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# Hail events in Germany, rare or frequent natural hazards?

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**Abstract.** Hail in Germany is a natural hazard that is not in everyone's focus, even though it can cause great damage. In this study we focus on hail frequency, sizes and spatial distribution in Germany based on crowd sourcing and weather radar data. We derive hail sizes from radar reflectivity through the use of vertically integrated ice (VII) and maximum estimated size of hail (MESH). With that we create a hail climatology for Germany out of 6 years radar data. We found that hail can occur over whole Germany, but is much more probable in the south. The size of hail depends heavily on the storm, as we see hail tracks with large hail sizes. June is the month with the most and largest hail events. The mountainous areas are hit more frequently by hail than the lower parts. We analyzed crowd data in a short study to obtain how well people can estimate sizes especially hail sizes. In summary, the mean of a crowd is a quite good fit, but individual estimates can be very wrong. In comparison to radar data we found that MESH overestimates the hail size clearly, VII is in our case study a good fit.

## 1 Introduction

Hail is a major natural hazard that causes severe damage and high costs, but is it also a problem for scientists? 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 1500 Mio €, another event in July 2013 to 3600 Mio € and the newest one in June 2023 with 740 Mio € total loss are the recent examples of very heavy, damaging hailstorms in Germany (dkk, 2021; gdv, 2023). In Australia for example, hailstorms are the hazard with highest total normalised loss with 35 % of all natural hazards (Crompton and McAneney, 2008). 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 technical infrastructure, but also to cars, houses and people. But how arises hail, what do we know about it and why is it so difficult to measure its size, occurrence and distribution?

Measuring hail is difficult task. There are different sources of hail observation: The human observation, indirectly through damages reported to the insurance companies, remote sensing, disdrometers and hailpads. Each of them has its own advantages and disadvantages. Human observation no matter whether professional at stations or voluntary through apps, 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 Section 4.2). The last problem occurs in every measuring method of hail: it melts through falling and laying

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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 population bias, weather radars can be a useful tool. They cover a large area and provide observations with high spatiotemporal resolution as well as the opportunity to use three dimensional data. We cannot derive hail size from radar data directly. Therefore, the challenge is finding a measure that provides us with the hail size and/or distribution. 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 size at the ground should hereby be proportional to the difference of heights. From that the probability of hail (POH) arose, that is represented with $0 \Rightarrow H_{45} - H_0 = 1.4 - 1.65$km to $100 \Rightarrow H_{45} - H_0 = 5.5 - 6$km (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), not to be confused with the Maximum Estimated Severe Hail Size (MESHS) (Trefalt et al., 2022). 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 in mm (Witt et al., 1998; Murillo and Homeyer, 2019). We must keep in mind that C-Band radars tend to underestimate hail sizes (Brook et al., 2024).

The upgrade of single- to dual-polarized radar systems was expected to make it easier and more accurate to estimate hail size. Aydin et al. (1986) and Depue et al. (2007) suggest the hail differential reflectivity $H_{\text{DR}}$ which combines the reflectivity $Z$ and the differential reflectivity $Z_{\text{DR}}$. Ryzhkov et al. (2013) however remark that the melting process of hail is neglected and thus propose a fuzzy-logic scheme that includes the cross correlation ratio $\rho_{\text{hv}}$ additionally. $\rho_{\text{hv}}$ describes the ratio between the horizontal and the vertical dimension of the echo, large hail is expected to have lower $\rho_{\text{hv}}$ 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 holding the hail stone longer in the cloud to collect more ice on its surface. $Z_{\text{DR}}$ columns can provide good information for the identification of updraft (Snyder et al., 2015). Another hint for updraft dimensions and thus hail size is the Specific Differential Phase ($K_{\text{DP}}$) 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

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(Handwerker, 2002). The hail climatology for Germany shows hotspots which are heavily dependent on the orography. Junghänel et al. (2016) added reported data to the radar data. Similar results also based on radar data were found by Fluck et al. (2021).All the hail climatologies have the hotspot of hail in the south of Stuttgart in common. Further on, they share the north-south descent of hail days. This was also observed in modeled hail days (Battaglioli et al., 2023).
In this paper we introduce a hail climatology based on vertically integrated ice on a six year analysis period for Germany. We compare it to crowd sourced data in its annual cycle and spatiotemporal frequency. In a case study we depict the similarities and differences. Further on, we focus on the questions, if we can rely on human observed data in their size estimation and how MESH and VII differ from each other in their hail estimation.

## 2 Data

### 2.1 Human observed data

For the human observed data there are three different data sources available.
The WarnWetter-App operated by Deutscher Wetterdienst (DWD) is a mobile phone application informing the public about the current and forecasted weather and integrates a warning function. The application enables users to submit reports concerning their observations of weather conditions as well as upload pictures. Upon reception, all submissions are quality-checked. Regarding hail reports, users are provided with the following report options: *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 founded in 2006. It contains data on severe convective storm events contributed by the public like eyewitness reports or voluntary spotters and is quality-controlled. With an update in the year 2008 the quality-control was further enhanced. 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 2cm. 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, 2014–2018 only a few reports were made (160–200 reports per year).
The largest dataset comes from stationary observations of the monitoring network operated by DWD. It combines manned weather stations and trained volunteer reports. Some reported hail on a daily base, some by the minute. In order to combine them, only the reported day of occurrence is taken into account. Due to the automation of weather observations, the number of reports decreases with time. First the number of volunteers dropped, later on the manned weather stations were replaced by automatic ones. For this reason the dataset only contains data up to 2017.
The problem of point observation data is, as usual, that spatial resolution is not very high and rural areas might be underrepresented as no one can report an event. Further on, only the stationary observations can give us a hint, about the absence of hail.

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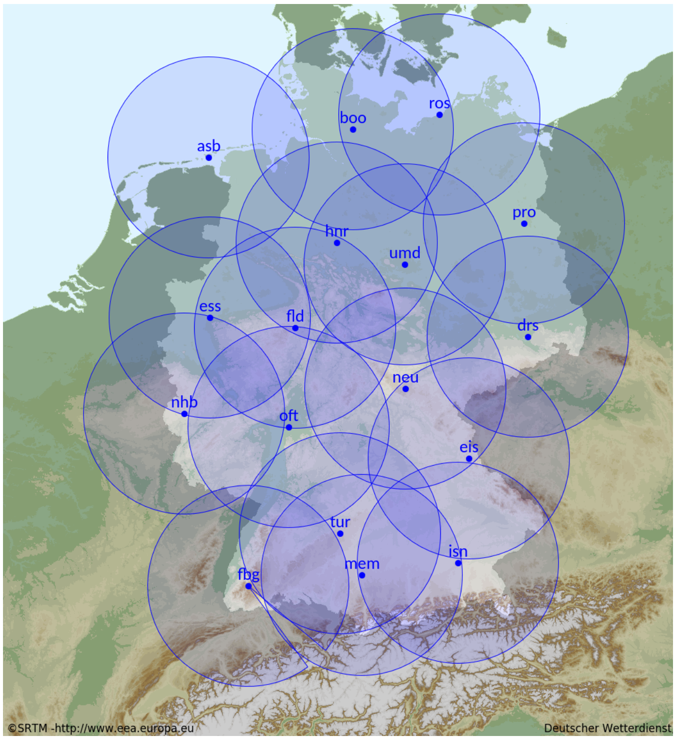


**Figure 1.** The German radar network with its 17 C-band radars.

The crowd sourcing data can only provide us with information about positive events, as no report does not automatically mean no hail.

All in all, there are 3769 hail reports in the ESWD from 2000 to 2020. There was no exclusion of reports because of their quality level. Further on, the reports of hail of the new WarnWetter-App of the DWD were used (since 2021). They are automatically quality controlled and partly included in the ESWD dataset, amounting to 39 142 reports. 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, reports of the stationary observations of the DWD are available. With 25 719 reports we could use another very large data set. In total the analysis includes 50 719 hail reports.

## 2.2 Radar data

The German radar network consists of 17 C-band doppler radars. The radar network covers almost all of Germany (see Fig. 1). Upgrading single- to dual-polarization radars was started in 2011 and concluded in 2021. Each radar provides 11 scans in different heights every 5 minutes (see Fig. 2).

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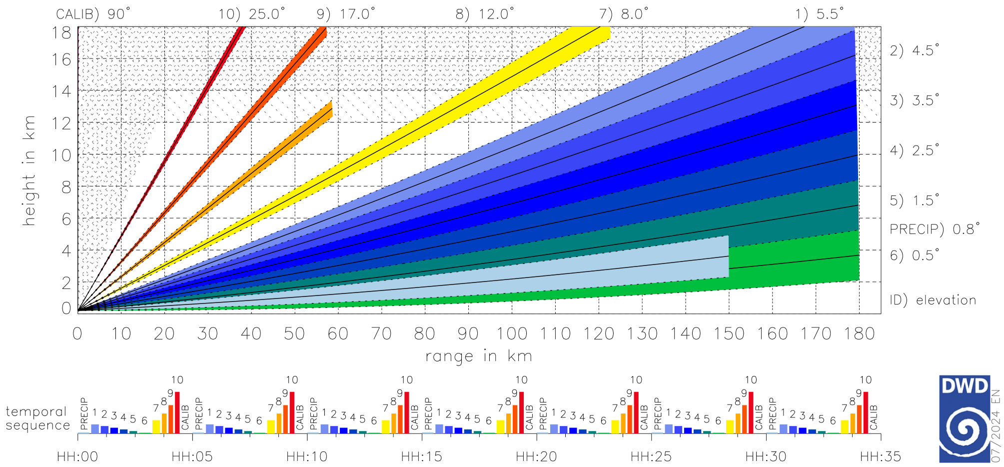


**Figure 2.** The DWD Radar-scan-strategy since 2012 with its 10 volume scans and 1 precipitation scan.

The volume scans range 180 km, the precipitation scan, a special volume scan which follows the orography, covers a range of 150 km. Both scan types have a horizontal resolution of 1° x 250 m with an temporal availability of 5 min.

In this study we will evaluate the years 2018–2023, with a particular focus on the months of April to September, as most convective cells arise during this time of the year.

### 2.3 Insurance data

The parent organization of all private insurance companies in Germany, the *German Insurance Association* (GDV), has kindly given us 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 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 Germany. This is because the damage cannot always be assigned to the precise day on which it occurred.

## 3 Methods

The first step as well for Vertically Integrated Ice (Section 3.1) as for Maximum Expected Size of Hail (Section 3.2) is to collect the 11 radar elevation scans that will be used to construct the 3D data cube, a composite in three dimensions. By incorporating the vertical temperature profile from the ICON model into the 3D data cube, the hail size can be retrieved.
For both algorithms, we assume hail only if the resulting hail size is greater than 7.5 mm.

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### 3.1 VII

The Vertically Integrated Ice (VII) describes the frozen water content in a vertical column. At the 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 height offset. VII is calculated by:

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

With the rule of thumb of VII_hailsize[mm] $=$ VII $\cdot\, 0.75$ that was described by our forecasters, we can achieve a hail size.

### 3.2 MESH

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 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 numerical models.

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

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

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 the MESH[mm] $= 2.54 \cdot \text{SHI}^{0.5}$.

Murillo and Homeyer (2019) revisited the approach, but used a lot more observations, 5897 in total, for fitting the power law. So this resulted in two new power laws, one again the MESH values higher than 75 % of the observations and one higher than 95 %:

$$\text{MESH[mm]}_{75} = 15.096 \cdot \text{ SHI}^{0.206} \tag{1}$$

$$\text{MESH[mm]}_{95} = 22.157 \cdot \text{ SHI}^{0.212} \tag{2}$$

Both fittings were made with C-band radars in the US. As we can make use of a great amount of observation data, we have derived our own MESH relationship.

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

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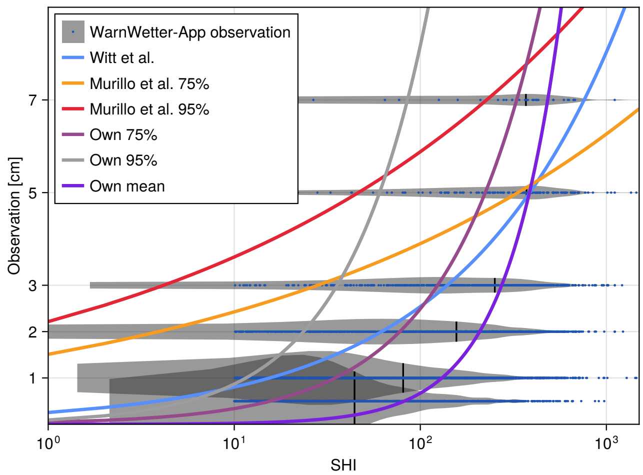


**Figure 3.** Comparison of all power laws to a violin plot including its median of the data from the German WarnWetter-App for the year 2023.

155 took place, as the report should be done after the hail reached the ground. Only data from the months of 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:

$$\mathrm{MESH[mm]}_{75} = 0.4607 \cdot \ \mathrm{SHI}^{0.8665} \tag{3}$$

$$\mathrm{MESH[mm]}_{95} = 0.9216 \cdot \ \mathrm{SHI}^{0.9739} \tag{4}$$

$$\mathrm{MESH[mm]}_{\mathrm{mean}} = 0.0071 \cdot \ \mathrm{SHI}^{1.4877} \tag{5}$$

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

165 ## 4 Pre-Study

### 4.1 Case study

For the comparison of MESH, VII and crowd data, we use the relationship of SHI to MESH of our own 75%. We compare the performance of MESH to the data of the reported sizes in the WarnWetter-App for case study of a hail event from 15 August 2021 (see Fig. 4). Further on, we have a look at differences between the resulting MESH sizes and the sizes retrieved by VII

170 (compare Fig. 4 (a) with Fig. 4 (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”.

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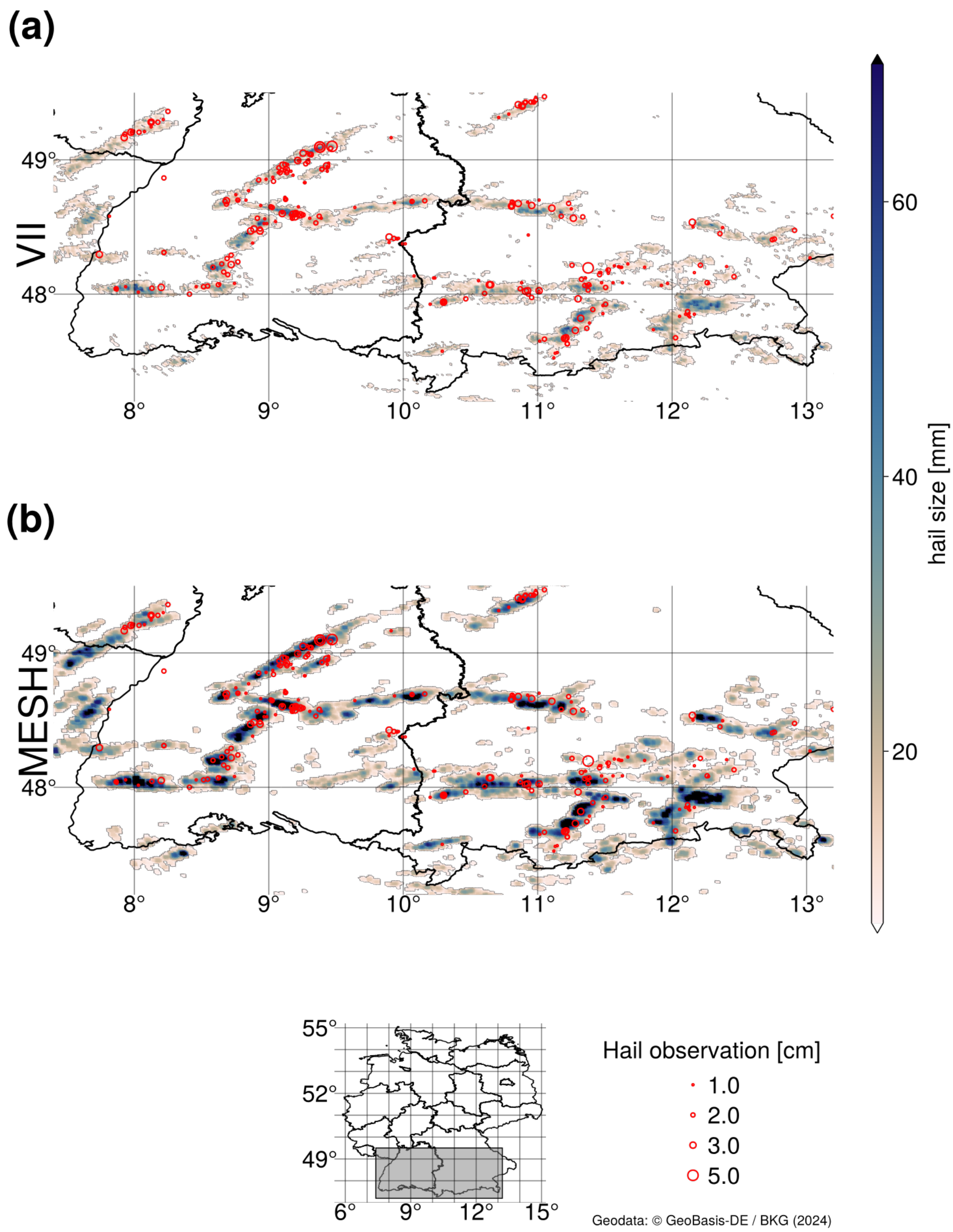


**Figure 4.** (a) VII with Crowd data from 15.08.2021 zoomed into southern Germany. (b) MESH with crowd data from 15.08.2021 zoomed into southern Germany.

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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 clearly, but VII seems to be a good fit.

### 4.2 Can we trust crowd sourcing observations?

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. 5).

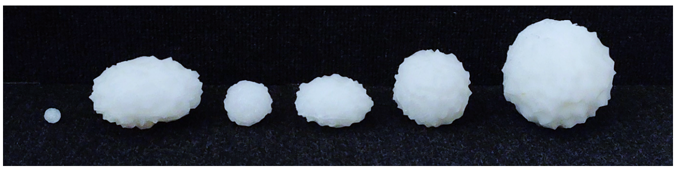

**Figure 5.** Six examples of 3D-printed hailstones in different sizes and forms.

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 Table 1. In Table 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.

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)

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| 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.

- 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)

At the end, demographic data was gathered.

#### 4.2.1 Results

The true value of the diameter of a 2 € coin is 2.575 cm. The estimated mean diameter 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. 6. 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 with 2.5 cm very good. 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 outlier with 5–6 cm. Having a look at the median, it is for the under 20 year olds too low.

Figure 7 depicts that with the categories as options, the participants had chosen the right category in most of the times (75.17 %). Nevertheless, in case of wrong categories most of the time smaller ones were chosen (18.79 %). There is no difference for round and oval hailstones visible. Figure 7 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 similar through all sizes, getting sharper with size.

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 8 clearly shows that there is no good linear relationship between those two answers.

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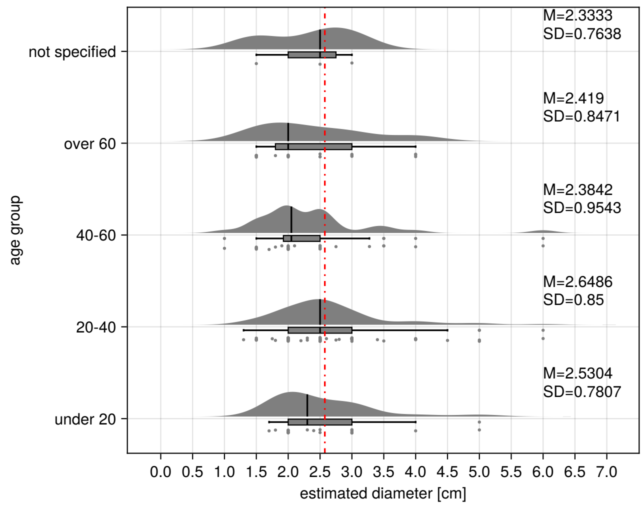


**Figure 6.** The distribution with its median of answers for the question *How large is a 2 € coin?* in the different age groups. The correct answer is shown as red dashed line. The mean and standard deviation for each group are presented in the figure on the right.

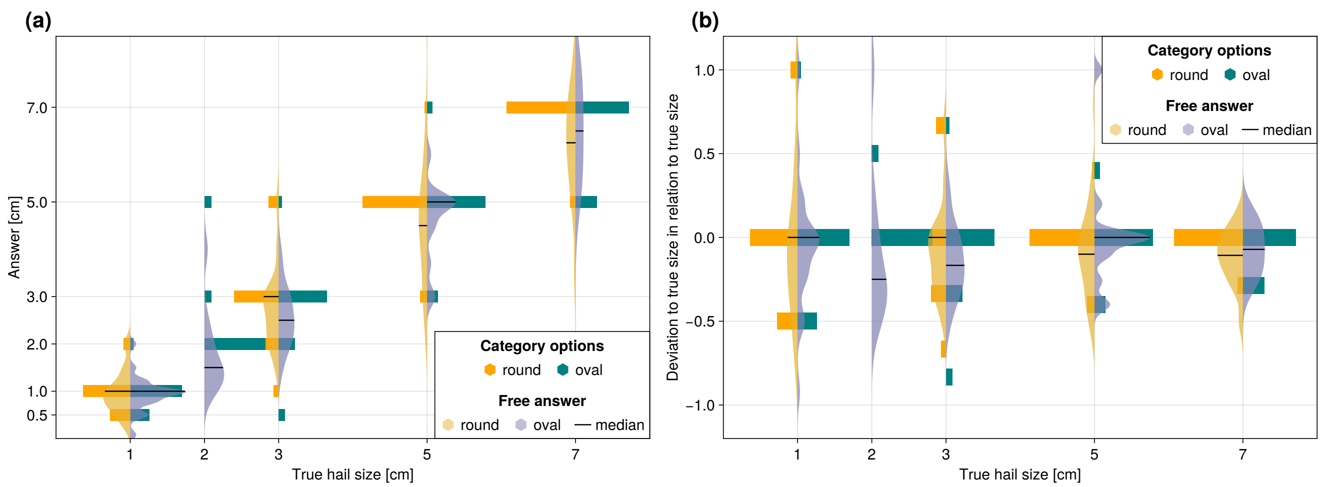


**Figure 7.** (a): The distribution of answers to the category options for estimating the size of the presented hailstone as bars and the free answers as kernel density estimation with its median. (b): The deviation to the true hail size in relation to the true hail size.

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.

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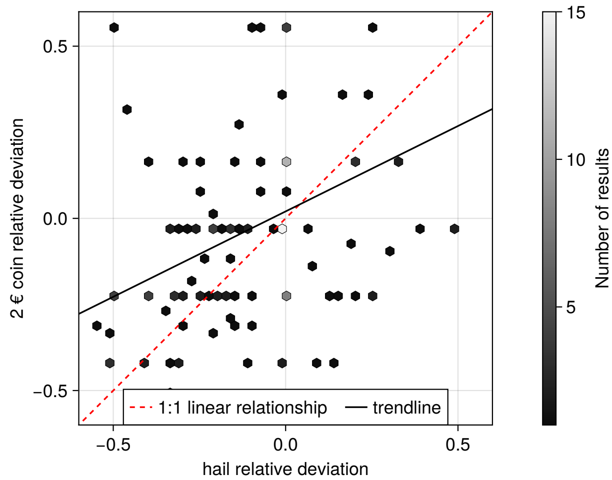


**Figure 8.** The comparison of deviations from the estimation of the size of a 2 € coin and the freely given answers to the hailstone size estimation.

#### 4.2.2 Bottom line

In a nutshell, we can say that the mean of the estimated sizes is quite good and close to the real value, but a single person can be quite bad in estimations. 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 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.

## 5 Results

### 5.1 Information retrieval from human observed data

The first questions we address with crowd data are if there is a diurnal cycle of hail, if in some months it is more likely to observe hail and if there are hail hotspots in Germany. In Fig. 9(a) the diurnal cycle of hail reports is depicted. For this analysis the stationary 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 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. 9(b)). Beyond the convective season the number of reports is negligible with the exception of March 2021

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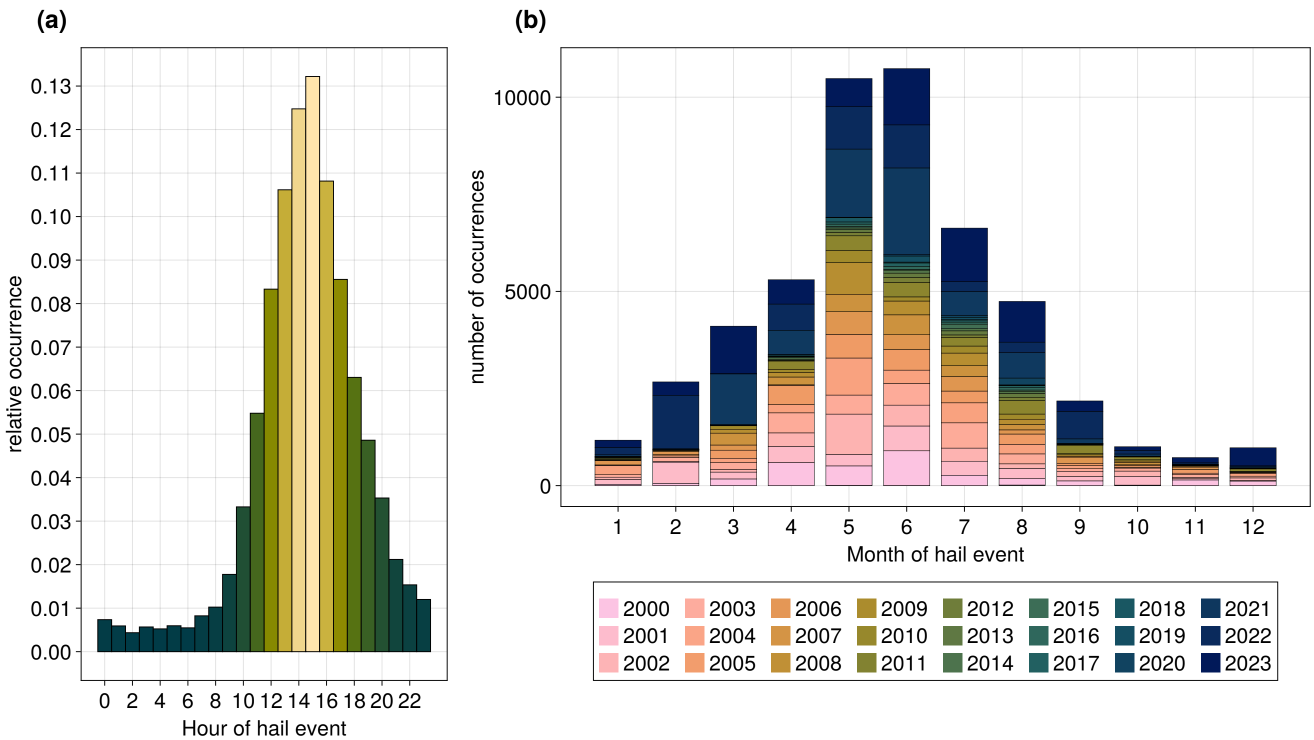


**Figure 9.** Hail observations in its (a) diurnal cycle based on data from ESWD and WarnWetter-App and (b) annual cycle based on data from stationary observations, ESWD and WarnWetter-App.

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 10 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.

The distribution of hail reports in Germany is displayed in Fig. 11 in hexagons of 0.05°. 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. The north of Germany has not that many reports. This reflects the observation-bias in urban areas.

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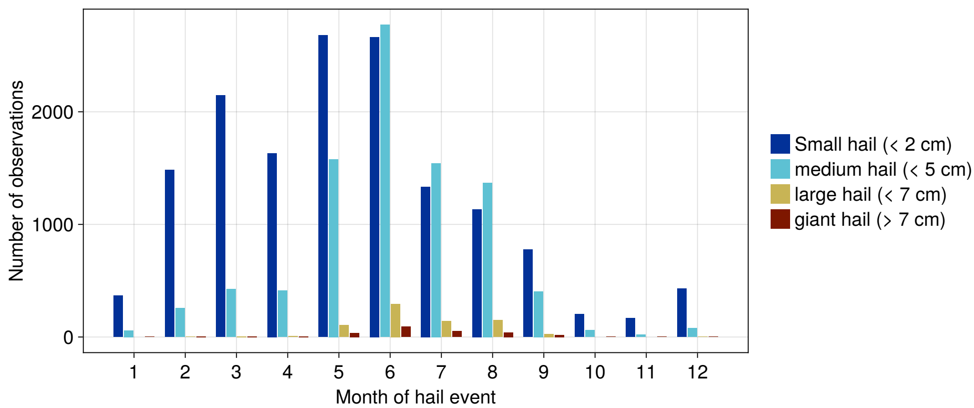


**Figure 10.** Distribution of hail sizes of observations in Germany from the ESWD and the WarnWetter-App.

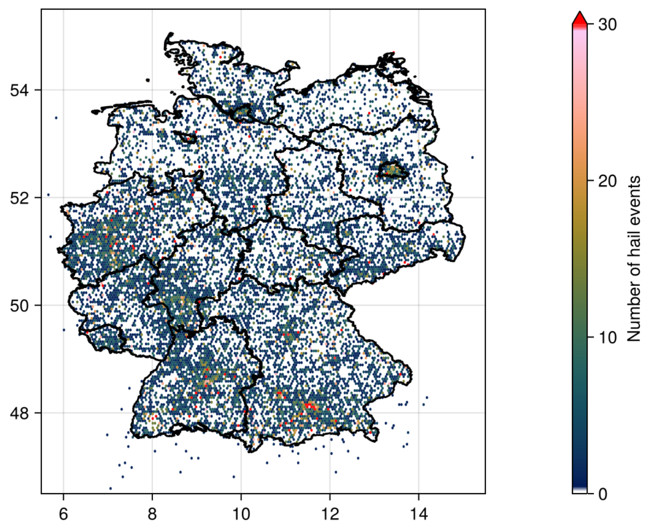


**Figure 11.** Number of crowd observations in Germany 2001–2023 based on data from stationary observations, ESWD and WarnWetter-App.

### 5.2 Vertical Integrated Ice (VII)

The climatology covers a relatively short period, 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.

The occurrence of hail is clearly higher in the south of Germany than in the north. However, 80.6 % of Germany is hit by hail at least once in those 6 years. The mean number of hail occurrences in a year is about 0.33, this means approximately 2 hail events in the analysed period. The maximum number of hail days for one gridcell is 19 days in the timeperiod. The largest

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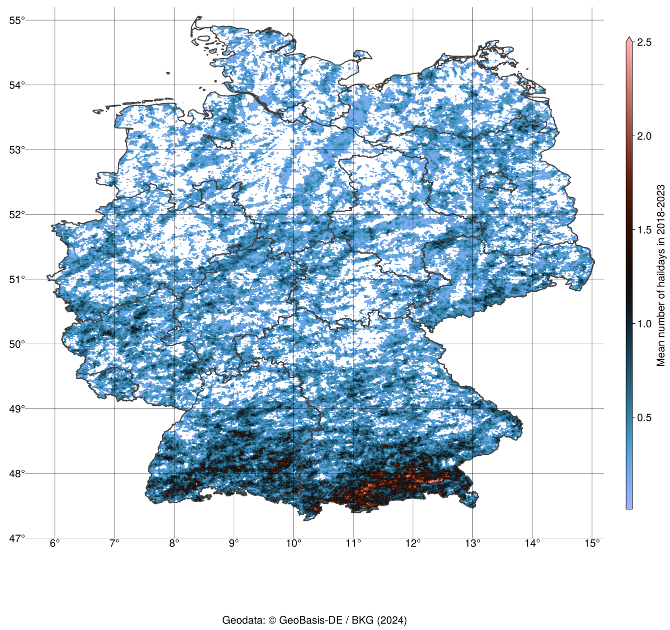


**Figure 12.** Mean number of hail days in a year based on VII from 2018-2023

amount of hail days can be found in the German low mountain ranges in the most southern part. Although, Fig. 12 shows a clear picture that hail is possible everywhere, it depends heavily on single storm tracks where and in which size the hail reaches the ground. 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))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 maximum hail sizes is situated directly over Kassel (mid of Germany). 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 which produce hailstones larger than 5 cm. Most of the hail is smaller than 2 cm.

From the analysis of observational data, it had already been demonstrated that there is an annual cycle of hail occurrence. Additionally, the VII data shows a clear annual cycle (see Fig. 16). 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. The same pattern can be observed for the maximum hail size

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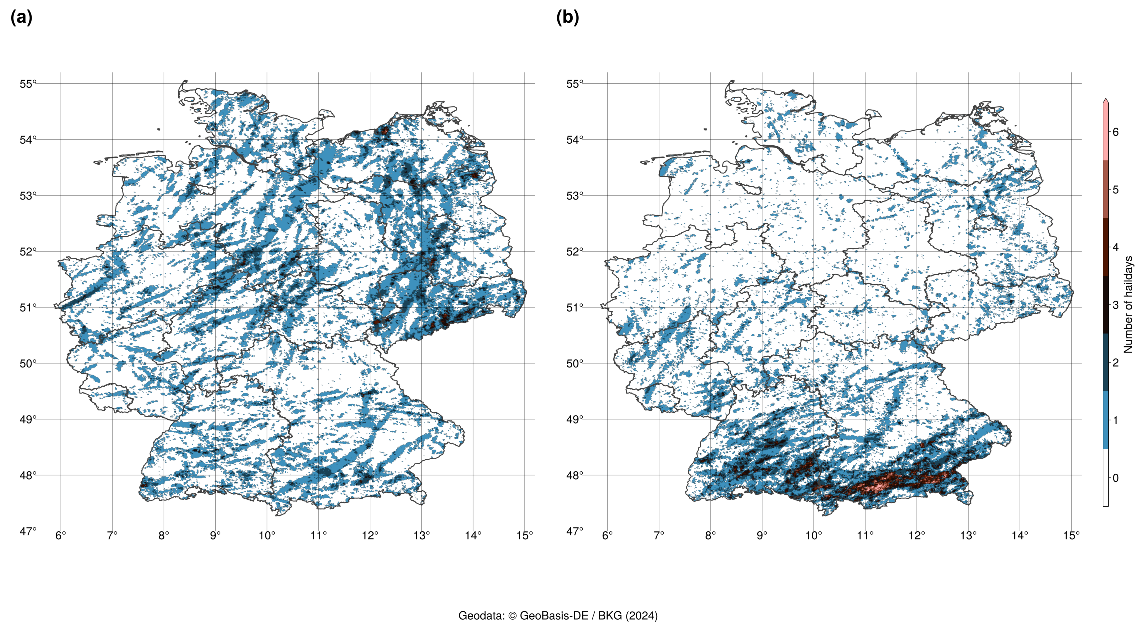


**Figure 13.** Two example number of the number of hail days basaed on VII with very distinct hotspots (a): in 2019 (b): in 2021

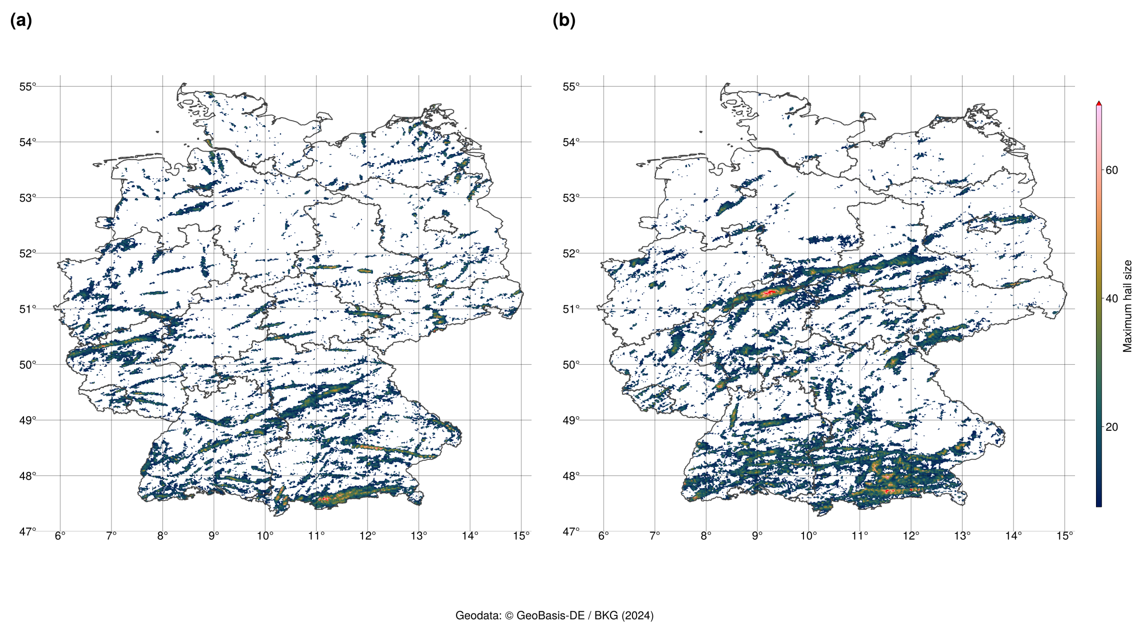


**Figure 14.** Two examples of the maximum hail size based on VII (a): in 2022 and (b): in 2023

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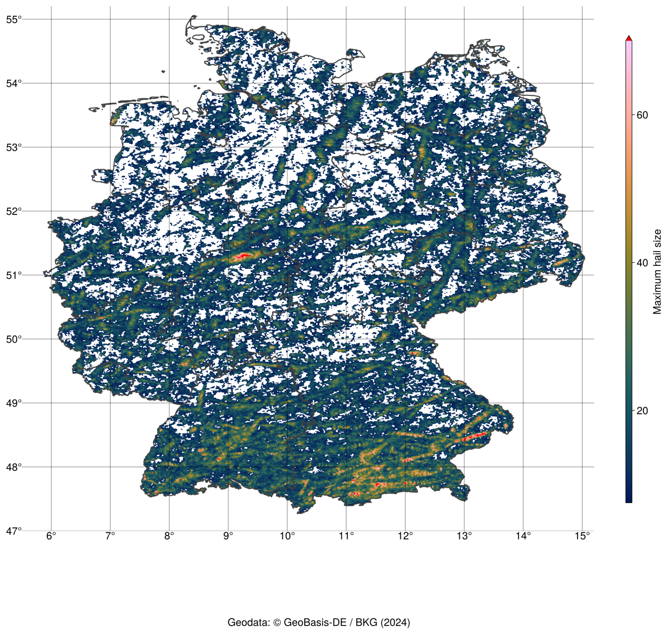


**Figure 15.** The maximum hail size based on VII for each pixel over 2018-2023.

(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)).

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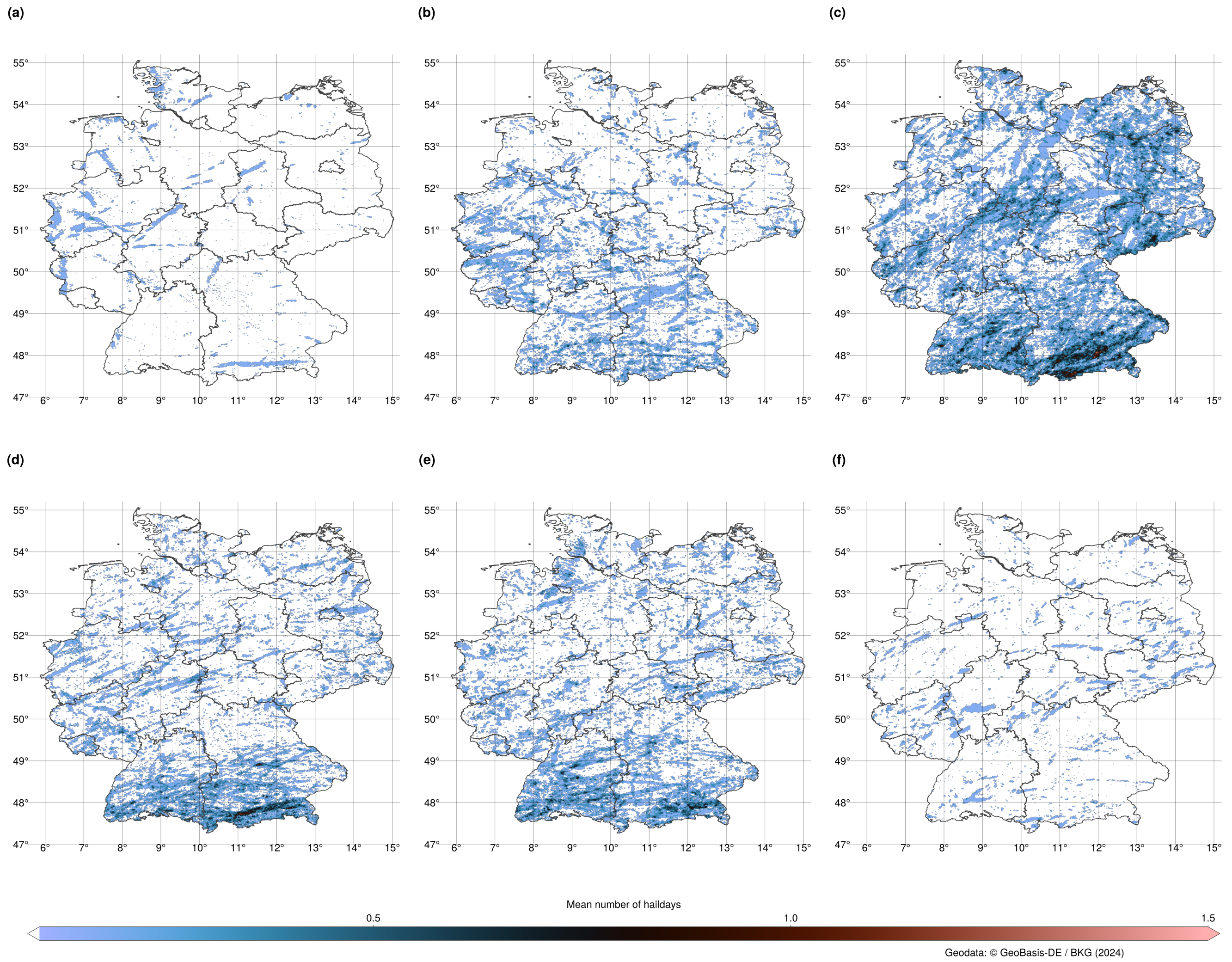


**Figure 16.** The annual cycle of hail days from 2018 to 2023 in Germany based on VII from (a): April ascending over (b): May reaching its prime time in (c): June and descending from (d): July (e): August to (f): September

### 5.3 Insurance data

For the insurance data Fig. 18 depicts that June is the most damaging hail month with a mean of 33 972 damage reports. July is a close second to June 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

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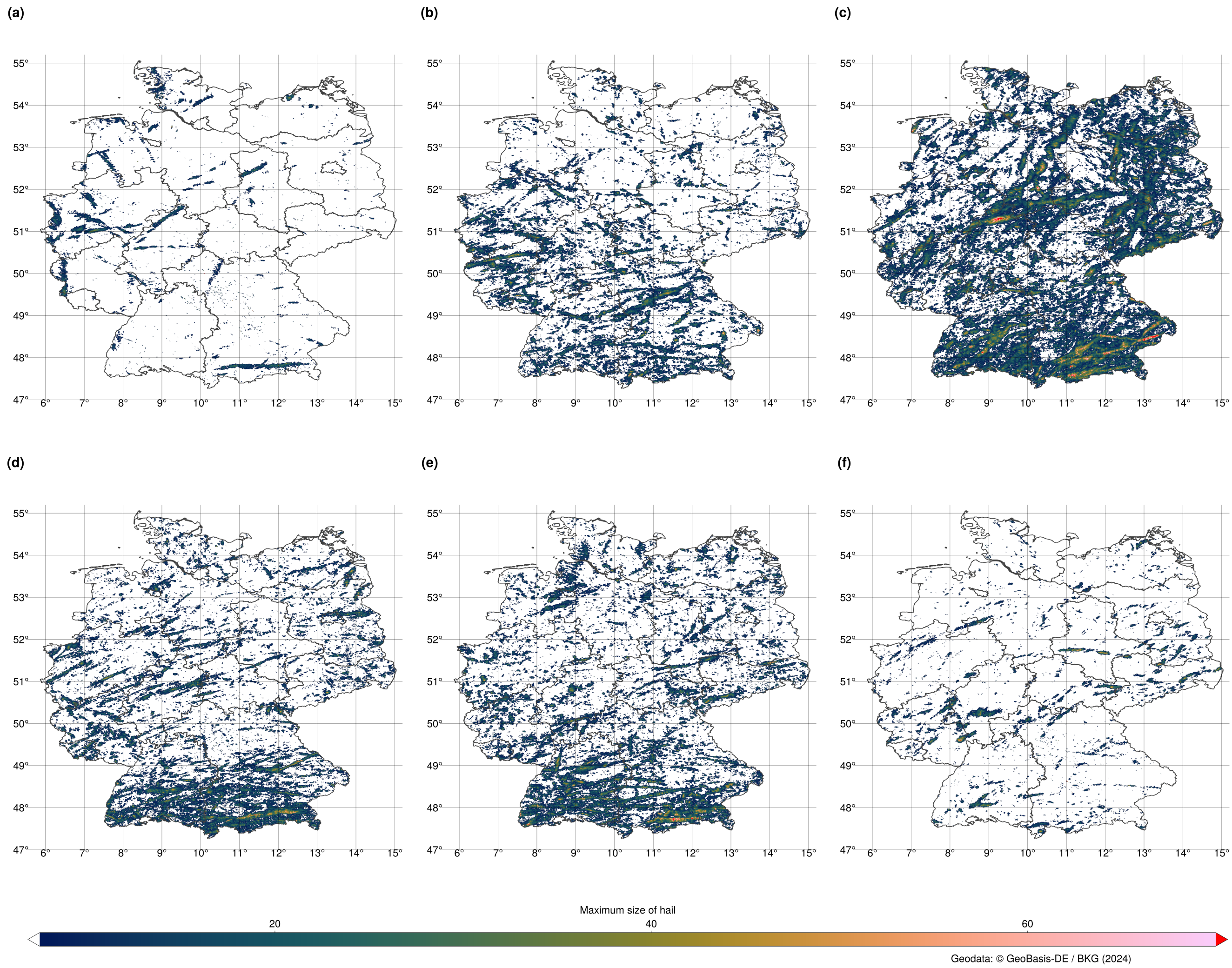


**Figure 17.** The annual cycle of hail sizes from 2018 to 2023 in Germany based on VII from (a): April ascending over (b): May reaching its prime time in (c): June and descending from (d): July (e): August to (f): September

(100.43 Mio €) and September (21.2 Mio €) are much higher than those months 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.

## 6 Summary and future work

To answer the title question "Hail events in Germany, rare or frequent natural hazards?" this study has a look at hail statistics derived from radar data using the methods vertically integrated ice (VII) and maximum estimated size of hail (MESH). We can answer it by "it depends". Large to giant hail is very rare in Germany. The south of Germany has a higher chance to be hit by

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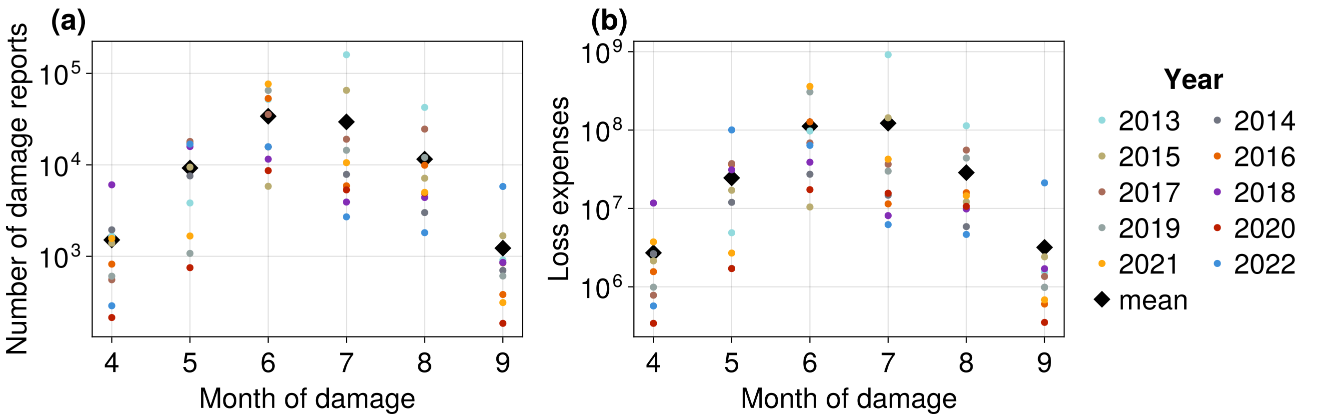


**Figure 18.** Insurance data for the summer months each year 2013-2022. (a) Number of damage reports. (b) Sum of loss expenses.

large hail and is typically hit more frequently by hail storms than the north. Nevertheless, also large to giant hail is possible all over Germany like the hailstorm in the middle of Germany 2023 has shown.

Púčik et al. (2019) and Kaltenböck et al. (2009) also used the ESWD data to analyse the diurnal cycle of hail. They had a look at whole Europe, but with shorter timeseries. Their findings that the prime time of hail is about 15–16 UTC can be confirmed also with the longer timeseries of this study for Germany. We must take into account that it is more probable for human observations to report hail at day time which can lead to a bias in observed times. Púčik et al. (2019) depicted a similar annual cycle pattern for southern Europe (south of 46°N latitude) to the annual cycle found by this study. For the North 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 the south, but also for the north of Germany.

From crowd data we expected hotspots of reports in the most populated areas in Germany. The analysis showed exactly what we assumed, many reports in the Ruhr and Rhine-Main area and in the larger cities like Berlin and Munich. The hotspot close to Stuttgart that was found previously (Puskeiler et al., 2016) is as well seen in the crowd data as in the VII.

Only through observation data it is currently not possible to calculate any trends in hail occurrence, due to a varying number 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 very different years, some with much e.g. 2021 and some with few hail e.g. 2020. Further on, the analysed period of 6 years is not long enough to define a trend.

The overarching question 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 large hail is being reported. Additionally, there is an estimation problem and a diurnal cycle for reporting. For future

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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.

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

*Competing interests.* The authors declare that they have no conflict of interest.

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