causes severe damage and high costs. Although hail is not the natural hazard with the highest damaging potential in Germany, it can lead to severe loss. A hailstorm in July 1984 in Bavaria led to insured damages of 1.5 Billion €, another event in July 2013 to 3.6 Billion € in Baden–Wuerttemberg and the most recent large hailstorm in June 2023 with 740 Mio € total loss are examples of very heavy, damaging hailstorms in Germany (dkk, 2021; gdv, 2023). On agriculture hail has the greatest impact during the growing season, whereby the actual damage depends on many factors such as hail size, crop type and growth condition (Sánchez et al., 1996). Further hail damage can be expected to the infrastructure.

Measuring and observing hail is a difficult task. There are different sources of hail observations: The human observations, indirectly through damages reported to the insurance companies, remote sensing, disdrometers and hailpads. Each of them has its own advantages and disadvantages. Human observations will always have the disadvantage of the spatial resolution. Most hail reports are made by people living in populous areas. Rural areas are very likely to be underrepresented. Thus, there is a reporting bias towards hail in cities and along roads (Allen and Tippett, 2015; McGovern et al., 2022). Further on, untrained reporters may have problems in estimating the size of hail (we further investigate this in Sec. 4.2). The last problem occurs in every measuring method of hail: it melts through falling and laying at the ground. That is one of the reasons why the exact size of a hailstone is hard to measure. It could also have an irregular shape, making sizing even more difficult.

For insurance data similar aspects are true as for human observation. It has a population bias and even a rich–poor bias, as the loss expense depends on the amount of insured property. The number of insured properties must also be accounted for. Another problem is the question of which hailstorms cause damage. Hohl et al. (2002) showed that the season must be included, as the high season produces less, but larger hailstones for the same kinetic energy than the low season. This is relevant for the mean damage, but has no noticeable influence on the total loss. Brown et al. (2015) highlight the need for diverse data that includes more than just weather, as the largest impact on loss is with 90 % damages at the roofing system and this depends heavily on the material and the condition of the roofing system. The largest damages nevertheless do not correlate with the maximum hail size (Ackermann et al., 2023).

To overcome the issue of the population bias, weather radars can be a useful tool. They cover a large area and provide three dimensional data with high spatiotemporal resolution. We cannot derive hail size from radar data directly. Therefore, the challenge is finding a measure that is used as a proxy for hail and hail size. A first approach with single-polarized radars uses the reflectivity in combination with heights of specific temperatures which are derived from model data. Early on in hail research, Waldvogel et al. did a large study with hailpads to find a criterion for hail. They used the height of 45 dBZ (H_{45}) and the melting layer H_0. The hail probability at the ground should hereby be proportional to the difference of heights. With this approach, the probability of hail (POH) is calculated with a stepwise function using the difference between H_{45} and H_0, whereby POH gets larger with increasing difference. (Holleman et al., 2000; Witt et al., 1998; Nisi et al., 2016). The stepwise function was then adapted to a curve by Foote et al. (2005) and used e.g in Trefalt et al. (2022).

Another method to estimate the hailsize is the Maximum Estimated Size of Hail (MEHS/MESH) (Witt et al., 1998). MESH is based on the Severe Hail Index (SHI) that takes the vertical integrated kinetic energy above the melting layer into account. The SHI is fitted to observed data to come up with a formula to obtain the maximum hail size (Witt et al., 1998; Murillo and Homeyer, 2019). Originally developed for S-band radars in the US, Brook et al. (2024) showed that MESH used with C-band radars tends to overestimate hail sizes. To overcome this issue, Brook et al. (2024) introduced an empirical correction based on the matching of S-band and C-band radars in overlapping regions. Forcadell et al. (2024) utilize convolutional neural networks (CNNs) to obtain MESH values due to threshold-based optimization. In this study, we undertook our own calibration of the MESH formula with hail reports compared to the SHI derived from German C-band radar values (Sec. 4.5).

The upgrade from single- to dual-polarized radar systems was expected to improve the estimation of hail size. Aydin et al. (1986) and Depue et al. (2007) suggest the hail differential reflectivity H_{DR} which combines the reflectivity Z and the differential reflectivity Z_{DR}. Ryzhkov et al. (2013), however, remark that the melting process of hail is neglected and propose a fuzzy-logic scheme that also includes the cross correlation ρ_{hv} additionally. ρ_{hv} is a measure of the uniformity of hydrometeors within a measured volume, large hail is expected to have lower ρ_{hv} values (Heinselman and Ryzhkov, 2006).

A different approach tries to estimate updrafts. For the development of large hailstones it is necessary to have strong updrafts. Z_{DR} columns, intend to estimate the presence and height of super-cooled water. It can provide information on the location and strength of updrafts (Snyder et al., 2015). Another hint for updraft dimensions and thus hail size is the Specific Differential Phase (K_{DP}) column (Snyder et al., 2017).

Puskeiler et al. (2016) and Puskeiler (2014) analyzed hail in Germany based on radar data with the cell tracking TRACE3D

(Handwerker, 2002). Their hail climatology for Germany shows hotspots that are strongly linked to the orography. Junghänel et al. (2016) combined reported data with reflectivity values of radar data. Similar results also based on radar data were found by Fluck et al. (2021). All the hail studies have the hotspot of hail in southern Baden–Wuerttemberg in common. Further on, they share the north–south increase of hail days. This was also observed in model-derived hail days (Battaglioli et al., 2023).

In this paper we derive multi annual hail data (2018–2023) for Germany based on vertically integrated ice (VII). We compare it to crowdsourced data and investigate their annual cycles and spatiotemporal frequencies. In a case study we depict the similarities and differences for different hail size estimation methods. We focus on two research questions:

– Can we rely on human observed hail data in their size estimation?

– Are the radar based algorithms VII and MESH suitable for determining hail (size) climatologies for Germany?

2 Data

2.1 Human observed data

For the human observed data there are three different data sources available in Germany: WarnWetter app, European Severe Weather Database, manned weather stations.

The first source are user reports obtained with the WarnWetter app. The mobile phone application operated by Deutscher Wetterdienst (DWD) informs the public about the current and forecasted weather and provides weather warnings. The application enables users to submit reports on their observations of weather conditions as well as upload pictures. Upon reception, all user reports are quality checked with reference data e.g. radar data (Spitzer et al., 2023). Regarding hail, users can select between the following: *Hagel unter 1 cm*, *Hagel 1 cm*, *Hagel 2 cm*, *Hagel 3 cm*, *Hagel 5 cm*, *Hagel größer 7 cm* (hail smaller 1 cm, hail 1 cm, hail 2 cm, hail 3 cm, hail 5 cm, hail larger 7 cm). The already quality checked reports are cleaned up for further analysis, so users who reported an event for a day no other user reported an event are blacklisted and for users, who reported more than one event in 30 minutes, only the report with the largest hail size is taken into account.

The European Severe Weather Database (ESWD) (Dotzek et al., 2009) was established in 2006. It contains data on severe convective storm events contributed by the public (eyewitnesses and voluntary spotters) and is quality controlled. With an update in the year 2008 the quality control was further enhanced. It contains four steps, from basic plausibility checks to fully verified (Dotzek et al., 2009). In this analysis we use data with basic plausibility checks (QC0+). The first reports are available for 2000 even though the test phase of the ESWD had started in 2004. A severe hail event is characterized by a maximum hail diameter larger than 2 cm. From 2021 on, some of the reports of the WarnWetter app are transferred to the ESWD. There is a continuous increase in reports from 2000 until 2008 with a maximum of approximately 300 reports in a year. Compared to the previous years, in which there was no major change, there was a drop of reports in the years 2014–2018 (160–200 reports per year).

The largest dataset comes from station observations of the monitoring network operated by DWD. It combines manned weather stations and trained volunteer reports. The temporal accuracy of those reports differs from daily reports up to the exact time of the hail event. In order to combine them, only the reported day of occurrence is taken into account. Due to the continuous

automation of weather observations, the number of reports decreases with time. For this reason the dataset only contains data up to 2017.

The problem of point observation data is the low and irregular spatial resolution. Rural areas might be underrepresented due to the lack of people who can report an event. Thus, the crowdsourcing data can only provide information about positive events, as no report does not automatically mean no hail. The station observations, however, can also give a hint about the absence of hail.

All in all, there are 3769 hail reports in the ESWD from 2000 to 2020. All reports independent of their quality level (QC0+ and higher) were used in our study. Further on, the reports of hail of the new DWD WarnWetter app were used (since 2021). They are automatically checked for plausibility and partially included in the ESWD dataset, amounting to 39 142 reports. Inclusion in the ESWD involves a manual check of the content and plausibility of the reports for hail sizes greater than 2 cm. Hail sizes smaller than 2 cm are not included. To ensure no duplicates were included in our analysis, ESWD data from 2021 and newer was excluded. The smallest category "Hagel unter 1 cm" (hail smaller 1 cm) was left out in the analysis due to the possibility to mistakenly reporting graupel instead of hail. With that, 21 231 reports remained in the analysis from the WarnWetter app. For the years 2000–2017, 25 719 reports of the station observations of the DWD are available. In total the analysis includes 50 719 hail reports.

2.2 Radar data

The German radar network consists of 17 C-band doppler radars and covers whole Germany and adjacent areas (see Fig. 1). Upgrading single– to dual–polarization radars was started in 2011 and finished in 2021. Each radar provides scans in 11 elevation angles every 5 minutes (see Fig. 2).

The volume scan has a range of 180 km. The precipitation scan, a low-elevation scan that follows the orography, covers a range of 150 km. Both scan types have a horizontal resolution of 1°x 250 m.

In this study, we will evaluate the years 2018—2023, with a particular focus on the convective season between April to September.

2.3 Insurance data

The federation of private insurance companies in Germany, the *German Insurance Association* (GDV), has kindly provided access to their hail damage data, with hail and storm forming one category. The decision for a category "hail", "storm" or "undefined" is unfortunately prone to errors. For this study we only included data with reports resulting in hail damage. For each date with hail damage information concerning the postal code, the damage expense, the number of damages, insurance expense and the number of insurance contracts in each postal code is provided. From April to September of 2013 to 2022 there are 526 444 insurance claims for different postal codes and days of hail. All in all, from 1830 possible days 1815 (99.18 %) are recorded as having at least one occurrence of hail damage in the area of Germany. This is because the damage cannot always be assigned to the precise day on which it occurred. The data is derived solely from postal code areas and may therefore not provide a complete picture of hail events. This limitation is why we chose to leave spatial analysis out of our examination of
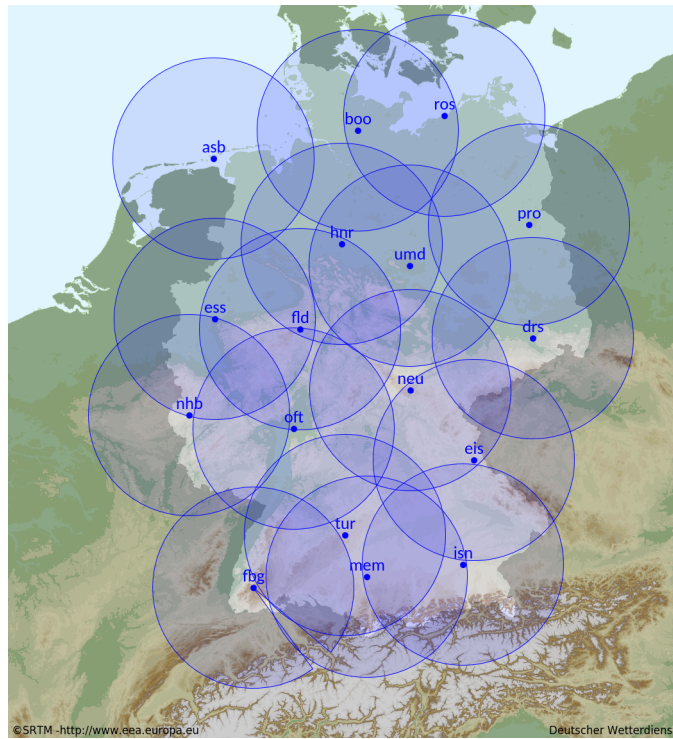
Figure 1. The German radar network with its 17 C-band radars.
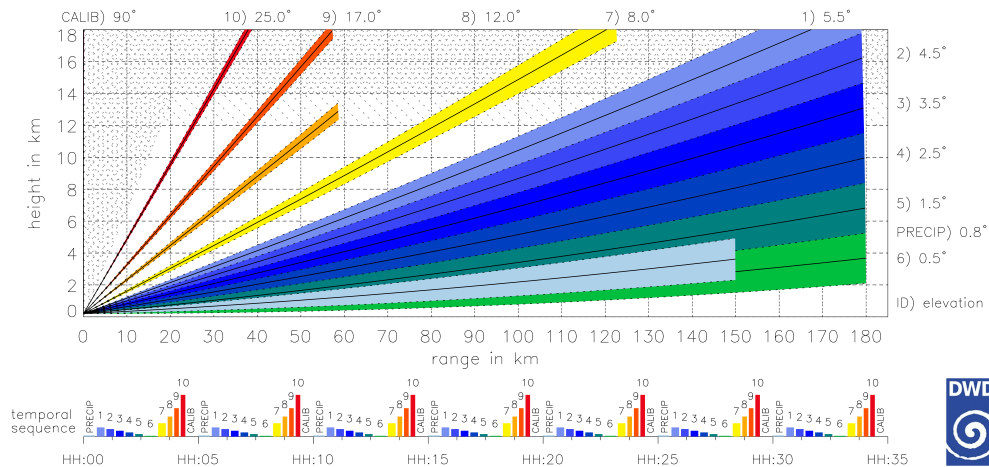
Figure 2. The DWD radar scan strategy since 2012 with its 10 volume scans and 1 precipitation scan.

insurance data. By focusing primarily on larger hail events, we may inadvertently overlook occurrences of smaller hail, which are equally significant. So we focus on the temporal analysis of hail occurrences of insurance data.

3 Methods

130   This study focuses on two different radar-derived proxies to detect hail size: Vertically Integrated Ice (VII) and Maximum Expected Size of Hail (MESH). The first step as well for VII (Sec. 3.1) as for MESH (Sec. 3.2) is to collect the 11 radar elevation scans that will be used to construct a 3D data cube of reflectivity measurements, a composite in three dimensions. The geometric height of different temperature levels is derived from vertical temperature profiles of ICON-D2 (Icosahedral Nonhydrostatic) model (Reinert et al., 2020) and combined with the 3D data cube.

135   For both algorithms, a minimum threshold of 7.5 mm is used to discriminate between hail and no hail.

3.1 VII

The Vertically Integrated Ice (VII) is a measure of the frozen water content in a vertical column. At DWD it is expressed in water equivalent and, therefore, differs from the definition established in the literature (Gauthier et al., 2006; Mosier et al., 2011). The height of the temperature with -10 °C H_{-10} is approximated by the height of the melting layer H_0 with a constant

140   height offset. VII is calculated from the radar reflectivity Z by:

$$VII = \int_{H_{-10}}^{H_{-\infty}} 3.44 \cdot 10^{-6} Z^{\frac{4}{7}} dH \tag{1}$$

During the internal evaluation process of the VII product, forecasters proposed a linear relationship between observed hail size and VII: VII_hailsize[mm] $=$ VII $\cdot 0.75$ (Böhme et al., 2017).

3.2 MESH

145   With the 3D data cube of reflectivities, it is possible to calculate the Severe Hail Index (SHI). The SHI is calculated by transforming reflectivity data (Z) between $Z_L = 40$ dBZ and $Z_U = 50$ dBZ $(W(Z))$ into hail kinetic energy flux $(\dot{E})$, applying a temperature weighting function $(W_T(H))$, and vertically integrating this value from the storm top to the radar level (Witt et al., 1998). The heights for the melting layer (H_0) and for a temperature of -20 °C (H_{-20}) are derived by ICON-D2.

$$W(Z) = \begin{cases} 0 & \text{for } Z \leq Z_L \\ \frac{Z - Z_L}{Z_U - Z_L} & \text{for } Z_L < Z < Z_U \\ 1 & \text{for } Z \geq Z_U \end{cases} \qquad W_T(H) = \begin{cases} 0 & \text{for } H \leq H_0 \\ \frac{H - H_0}{H_{-20} - H_0} & \text{for } H_0 < H < H_{-20} \\ 1 & \text{for } H \geq H_{-20} \end{cases}$$

$$\dot{E} = 5 \cdot 10^{-6} \cdot 10^{0.084 Z} W(Z) \qquad \text{SHI} = 0.1 \int_{H_0}^{H_T} W_T(H) \dot{E} \, dH$$

150   From that we can deduce the Maximum Expected Size of Hail (MESH). First, MESH was derived by Witt et al. (1998). They used 147 hail observations for their derivation of SHI to MESH. As the intention of MESH is to anticipate the maximum

possible hail diameter, the resulting value should be higher than 75 % of the observations. This leads to:

$$\text{MESH[mm]} = 2.54 \cdot \text{SHI}^{0.5} \tag{2}$$

Murillo and Homeyer (2019) revised the approach and used 5897 observations to fit the power law. The resulting new power laws, one again with the MESH values higher than 75 % of the observations and one higher than 95 %:

$$\text{MESH[mm]}_{75} = 15.096 \cdot \text{SHI}^{0.206} \tag{3}$$

$$\text{MESH[mm]}_{95} = 22.157 \cdot \text{SHI}^{0.212} \tag{4}$$

Both fittings were made with S-band radars in the US. As we can make use of a great amount of observation data, we have derived our own SHI–MESH relationships for the German C-band radar network.

With the WarnWetter app we also have the opportunity to derive a power law for our region of interest. We must take into account, that the observations made via the WarnWetter app are given in categories. Therefore, we have selected the reference values as our observation. For the category "under 1 cm" a value of 0.5 cm and for "above 7 cm" a value of 7 cm were defined as reference. We took the highest SHI in a 5 km radius around the observation and in the last 15 minutes before the observation took place, as the report should be done after the hail reached the ground. Only data from April to September of the year 2022 and 2023 was used and SHI–observation pairs where the SHI was higher than 0. Our fittings for the larger hail sizes may not be optimal due to the lack of data. We had only 36 observations for 7cm, as they are prone to errors and varied a lot in their SHI values, we left them out in the fitting. With that we receive the power laws out of 9556 observations:

$$\text{MESH[mm]}_{75} = 0.4607 \cdot \text{SHI}^{0.8665} \tag{5}$$

$$\text{MESH[mm]}_{95} = 0.9216 \cdot \text{SHI}^{0.9739} \tag{6}$$

$$\text{MESH[mm]}_{\text{mean}} = 0.0071 \cdot \text{SHI}^{1.4877} \tag{7}$$

Figure 3 depicts the relations of SHI to reported hail sizes. It is important to note that the fitting to the power law is very sensitive.

4   Results

In the following, we present the results for hail observations in Germany, focusing on three key areas. First, we examine the human observed data, highlighting its quality and characteristics. Next, we analyze hail sizes and occurrences as detected by C-band weather radars, comparing the findings of two different algorithms with human observed data to assess their quality. Finally, we explore the economic impact of hail events through insurance data and show how hail events can lead to significant financial losses in the region.
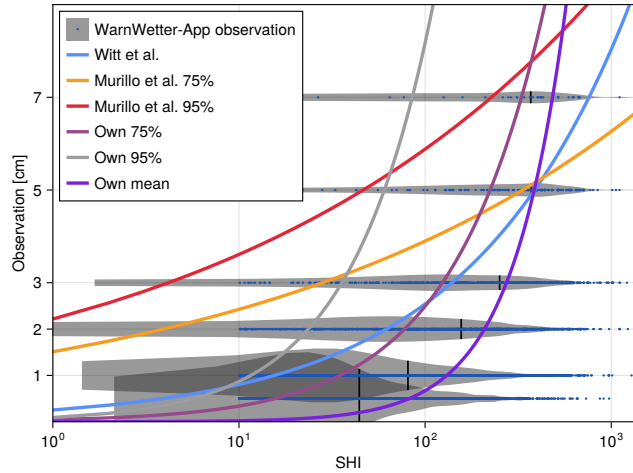
Figure 3. Comparison of all power laws to a violin plot including its median of the data from the German WarnWetter app for the year 2023.

4.1 Human observed data

In this section, we examine various sources of human observed data. We first assess the quality of crowdsourced data through a survey. This study used 3D printed hailstones to evaluate how precisely people estimate the size of hail. With these finding as context, we then present spatial and temporal patterns of human observed data across Germany.

4.2 Assessing the quality of human observed data

To develop and improve algorithms that identify hail events from radar observations, validation data is required. However, it is unclear whether user reports from the WarnWetter app are reliable enough to provide additional information for validation purposes. To answer this question, we conducted a brief study using 3D printed hailstones based on hail models (Mirkovic and Zrnic, 2023) (see Fig. 4).

Figure 4. Six examples of 3D printed hailstones in different sizes and forms.

In total we had 12 hailstone samples in use, 6 round and 6 oval ones (diameter 2:1) with sizes of the larger diameter of 0.5 cm, 1 cm, 2 cm, 3 cm, 5 cm and 7 cm. In the study we asked questions relating to 9 of those hail stones. In total we asked 149 participants (76 male, 68 female) with an age distribution found in Tab. 1. In Tab. 2 the number of interviews for the different

sizes and the form of the hailstones are listed. After the participants accepted the data processing, they were asked to estimate

Age range	Participants
under 20	23
20–40	72
40–60	30
above 60	21
no answer	3

Table 1. The number of people asked in the different age groups categorized by age.

Size	Form	Number of interviews
3 cm	round	15
3 cm	oval	23
7 cm	oval	7
1 cm	round	11
5 cm	oval	14
2 cm	oval	11
7 cm	round	14
1 cm	oval	23
5 cm	round	31

Table 2. The number of interviews for each hailstone.

the diameter of a 2 € coin to obtain a control value for their ability to estimate sizes, independently of a hailstone. Afterwards, they were asked to estimate the size of the presented hailstone. The survey included two separate values. In the first phase, participants were asked to answer freely. In the second phase, they were given options for their answers. The options were the same as in the reporting process of the WarnWetter app.

Hagelkorngröße (hail size)

- Unter 1 cm (Linse) (under 1 cm lentil)

- 1 cm (Erbse) (1 cm pea)

- 2 cm (10 Cent Münze) (2 cm 10 cent coin)

- 3 cm (Kronkorken) (3 cm crown cork)

- 5 cm (Golfball) (5 cm golfball)

- Über 7 cm (Tennisball) (above 7 cm tennisball)

In addition, demographic data was gathered for statistical evaluation.

205 The true value of the diameter of a 2 € coin is 2.575 cm. The estimated mean diameter of all survey participants is $M = 2.538$ cm, with a minimum of 1 cm and a maximum of 6 cm. The distribution of answers for the different ranges of age can be found in Fig. 5. Most of the age groups underestimated the size of the coin, only the 20–40 year olds overestimated the size in the mean, but in the median they were very good with 2.5 cm. The best mean achieved the under 20 year olds with $M = 2.508$ cm, but they had as well as the 20–40 year olds some outliers with 5–6 cm and the median is too low.

Figure 6 depicts that with the categories as options, the participants had chosen the right category in most of the times (75.17
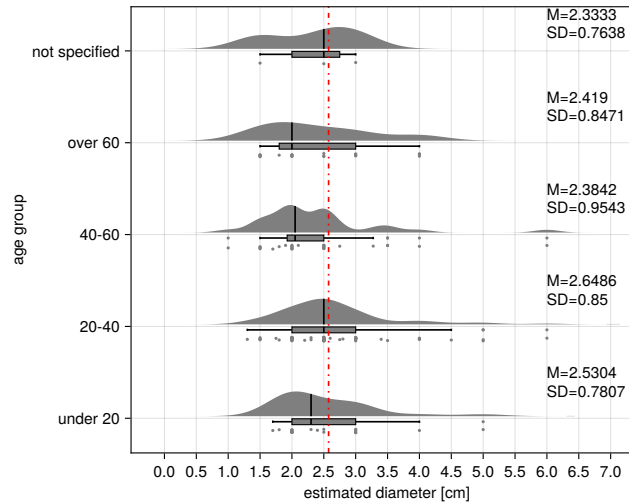
Figure 5. The distribution with its median of answers for the question *How large is a 2 € coin?* in the different age groups. The correct answer is shown as red dashed line. The mean and standard deviation for each group are presented in the figure on the right.

210

%). Nevertheless, in case of wrong categories mostly smaller ones were chosen (18.79 %). There is no difference for round and oval hailstones visible. Figure 6 also shows the free estimation of hail stone size in cm as a kernel density estimation. Without the option to choose a category, the distribution of answers is much broader, still with a median that is close to the right size. The distributions are almost symmetrical, with a median which tends to be too small. The deviation to the true value stays

215 similar through all sizes.

At the end, we compared the results of the initial estimation question about the size of the 2 € coin with the results of the freely given answers for the hailstones. Figure 7 clearly shows that there is no clear linear relationship between those two answers. This may be due to the fact, that the hailstone was presented and could be touched. Most of the participants needed to imagine the size of a 2 € coin.

220 In a nutshell, we can say that the mean of the estimated sizes is quite good and close to the real value, but individual estimations can be quite inaccurate. It seems that estimating the size of an object of imagination, like the 2 € coin in our survey, is not directly comparable to an object that is visible. Most of the answers to the categorical options were right, but
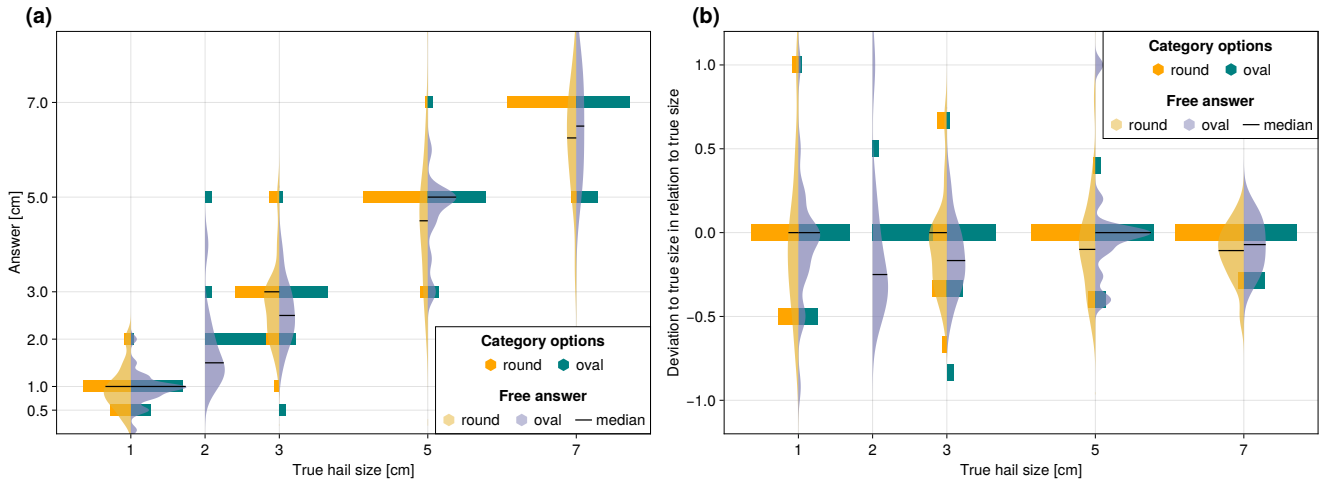
Figure 6. (a): The distribution of answers to the category options for estimating the size of the presented hailstone as bars and the free answers as kernel density estimation with its median. (b): The deviation to the true hail size in relation to the true hail size.
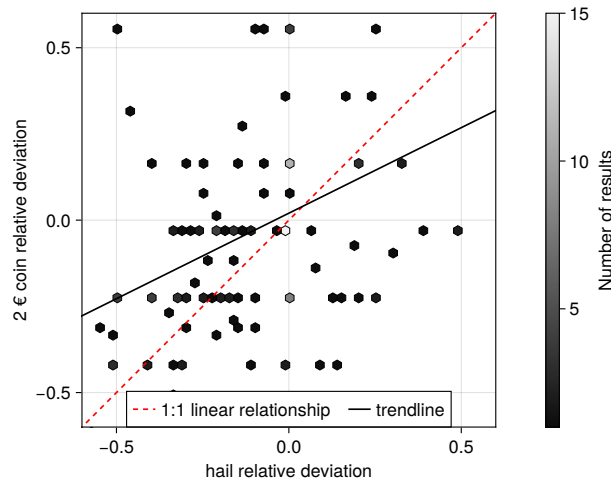
Figure 7. The comparison of deviations from the estimation of the size of a 2 € coin and the freely given answers to the hailstone size estimation.

there are also some wrong answers. As we have a low spatial density of observations in the WarnWetter app most of the time, we need to keep in mind, that there might be wrong values due to bad estimation abilities. If the estimation of the size is off, it is likely to be underestimated. Giving the categories seemed useful, as only for small hail sizes, the number of wrong categories is noticeable.

4.3 Analysis of crowdsourced data in Germany

Based on crowdsourced data from ESWD, WarnWetter app and station observations we will address the questions of diurnal and annual cycles and hotspots of hail in Germany. In Fig. 8(a) the diurnal cycle of hail reports is depicted. For this analysis the station observations were excluded due to missing information concerning the time of the hail event.

The number of hail observations clearly shows a diurnal cycle, as the reports are very close to be normally distributed around

(a)

(b)
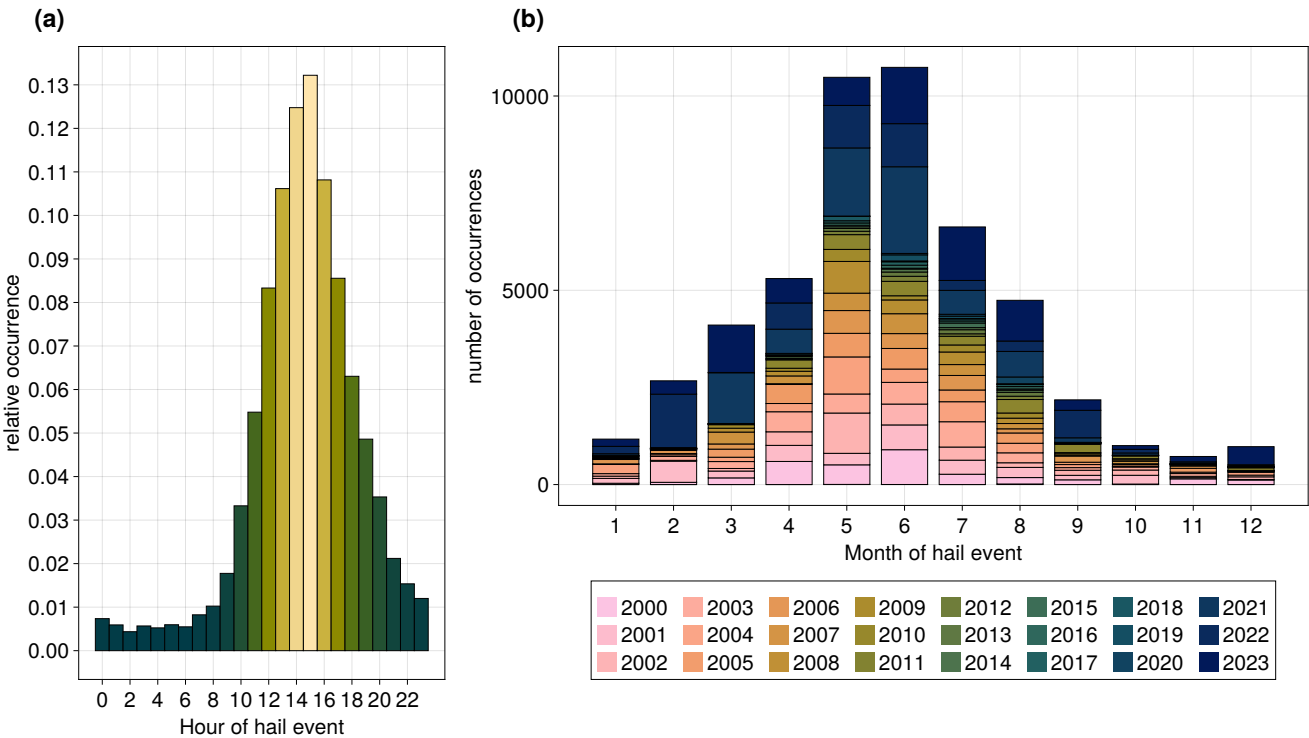
Figure 8. Hail observations in its (a) diurnal cycle based on data from ESWD and WarnWetter app and (b) annual cycle based on data from station observations, ESWD and WarnWetter app.

15 UTC (17 CEST), with a standard deviation of about 3 hours. Reports of night time (23 UTC–8 UTC, 1 CEST–10 CEST) hail events are rare. There are also two months in which there is a higher probability of hail being observed, namely May and June (see Fig. 8(b)). Beyond the convective season the number of reports is negligible with the exception of March 2021 and February 2022. All in all, there are much more reports of the WarnWetter app than from the ESWD, visible through the higher numbers since 2021. Figure 9 depicts the reported sizes in the ESWD and the WarnWetter app. Small hail is more prominently occurring from February to September, medium hail occurs mainly in June, but also in May, July and August. In Germany only a few reports of hail that exceeded 5 cm were recorded in the last 23 years. Large to giant hail is most likely to occur from May to August.
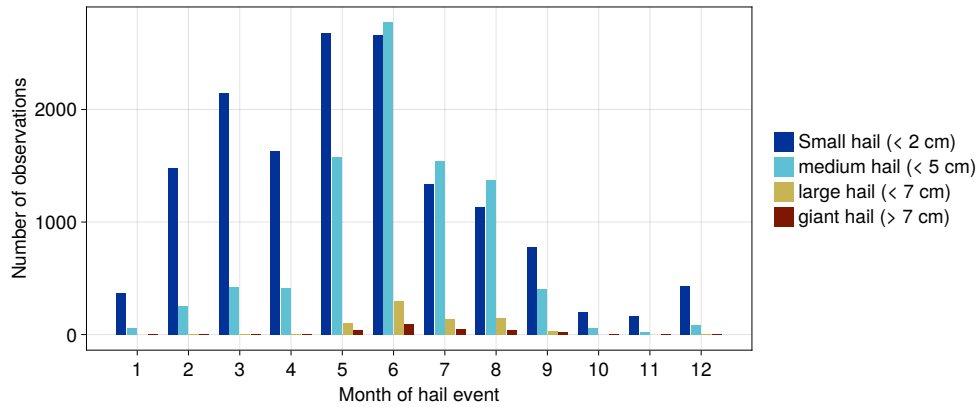
Figure 9. Distribution of hail sizes of observations in Germany from the ESWD and the WarnWetter app.

The distribution of hail reports in Germany is displayed in Fig. 10(a) in a h3 grid of level 6 (Uber Technologies Inc., 2018). There are some hotspots visible in the south of Bavaria (close to Munich), in the middle of Baden–Wuerttemberg (close to Stuttgart), North Rhine–Westphalia in the Ruhr valley, Hessia in the Rhine–Main region and Berlin. In the north of Germany there are only a few hail reports. All areas with hail hotspots have a high population (see Fig. 10(b)). To examine whether the observations underlay an urban reporting bias, Fig. 10(c) shows the number of observations in a cell, normalized to the population. No such hotspots are visible any longer, only the Pre–Alps have a slightly higher number of observations than the rest of Germany. Some cells are more noticeable because of station observations that have been in one place for a long time and therefore reported hail for each day if apparent. In conclusion, the absence of hotspots in the normalized Fig. 10(c) clearly emphasizes the existence of an urban reporting bias, as there is no longer a visible difference in hail occurrence over Germany.
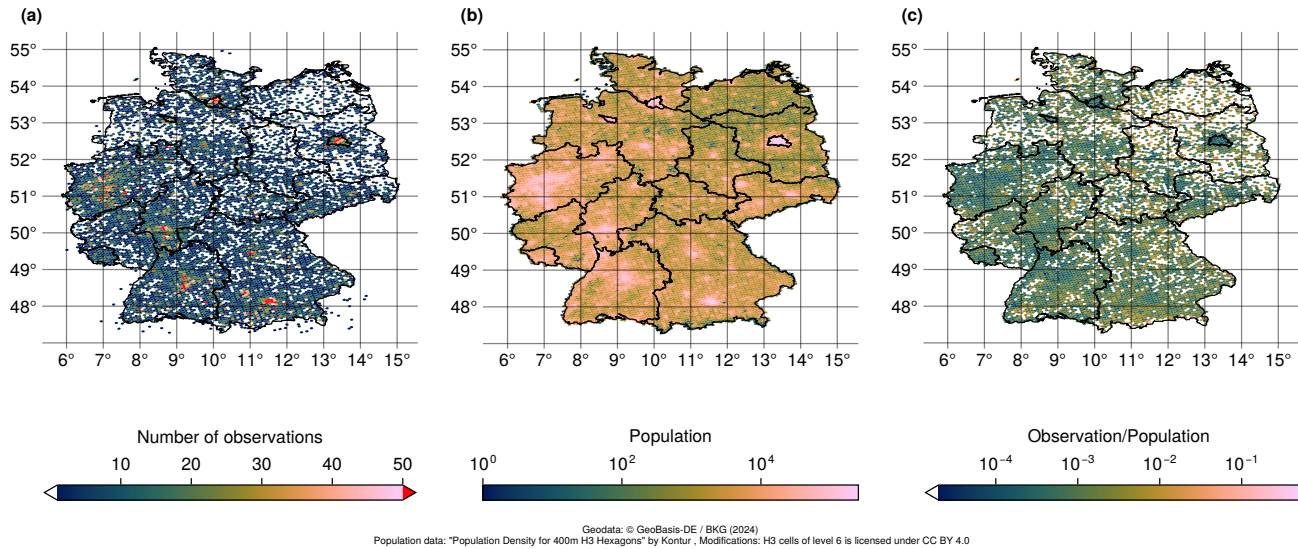
Figure 10. (a) Number of crowd observations in Germany 2001–2023 based on data from station observations, ESWD and WarnWetter-App. (b) Population in Germany (c) Normalized number of observations to the population

4.4 Radar data

250 In this section, we use a case study to analyze hail sizes derived from C-band weather radars using two methods: MESH and VII. We then compare these results with human observations. Based on our results, we focus on VII to describe hail characteristics in terms of size and occurrence across Germany.

4.5 Comparison of VII and MESH

For the comparison of MESH, VII and crowd data, we use the relationship of SHI to MESH we developed for the German C-
255 band radar network of 75% (Eq. 5). We compare the performance of MESH to the data of the reported sizes in the WarnWetter app for a case study of a hail event from 15 August 2021 (see Fig. 11). Further on, we have a look at differences between the resulting MESH sizes and the sizes retrieved by VII (compare Fig. 11 (a) with Fig. 11 (b)). Assuming the presence of hail for both algorithms, only if their value is greater than 7.5 mm, we might not account for reports of the category "smaller than 1 cm".

260 Generally, we see that the hail track is matched quite well for MESH and VII in comparison to the crowd data. The MESH hail size is larger than the VII hail size. The MESH track shows more areas with small hail sizes. Most of the crowd data are reported within those two tracks, only a few reports of small hail are located outside the tracks. MESH overestimates the sizes
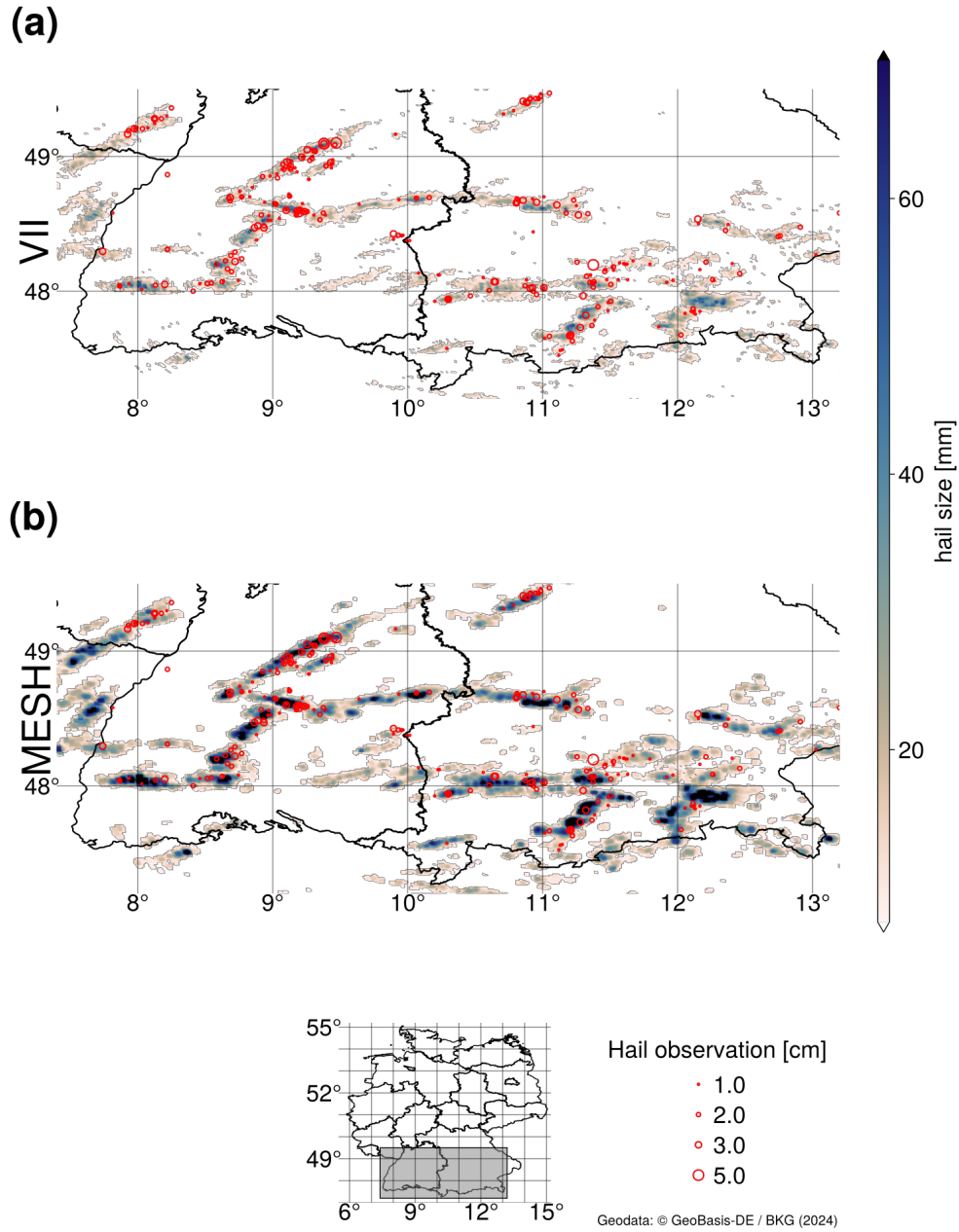
Figure 11. (a) VII with Crowd data from 15.08.2021 zoomed into southern Germany. (b) MESH with crowd data from 15.08.2021 zoomed into southern Germany.

clearly. VII has similar magnitudes of hail size to the observations, and the locations also fit quite well. For this reason, the following analysis is done for VII over the period 2018–2023.

4.6 Multi annual analysis of Vertical Integrated Ice (VII) in Germany

The study covers a relatively short period of 6 years from 2018–2023, but nevertheless it can give great insides to the hail distribution over Germany. First we have a look at the total hail days in the period under review. In Fig. 12 the mean number of hail days from 2018–2023 based on VII is shown.

Geodata: © GeoBasis-DE / BKG (2024)
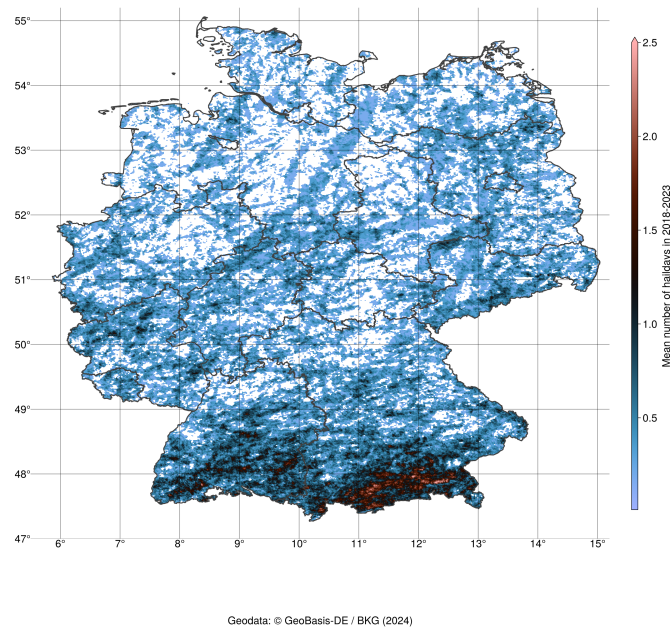
Figure 12. Mean number of hail days in a year based on VII from 2018–2023

The occurrence of hail shows a gradient from north to south with a maximum in the alpine foothills of Bavaria. However, according to the VII approach, 80.6 % of Germany within a 1x1 km^2 area is hit by hail at least once in those 6 years. The mean number of hail occurrences per year is about 0.33, this means approximately 2 hail events in the analyzed period. The maximum number of hail days for one gridcell is 19 days in the timeperiod. The largest amount of hail days can be found in the German low mountain ranges in the most southern part. Although, Fig. 12 shows that hail is possible everywhere in Germany, hail occurrence and hail size strongly depend on single storm tracks. The number of hail days in 2019 in Fig. 13(a) shows hot spots in the eastern part of Germany, contrary to 2021, in Fig. 13(b), where there are hot spots in the Pre–Alps. In 2019 only 25 km^2, in 2021 almost 900 km^2 had more than 4 hail days in Germany.

Also the maximum hail size in each year is highly influenced by single storms (see Fig. 14). On average the maximum hail size is about 1.5–3cm depending on each year. Single storms producing clearly visible hail tracks (see Fig. 14(a)) which also lead to larger hail sizes. One of the largest hail storms in the recent years can also be seen in Fig. 14(b). The hotspot of

Geodata: © GeoBasis-DE / BKG (2024)
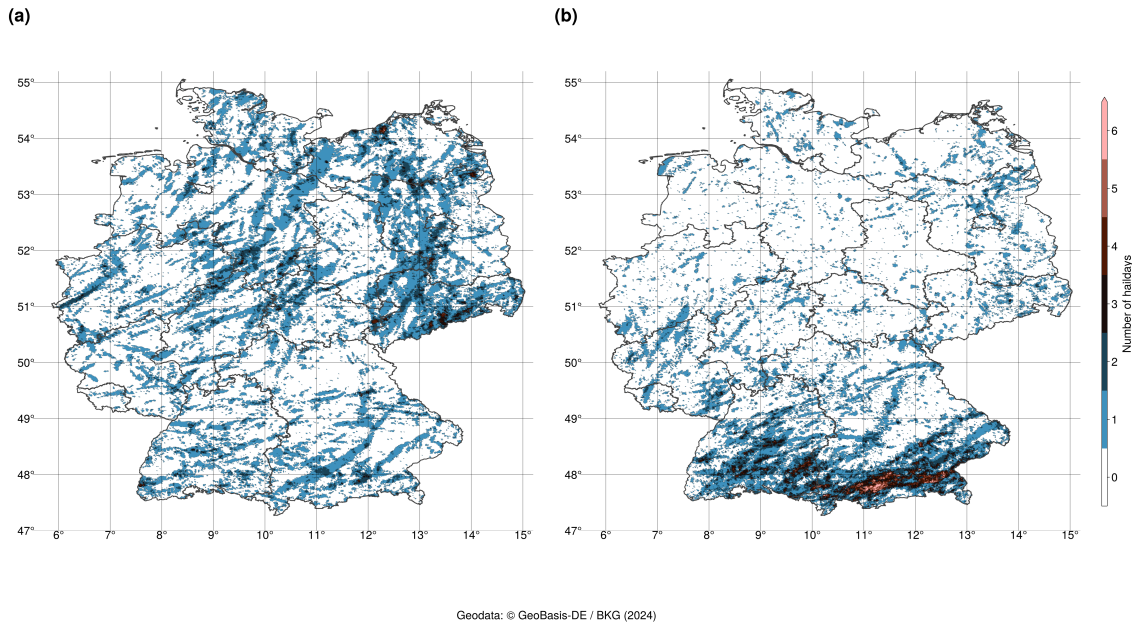
Figure 13. Two example number of the number of hail days basaed on VII with very distinct hotspots (a): in 2019 (b): in 2021

maximum hail sizes is situated directly over Kassel (mid of Germany) with hail larger than 7 cm. The area with extreme hail has a large track and a large width.

The maximum hail size over 2018–2023 is shown in Fig. 15. There are only very few hail days where individual supercells produced hailstones larger than 5 cm. Most of the detected hail sizes are smaller than 2 cm. The occurrence of hail using VII shows a clear annual cycle (see Fig. 16) which is in accordance to the results with crowdsourcing data (Sec. 4.1). From April to June (Fig. 16(a)–(c)) the number of hail days increases, with numbers subsequently decreasing again afterwards till September (Fig. 16(d)–(f)). Before April and after September, VII cannot detect any reasonable amounts of hail. A similar annual cycle can be observed for the maximum hail size (see Fig. 17). In April (Fig. 17(a)) there are some hailstorms, but with only small sizes. In May (Fig. 17(b)) the sizes are getting larger, until finally peaking in June (Fig. 17(c)). In the Pre–Alps large hail also occurred in August (Fig. 17(e)) during the investigated period.

Geodata: © GeoBasis-DE / BKG (2024)
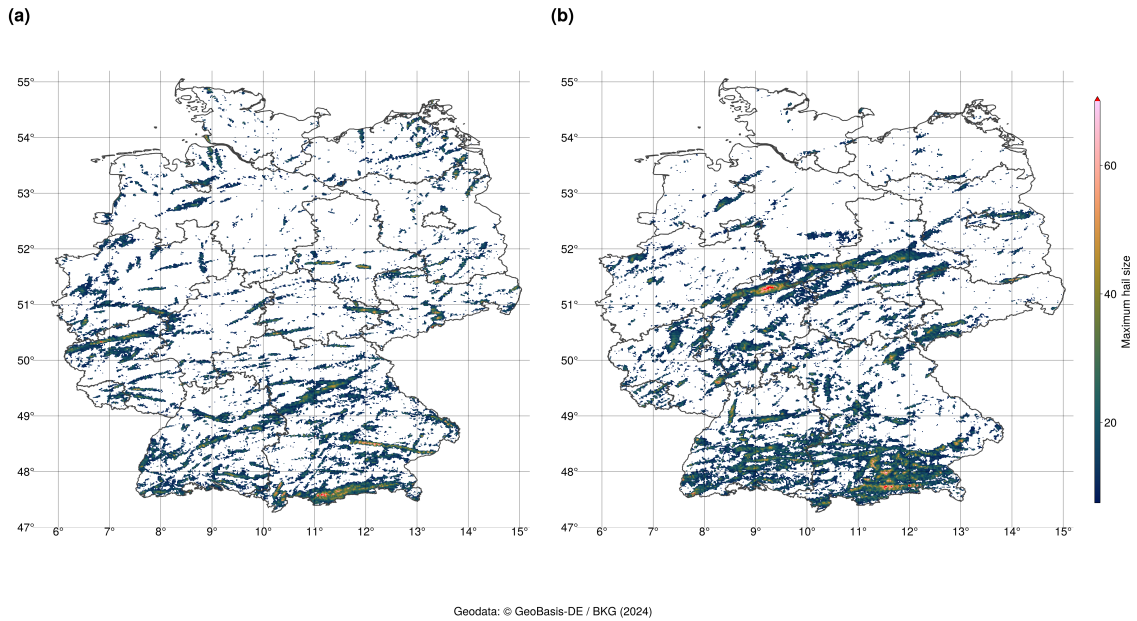
Figure 14. Two examples of the maximum hail size based on VII (a): in 2022 and (b): in 2023

4.7 Insurance data

The analysis in Fig. 18 depicts that June is the month with the most damage caused by hail with a mean of 33 972 damage reports. In July, a similar mean number of damages is reported in terms of the number of damage reports, with a mean of 29 492. The hailstorm that occurred in July 2013 had a significant impact on the mean number of damage reports. If 2013 is left out of this analysis, the mean drops to only approximately 15 002 damage reports. The number of reports on damage in April ($M = 1509$) and September ($M = 1228$) is relatively low, while in May ($M = 9230$) and August ($M = 11526$), the number of reports is in the midfield. The loss expenses show a very similar picture to the number of damage reports. It is quite interesting that in 2022 the loss expenses in May (100.43 Mio €) and September (21.2 Mio €) are much higher than in the years before (May: $M =$ 24.53 Mio €; September: $M =$ 3.18 Mio €). In June, July and August 2022 the loss expenses are on a similar level or smaller.

5 Summary and future work

As hail is a weather phenomena which is hard to observe and measure, only a few studies about spatial and temporal patterns for hail in Germany exist. In this study we investigated hail statistics for Germany derived from human observed data and C-band weather radar data using the methods vertically integrated ice (VII) and maximum estimated size of hail (MESH). We used crowdsourced data by the WarnWetter app operated by the DWD, manned weather stations and ESWD data to analyze mainly temporal patterns of hail occurrence. With the benefit of spatial coverage, radar data were used to overcome the lack of

Geodata: © GeoBasis-DE / BKG (2024)
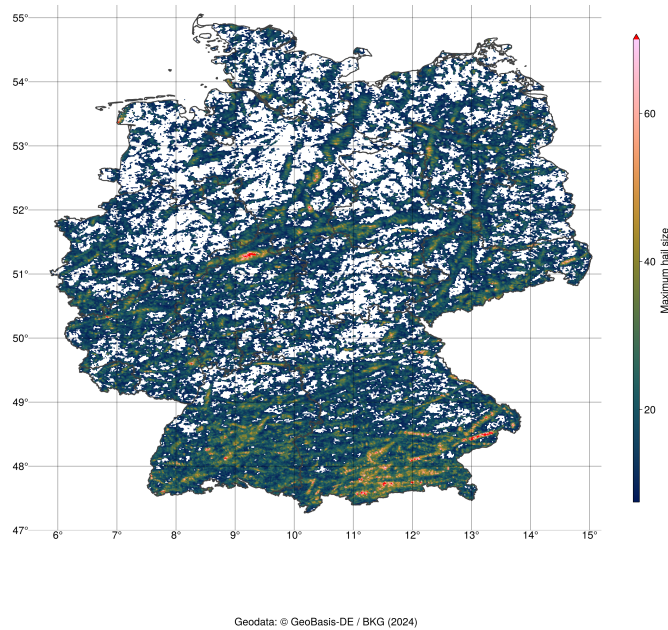
Figure 15. The maximum hail size based on VII for each pixel over 2018–2023.

spatial information in human observed data. Insurance data give us a hint on the destructiveness of hail in the measure of loss expenses.

In what follows, we attempt to answer the questions posed in the introduction. Our first focus is on the question "Can we rely on human observed hail data in their size estimation?". The use of human observation data is challenging for the use of hail size
310   estimation. The location, date and time may be more reliable than the actual size of the hail estimate. In our study, we found that the mean of many observations is usually very good, but individual observations can be misleading. If the size is wrongly estimated, it is more probable to be underestimated. Giving a category with a known object for reference in mobile phone applications brings a benefit over freely given values. Further on, the number of observations underlays the urban reporting bias, as more observations are reported in areas with higher population. Therefore, human observations should be treated with
315   caution, but can still give us a good first idea of the hail event.

To overcome the problem of urban reporting bias, radar data can be used, but "Are the radar based algorithms VII and MESH suitable for determining hail (size) climatologies for Germany?" Even despite the use of the own developed relationship of SHI and hail size, MESH clearly overestimates the hail size in comparison with crowdsourced data. VII gives similar hail sizes as human observed data in our case study. Therefore, we used VII for showing maximum hail sizes and hail occurrences in
320   Germany for our study period of 2018–2023.

For answering the question if hail events in Germany are rare or frequent natural hazards, we can combine results of radar
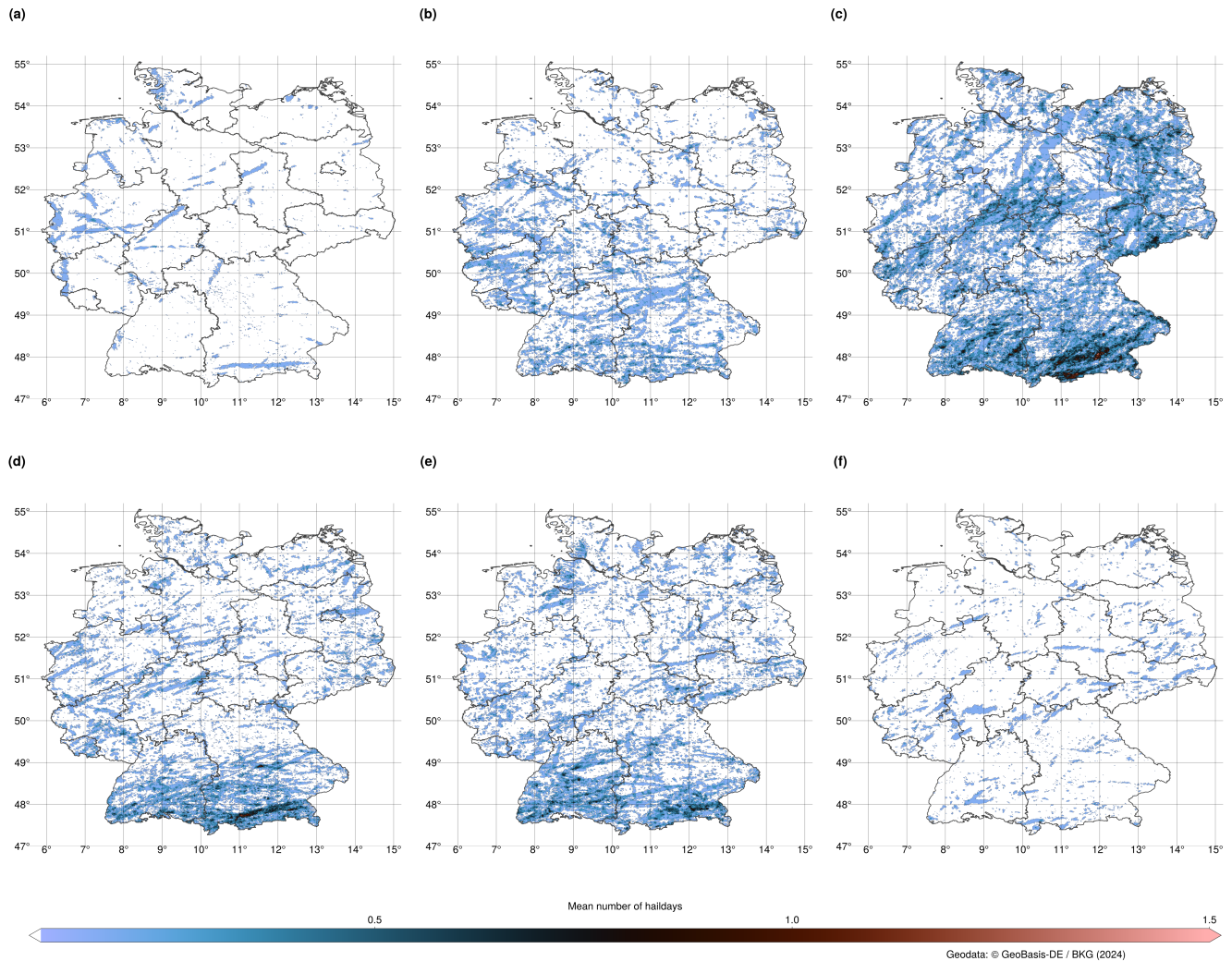
Figure 16. The annual cycle of hail days from 2018 to 2023 in Germany based on VII from (a): April ascending over (b): May reaching its prime time in (c): June and descending from (d): July (e): August to (f): September

data and human observed data. Unfortunately, there is no clear answer to this question because the frequency of hail is quite variable in Germany. Large to giant hail is very rare in Germany. The south of Germany has a higher chance to be hit by large hail and is typically hit more frequently by hail storms than the north. Nevertheless, also large hail events are possible all over Germany like the hailstorm in the middle of Germany 2023 has shown. Púčik et al. (2019) and Kaltenböck et al. (2009) used the ESWD data to analyze the diurnal cycle of hail in Europe. Their findings that the diurnal peak of hail occurrence is about 15–16 UTC can be confirmed also with the longer timeseries of this study for Germany. It must be noticed that crowdsourced data are likely biased in terms of diurnal cycle with an underrepresentation during night. Púčik et al. (2019) depicted a similar annual cycle pattern for southern Europe (regions south of 46°N latitude) to the annual cycle found by this study. For regions
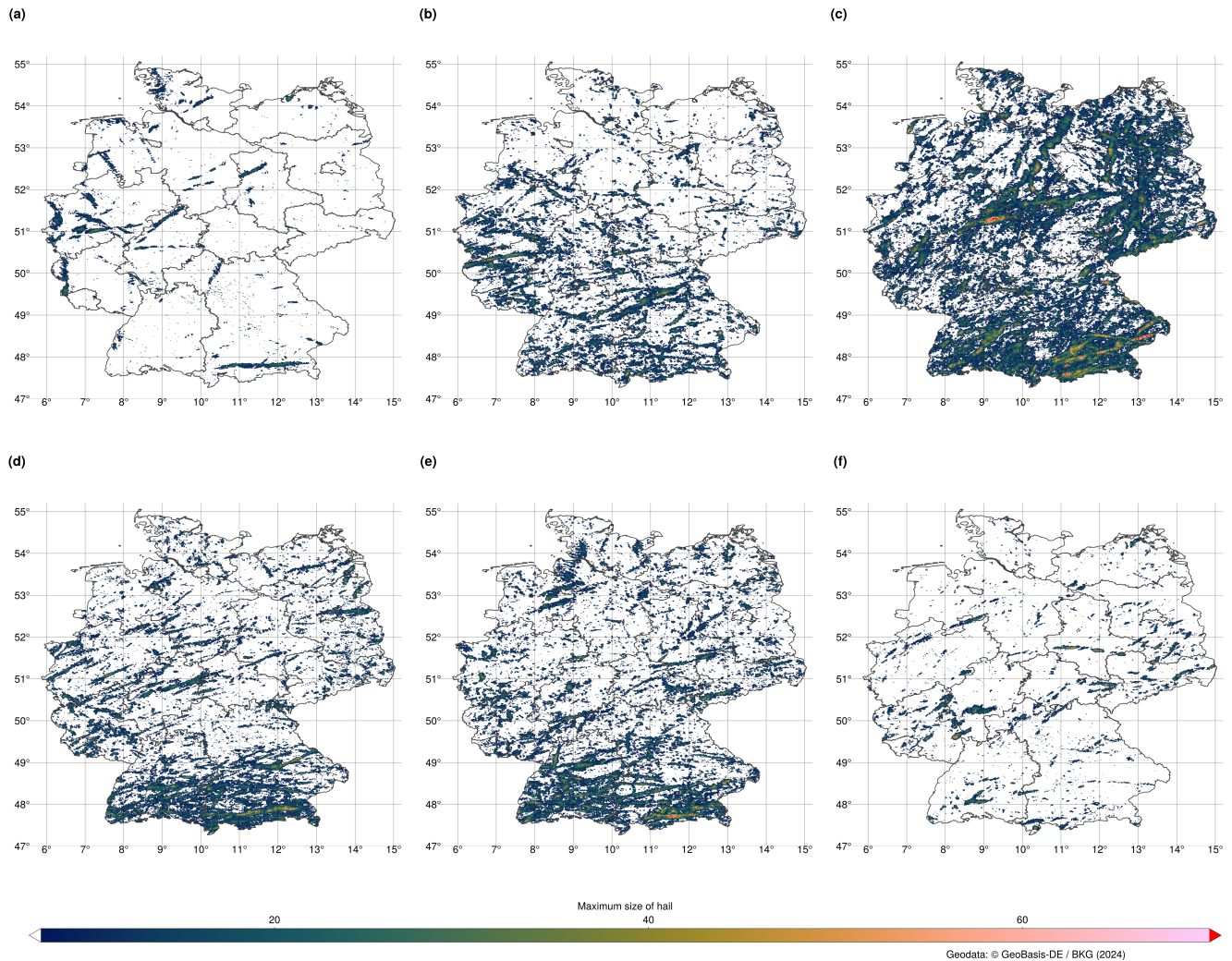
Figure 17. The annual cycle of hail sizes from 2018 to 2023 in Germany based on VII from (a): April ascending over (b): May reaching its prime time in (c): June and descending from (d): July (e): August to (f): September

north of 46°N they found more activity in July. With the VII derived from radar data we clearly see June as the month with the most hail days for whole Germany.

For crowdsourced data the analysis showed many reports in the highly populated Ruhr and Rhine–Main area and in the larger cities like Berlin and Munich (urban reporting bias). The hotspot close to Stuttgart (south–west Germany) that was found previously (Puskeiler et al., 2016) can be seen in the VII data.

With the use of radar based algorithms, we can produce a picture of hail over the whole of Germany. We can confirm the overestimation of MESH, which Brook et al. (2024) has overcome with an empirical correction. We have chosen VII for the multi year analysis, as it fits better the crowd data in our case study in terms of hail size. The case study shows that the hail
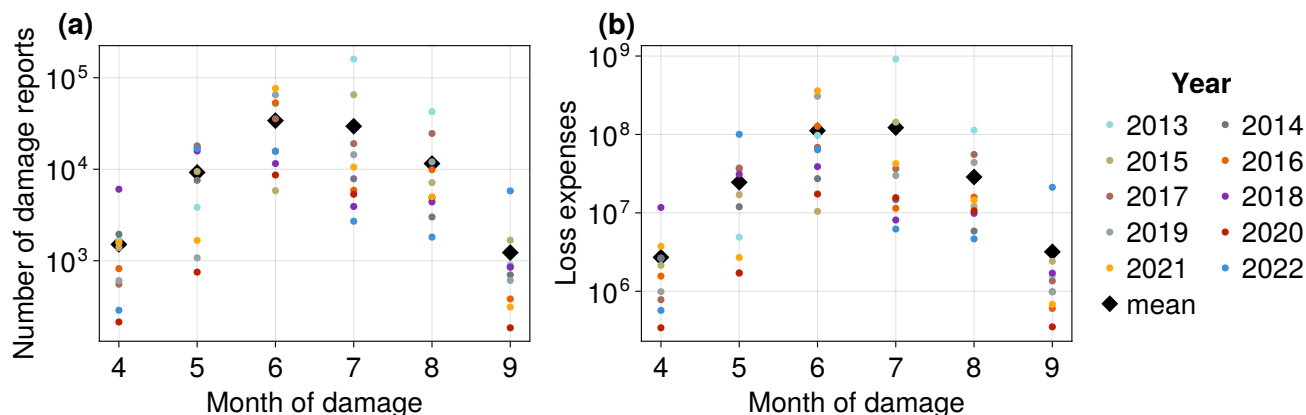
Figure 18. Insurance data for the summer months each year 2013–2022. (a) Number of damage reports. (b) Sum of loss expenses.

tracks of MESH and VII fit perfectly to the observations.

Only through observation data it is currently not possible to calculate any trends in hail occurrence, due to a varying number

340 of observers over the years. The WarnWetter app introduces much more active observers than we had before. The same is true for the ESWD data that increased in number of reports over time. With radar data we see years with a lot of hail, e.g. 2021, and years with few hail, e.g. 2020. Overall, the analyzed period of 6 years is not long enough to define a trend and was out of scope of this study. For trend analysis modelled data (Battaglioli et al., 2023; Wilhelm et al., 2024) might be a better fit as long as other consistent time series are too short.

345 A question for the future is to determine the most appropriate metric for determining the severity of hailstorms. Should the largest individual hailstone be used as the benchmark? Alternatively, could we consider an average diameter? What is the ground truth for this approach? An alternative approach would be to omit the exact hail sizes and identify the impact or damages directly (e.g. (Schmid et al., 2023)). If crowdsourced data is used, it is important to consider the potential biases that may affect the results. The position may be inaccurate, there may be a population bias, and there is a possibility that only

350 large hail is being reported. Additionally, there is an estimation problem and a diurnal cycle for reporting. For future work, it might be interesting to recalculate VII for earlier years to see if there are any patterns or trends in hail occurrence in Germany. Furthermore, the SHI–MESH relationship could be fitted to a longer time series of observed data. As we have some diverse data sources, artificial intelligence methods could be beneficial to combine all data sources and result in impacts for the population or hail probability.

355 *Author contributions.* TW prepared the original draft of the manuscript, performed data analysis, including coding and plotting. MS implemented the algorithms. All authors have contributed to the manuscript and to the interpretation of the results.

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