Severe thunderstorms with large hail across Germany in June 2019

Jannik Wilhelm1, Susanna Mohr1,2, Heinz Jürgen Punge1, Bernhard Mühr2,3, Manuel Schmidberger1, James E. Danieli2,4, Kristopher M. Bedka5 and Michael Kunz1,2

1Institute of Meteorology and Climate Research (IMK), Karlsruhe Institute of Technology, Karlsruhe, Germany
2Center for Disaster Management and Risk Reduction Technology (CEDIM), Karlsruhe Institute of Technology, Karlsruhe, Germany
3EWB Wetterberatung, Karlsruhe, Germany
4Geophysical Institute (GPI), Karlsruhe Institute of Technology, Karlsruhe, Germany
5NASA Langley Research Center, Hampton, Virginia, USA

Introduction
Between 10 and 12 June 2019, a series of severe convective storms (SCSs) affected large parts of Germany, particularly the southern and eastern parts of the country. Hail with diameters of up to 6cm, wind gusts reaching gale, and occasionally even hurricane force, as well as heavy rain with daily totals up to 100mm entailed considerable damage to buildings, vehicles, infrastructure and agriculture. Munich Re reported a total loss of almost EUR 1.0 billion (insured loss of ~EUR 0.75 billion) caused by one storm in the Munich area solely (Munich Re, 2020). Although inferior in losses compared to the famous Munich hailstorm on 12 July 1984 (Heimann and Kurz, 1985) or the hailstorms on 27/28 July 2013 (depression Andreas; Kunz et al., 2018), this event ranks at least about eighth or ninth on the list of the costliest hail-related loss events of the past 40 years in Europe (cf. Půčík et al., 2019; note that insurers usually define an event as a 72-hour timespan).

The 3-day storm series began on 10 June, with scattered thunderstorms and a supercell passing over the northwestern suburbs of Munich as well as a couple of neighbouring counties. This supercell (hereinafter referred to as MUC-19 hailstorm) produced large hail (Figure 1) and hurricane-force wind gusts, causing blocked roads due to toppled trees for several hours to days. At Munich Airport, numerous flights were delayed and a few had to be cancelled. From the evening of 10 June onwards, several SCSs accompanied by heavy rain, (large) hail and severe wind gusts affected wide areas mainly in eastern Germany. Of two tornadoes observed near Dresden in Saxony (eastern Germany), one caused considerable damage to 30 to 40 houses (Tornadoliste, 2019).

In this article, we use operational in situ and remote sensing observations as well as eyewitness reports to investigate the 3-day SCS episode with a special focus on the MUC-19 hailstorm. The purposes of this study are (i) to analyse the occurrences and characteristics of the convective cells, (ii) to relate SCS occurrences and intensities to the synoptic-scale and mesoscale environment, (iii) to estimate the damage pattern and to find reasons for the large losses caused by hail and (iv) to establish similarities of the MUC-19 hailstorm to other famous hailstorms in Germany.

Temporal evolution of thunderstorm activity and hail reports
During the 3-day investigation period, the European Severe Weather Database (ESWD; Dotzek et al., 2009) recorded 217 severe weather reports in Germany, and a further 119 reports in its vicinity, especially in Poland and the Czech Republic (Figure 2). All reports are quality-controlled with more than 89% exhibiting the quality control level QC1 (reliably confirmed) and less than 11% holding QC0+ (plausibility checked).

Approximately 47% of the German reports are related to hail (up to 6cm), 32% to heavy precipitation (defined, for example, as at least 35mm in 1 hour or 60mm in 3 hours; ESSL, 2014), 19% to severe convective wind gusts (>25ms⁻¹), and two reports to the tornadoes in Saxony. On 10 June, the day of the MUC-19 hailstorm, most of the 82 severe weather reports came from Bavaria and Saxony; on 11 June from eastern Germany (92 reports); and on 12 June exclusively from northeastern Germany (43 reports).

On 10 June, thunderstorm activity had already started in the early morning in Switzerland. At around 1100 UTC (1300 CEST), a long-lived thunderstorm complex crossed central Europe (Figure 2). At 1300 UTC (1500 CEST) on 10 June, the system reached Germany and continued moving south. In situ and remote sensing observations revealed that the system consisted of several SCSs, which affected the southern and eastern parts of Germany.

The colouring indicates the respective report day. The map is supplemented by ESWD reports (quality control level QC0+ and higher; 336 in the domain) from 10 to 12 June 2019 for hail (▲), heavy precipitation (●), convective wind gusts (■) and tornadoes (▼).
the German border in a northeasterly direction and dissipated northeast of Stuttgart 4 hours later (Figure 3a). This track also marked the western border of the area with high convective activity, roughly stretching from Zurich via Berlin to the Baltic Sea.

At the border triangle of Switzerland/Austria/Germany (~47.5°N, 9.7°E), the future MUC-19 hailstorm developed around 1400 UTC. A special feature of this convective system was its initial width of several tens of kilometres, clearly visible in radar observations of the German Weather Service (Deutscher Wetterdienst, DWD; Figure 4a). The broad storm track suggested an expanding squall line. However, a supercell formed at its southeastern flank, as confirmed by reports from storm chasers (e.g. M. Kaschuba, pers. comm., 2019; cf. video documentation, Kaschuba, 2019). This supercell passed rapidly over the northwestern suburbs of Munich at around 1600 UTC (Figure 5). At Munich airport, a maximum wind gust of 32.9 ms\(^{-1}\) was measured. Satellite image-derived detections

---

**Figure 3.** Lightning maps of central Europe for the timespan (a) 10/11 June 2019; (b) 11/12 June 2019; (c) 12/13 June 2019 (0600 UTC in each case). The colouring indicates the relative time of day (EUCLID/BLIDS).

**Figure 4.** Radar-derived maps of maximum reflectivity factor (in dBZ; a–c) and satellite-derived maps of overshooting tops based on observations of Meteosat Second Generation (MSG; d–f) for different parts of Germany on 10 June (left column), 11 June (middle) and 12 June (right). The corresponding hail reports from the ESWD are added as red triangles (size scaled by reported diameter). Note that the overshooting top detections – represented by a unitless index indicating the likelihood of large hail – are based on MSG measurements in the visible channel. Therefore, the product shown does not capture nocturnal overshooting tops, such as those from the storms and the MCC around Berlin and in northeastern Germany during the night from 11 to 12 June.
Severe thunderstorms with large hail across Germany

Weather – July 2021, Vol. 76, No. 7

were registered over central Europe in the domain shown in Figure 2 from 10 to 11 June (0600–0600 UTC). If storms in the Alpine region as well as over northeastern France, Benelux and northwestern Germany are excluded, the lightning number was around 170 000 in the smaller domain (SMD) north of 47.5°N and east of 7.5°E. Some of these storms had a track length of more than 100km, but with much lower lightning rates, extents and intensities than those in southern and eastern Germany.

On 11 June, the main thunderstorm activity shifted to northeastern and partly also to central Germany (Figures 4b and e). The first isolated thunderstorms appeared between 1500 and 1600 UTC over the Bavarian Alps and over Saxony (Figure 3b), and a little later also across the lower mountain ranges in central Germany. Hail diameters up to 5cm were reported for cells between the Ore Mountains and Berlin (Table 1). Unlike the day before, these thunderstorms headed strictly northwards. Shortly after 1900 UTC, a tornado (yet unclassified) in Mulda, 35km southwest of Dresden, caused only slight damage (Tornadoliste, 2019). Hailstones measuring 5cm across fell there, too. During the late evening, the cells merged into a large cluster that met all criteria of a mesoscale convective complex (MCC) as radar (and satellite) imagery indicate. This MCC produced high precipitation totals (e.g. 95.9mm within 24 hours at Jueterbog, 60km southwest of Berlin). The lightning count was even higher than the day before at 250 000 (210 000 in SMD).

On 12 June around 1200 UTC, thunderstorms preferentially developed over the lower mountain ranges in eastern central Germany (Figure 3c). At 1340 UTC, another tornado (F1) damaged 30 to 40 houses considerably and toppled numerous trees in Penig-Tauscha, 70km west of Dresden (Tornadoliste, 2019). The initially isolated thunderstorms quickly grew into larger complexes with high lightning rates. The SCs shifted northwards forming an arc-shaped corridor of more than 100km width to arrive at the Baltic Sea at around 1800 UTC. One cell that developed southeast of Erfurt had a particularly long track of approximately 250km with high radar reflectivity and a moderate overshooting top indicator (Figures 4c and f). This storm produced wind gusts exceeding gale force (e.g. 30.5ms⁻¹ at Berlin-Schoenefeld), as did many other storms along the corridor. Reported hail diameters varied mostly between 2cm and 4.5cm. During the night, the SCs advanced further north and hit large parts of Denmark, southern Sweden, and even the Oslo area in Norway (not shown). The number of lightning strikes reduced to 136 000 (128 000 in SMD) on that day.

Synoptic overview

The average 500hPa geopotential height from 10 to 12 June 2019 shows three extended long-wave troughs (incl. cut-off lows). The most relevant for the convection episode was centred over Brittany, France with its axis spanning from northern England to Gibraltar. The second was located upstream, south of Greenland, and the third was centred over western Turkey (Figure 6a). Downstream of the central trough, a large-scale ridge prevailed over northern Europe (Scandinavia). This constellation resembles two of the North Atlantic-European weather regimes as defined by Grans et al. (2017) – Scandinavian Blocking and Greenland Blocking – each supporting a quasi-stationary persistent flow. During Scandinavian blocking situations (in combination with cut-offs, in particular, over southwestern Europe), warm, moist and unstable air masses are transported north- and north-eastward, favouring strong convection over central Europe (Mohr et al., 2019, 2020).

The general flow constellation during these days resembled the Spanish plume pattern (Morris, 1986). In such situations, an elevated mixed layer (EML; Carlson et al., 1983), typically originating from the Iberian plateau, is advected to western and central Europe. On its way, this air is lifted dynamically or orographically, creating...
Table 1

Complete list of maximum reported hail stone diameters in Germany based on ESWD reports from 10 to 12 June 2019 (minimum 5cm, quality control level QC1). Reports associated with the MUC-19 hailstorm are marked with an asterisk (*).

| Station                | Lat. (°N) | Long. (°E) | Date and time (UTC) | Max. hail diameter (cm) |
|------------------------|-----------|------------|----------------------|-------------------------|
| Gilching*              | 48.11     | 11.29      | 10 June 1535         | 6.0                     |
| Hofstetten*            | 48.01     | 10.97      | 10 June 1511         | 5.0                     |
| Schondorf a. Ammersee* | 48.05     | 11.09      | 10 June 1517         | 5.0                     |
| Finning*               | 48.02     | 11.01      | 10 June 1517         | 5.0                     |
| Hechendorf a. Pilensee*| 48.03     | 11.18      | 10 June 1526         | 5.0                     |
| Unterpaffenhofen*      | 48.13     | 11.37      | 10 June 1541         | 5.0                     |
| Germering*             | 48.14     | 11.36      | 10 June 1542         | 5.0                     |
| Puchheim*              | 48.15     | 11.35      | 10 June 1543         | 5.0                     |
| Achering*              | 48.35     | 11.71      | 10 June 1625         | 5.0                     |
| Bad Gottleuba          | 50.85     | 13.95      | 10 June 2155         | 5.0                     |
| Hoyerswerda            | 51.44     | 14.22      | 11 June 1735         | 5.0                     |
| Zelz                   | 51.62     | 14.75      | 11 June 1750         | 5.0                     |
| Grosssedlitz           | 50.97     | 13.88      | 11 June 1755         | 5.0                     |
| Dohna                  | 50.96     | 13.86      | 11 June 1755         | 5.0                     |
| Pusack                 | 51.59     | 14.73      | 11 June 1755         | 5.0                     |
| Bahren                 | 51.64     | 14.75      | 11 June 1800         | 5.0                     |
| Mulda                  | 50.81     | 13.41      | 11 June 1925         | 5.0                     |

steep mid-tropospheric lapse rates and high potential instability that support the development of SCs. From 9 to 11 June, an EML plume from the Algerian Sahara crossed the western Mediterranean and the Alps to reach central and eastern Europe, as model backward trajectories suggest (not shown). Foehn-like conditions lead to additional adiabatic warming and thus lapse rate increase north of the Alps. Positive vorticity advection due to the location downstream of the upper-level trough, increasing with height, combined with positive layer thickness advection on 10 and 11 June (not shown) led to large-scale lifting over central Europe, which repeatedly triggered convection.

From 11 June onwards, a quasi-stationary air mass boundary stretched meridionally across Germany and extended further to the Mediterranean (Figure 6b). Most SCs developed in the unstable air mass east of the related cold front. The arc-shaped low-pressure system named Klaus, associated with the central trough, stretched from southern England to northern Germany. On 12 June, Klaus deepened slightly while its centre shifted to the Bay of Biscay west of France. The day before, a second thermal and thus shallow low named Joern had developed over Austria without significant air mass boundaries. However, on 12 June (0000 UTC), the analysis revealed a convergence line extending from the very northeast to southeast of Germany, providing ideal conditions for strong lifting and SC development (not shown).
Storm environment

During the 3-day period, air masses were very warm and moist especially in the eastern half of Germany. Temperatures rose to 30–35°C. In contrast, to the west of the cold front associated with Klaus, temperatures only reached around 20°C. High moisture content in the lower troposphere, very high thermal instability and sufficient wind shear provided the ingredients for organised SCS development. We investigated these environmental conditions by assimilation analyses with the high-resolution Consortium for Small-scale Modelling model (COSMO-D2; Baldauf et al., 2018) and radiosonde data from DWD.

Available moisture is estimated by the vertically integrated water vapour content (IWV) across a tropospheric air column. During convection-favouring periods, IWV typically ranges between 25 and 35 kg m\(^{-2}\) in central Europe. Instability is estimated by the Surface Lifted Index (SLI), defined as the temperature difference at 500 hPa between the environment and an air parcel rising (pseudo-)adiabatically from the ground. Negative values indicate unstable stratification, values below −8 K are observed only on a few days per year (e.g. Kunz et al., 2018). Wind shear, the third important ingredient, is expressed by the storm-relative helicity (SRH), a measure of streamwise vorticity indispensable to supercell formation. It quantifies the area on the hodograph covered by the vectors between the ground and (usually) 3 km height, relative to the storm motion vector. Finally, as a combined parameter we computed the Significant Hail Parameter (SHIP; NOAA SPC, 2014), designed as indicator for environments favourable to hail. It is multiplicatively composed of five quantities: 500 hPa temperature; 700–500 hPa lapse rate; water vapour mixing ratio of an ascending air parcel; the respective convective available potential energy (CAPE); and deep layer shear (DLS), the wind vector difference between the ground and 6 km height. SHIP can distinguish between environments supporting the formation of small and large hail (>2 in ≈ 5 cm) with SHIP = 1.0 as dimensionless threshold.

On 10 June, IWV already reached values between 30 and 35 kg m\(^{-2}\) across Germany, including western parts (Figure 7a). SLI was...
higher negative (Figure 7d), with the lowest values (highest instability) below −5K in southern Bavaria in the late afternoon. The MUC-19 hailstorm is clearly visible in the 1600 UTC analysis, where SLI rapidly increased to positive values just behind the supercell. SHIP ranged around 1.0 in southeastern Bavaria and Saxony (Figure 7g), which is well in line with the observed hailstone sizes of 3–5cm in these regions. The EML advection caused fairly strong convective inhibition at 1200 UTC at the sounding station of Oberschleissheim – located within the track of the MUC-19 hailstorm (Figure 8a). However, due to diurnal boundary layer heating, sufficient CAPE of around 1500 J kg⁻¹ developed in southern Bavaria during the afternoon, providing excellent conditions for supercell development in combination with high DLS values of 25–30 m s⁻² and SRH values of 300–400 m² s⁻³, respectively (not shown).

On the two following days, when the quasi-stationary cold front related to Klaus extended across Germany, IWV increased to exceptional values between 35 and 45 kg m⁻² over eastern Germany and western Poland with the highest values along the convergence line (Figures 7b and c). SLI fell to extraordinarily low values of −8K, regionally even −10 or −11 K (Figures 7e and f). Mixed-layer CAPE reached 2500 J kg⁻¹ across large areas, and 4000 J kg⁻¹ at some local hot spots in western Poland and northern Czech Republic (not shown).

The 1200 UTC sounding of Lindenberg (northeast of Berlin) on 11 June (Figure 8b) illustrates a very thick layer of well-mixed air between 850 and 550 hPa, capping the moist boundary layer until the evening hours. At 1800 UTC, mixed-layer CAPE exceeded 3100 J kg⁻¹. SHIP values widely exceeded 2.0, locally even 3.0, reflecting very good conditions for large hail (>5 cm; Figure 7h). Despite these high values, the reported hailstone sizes in Germany were only 3–5 cm. However, one SCS in western Poland indicates that the conditions allowed for the formation of even larger hail: in Gorzów-Wielkopolski, 125 km east of Berlin, eyewitnesses reported giant hailstones with diameters up to 12 cm (ESSL, 2020; Figure 2). SHIP values exceeded 3.0, SLI was below −10 K, mixed-layer CAPE above 3500 J kg⁻¹ and IWV above 40 kg m⁻¹. DLS and SRH reached values of 15–20 m s⁻² and 200–300 m² s⁻³, respectively, sufficient for the formation of very severe thunderstorms. The Gorzów-Wielkopolski hailstorm marked the eastern boundary of SCS activity.

During night-time, sustained positive vorticity and layer thickness advection in combination with sufficient DLS made the evolution of the cell clusters to an MCC possible. On 12 June, conditions were very similar to the day before over northeastern Germany and western Poland (Figures 7c, f, i). Mid-tropospheric lapse rates flattened slightly (Figure 8c), whereas DLS increased moderately. Reported hailstone diameters were below 5 cm. The eastward advancing cold front of Klaus led to earlier convection initiation than the day before. Large-scale lifting was weak, resulting in the formation of an arc-shaped cluster of SCSs, moving quite fast and dispelling the warm and moist air masses.

**Wind gust and precipitation measurements**

Besides large hail, the environmental conditions favoured heavy precipitation and severe convective gusts as well. During the study period, strong wind gusts were recorded at several stations (Table 2). Muehldorf am Inn, 75 km east of Munich (in operation since 1953), registered the strongest gust during the 3-day period with 33.3 m s⁻¹ on 10 June, representing a new station record for the summer months. The gust produced by the MUC-19 hailstorm at Munich Airport (since 1992) is in second place with 32.9 m s⁻¹, also a new summer record. In southern Germany, such convective wind gusts show return periods of 20–50 years depending on local conditions (Mohr et al., 2017). Two other stations measured the highest wind speeds in June since their records began: Angermuende (since 1947), 75 km northeast of Berlin, with a peak gust of 26.3 m s⁻¹ and Heckelberg (since 2007), 35 km northeast of Berlin, with 24.7 m s⁻¹. Both were hit by the same storm as Berlin-Schoenefeld (30.5 m s⁻¹) on 12 June.

A few stations in Germany reported very high rain totals (Tables 3 and 4; cf. Figure 9). On 11 June, Potsdam (close to Berlin; since 1893) recorded 79.7 mm, the highest value ever observed on a day in June at that site. The daily totals of Annaburg (92.4 mm; since 1901) and Jueterbog (95.9 mm; since 1951), both between Leipzig and Berlin, represent new monthly records as well. The extraordinary rain amounts resulted from long-lasting intense precipitation in conjunction with the evolving MCC in the late evening on 11 June (see above). The highest 1-hour precipitation amount caused by the MCC was registered at Berlin-Buch with 46.2 mm (Table 3). Note that the highest 1-hour precipitation sum during the 3-day period was measured at Hude, 25 km west of Bremen, in northwestern Germany on 10 June. The 69.1 mm precipitation total was caused by a back-building isolated cell that moved very slowly (cf. Figure 9a). The MUC-19 hailstorm on 10 June and the SCSs on 12 June were accompanied by heavy rainfall too, but without record-breaking accumulation.

**Damage**

Damage reports from insurers are quite diverse, depending on their portfolio, area of operation, as well as reporting time and...
Table 2
Complete list of outstanding wind gust observations in Germany (DWD stations) from 10 to 12 June 2019 (minimum Beaufort 10). Stations hit by the MUC-19 hailstorm are marked with an asterisk (*).

| Station               | Lat. (°N) | Long. (°E) | Date and time (UTC) | 1-hour max. gust speed (ms⁻¹) |
|-----------------------|-----------|------------|---------------------|-------------------------------|
| Muehldorf/Inn         | 48.28     | 12.50      | 10 June 1800        | 33.2                          |
| Muenchen-Flughafen*   | 48.35     | 11.81      | 10 June 1700        | 32.9                          |
| Berlin-Schoenefeld    | 52.38     | 13.53      | 12 June 1700        | 30.5                          |
| Kyritz                | 52.94     | 12.41      | 12 June 1600        | 28.4                          |
| Angermuende           | 53.03     | 13.99      | 12 June 1800        | 26.3                          |
| Altenstadt*           | 47.83     | 10.87      | 10 June 1600        | 26.2                          |
| Holzdorf (Flugplatz)  | 51.77     | 13.17      | 12 June 1600        | 25.2                          |
| Ueckermuende          | 53.74     | 14.07      | 12 June 0100        | 24.8                          |
| Bertsdorf-Hoernitz    | 50.89     | 14.81      | 10 June 2300        | 24.8                          |
| Berlin-Tempelhof      | 52.47     | 13.40      | 12 June 1700        | 24.8                          |
| Heckelberg            | 52.75     | 13.84      | 12 June 1800        | 24.7                          |
| Potsdam               | 52.38     | 13.06      | 12 June 1700        | 24.7                          |

Table 3
As Table 2, but for 1-hour precipitation (minimum 35mm).

| Station               | Lat. (°N) | Long. (°E) | Date and time (UTC) | 1-hour max. rain sum (mm) |
|-----------------------|-----------|------------|---------------------|---------------------------|
| Hude                  | 53.12     | 8.42       | 10 June 1900        | 69.1                      |
| Berlin-Buch           | 52.63     | 13.50      | 11 June 2300        | 46.2                      |
| Marienberg-Ruebenau   | 50.58     | 13.30      | 10 June 2000        | 41.7                      |
| Berlin-Dahlem         | 52.45     | 13.30      | 11 June 2300        | 39.7                      |
| Schwanewede-Neuenkirchen | 53.23   | 8.51       | 10 June 1900        | 39.1                      |
| Staaken               | 52.54     | 13.12      | 11 June 2200        | 38.4                      |
| Helmstedt-Emmerstedt  | 52.25     | 10.96      | 11 June 2300        | 35.8                      |
| Felgentreu            | 52.10     | 13.00      | 11 June 2200        | 35.7                      |
| Zinnwald-Georgenfeld  | 50.73     | 13.75      | 10 June 2200        | 35.6                      |

Table 4
As Table 2, but for 24-hour precipitation (0600–0600 UTC; minimum 75mm). The date refers to the start date of the timespan.

| Station    | Lat. (°N) | Long. (°E) | Date       | 24-hour max. rain sum (mm) |
|------------|-----------|------------|------------|---------------------------|
| Jueterbog  | 52.00     | 13.10      | 11 June    | 95.9                      |
| Annaburg   | 51.73     | 13.06      | 11 June    | 92.4                      |
| Langerwisch| 52.32     | 13.07      | 11 June    | 91.3                      |
| Hude       | 53.12     | 8.42       | 10 June    | 85.6                      |
| Staaken    | 52.54     | 13.12      | 11 June    | 80.4                      |
| Potsdam    | 52.38     | 13.06      | 11 June    | 79.7                      |

Severe thunderstorms with hail and heavy rain across Germany.

Time span considered. The Bavarian insurance group Versicherungskammer Bayern (VKB) alone reported 37 000 claims from aggrieved parties with a total amount of EUR 80 million related to the MUC-19 hailstorm on 10 June (VKB, 2019). Damaged windows are responsible for a major fraction of total losses in the vehicle sector, whereas damage to thermal insulation, solar energy systems and soundproofing facilities caused high losses in the building insurance market. The German Insurance Association (Gesamtverband der Deutschen Versicherungswirtschaft, GDV) registered 115 000 damage reports to hull-insured vehicles causing a loss of approximately EUR 400 million for the period from 10 to 12 June. A further EUR 300 million loss corresponds to 120 000 reports about damage to buildings, household effects, commercial and industrial premises (GDV, 2019, 2020).

Hail and wind gusts caused the largest share, whereas heavy rain accounted only for around 13%. However, only 45% of residential houses in Germany are insured against heavy rain and flooding. Munich Re reported a total loss of almost EUR 1.0 billion (insured loss of ~EUR 0.75 billion) for the MUC-19 hailstorm on 10 June solely (Munich Re, 2020).

In the agricultural sector, the Vereinigte Hagelversicherung reported an area of 1000km² severely damaged by hail during the first half of June. Expected compensation payments amounted to more than EUR 25 million and total damage was projected to around EUR 45 million (Vereinigte Hagel, 2019). The affected area corresponds to approximately 0.8% of the crop land and 0.6% of the entire agricultural area in Germany (BMEL, 2018). These estimates include not only the events from 10 to 12 June, but also some thunderstorms in Germany at the beginning of June.

The main reason for the large losses around Munich is the high asset concentration in that area (Figure 10). Using data from the German Federal Statistical Office (Destatis), the Institute of Economic
Severe thunderstorms with large hail across Germany

Figure 9. As Figure 3, but for 24h precipitation totals based on a combination of in situ and radar-derived observations (RADOLAN, DWD).

Figure 10. Asset map of capital stock (in million EUR per km²: reference year 2019, Destatis; cf. Daniell, 2014), overlaid by the smoothed radar-derived storm-affected area (reflectivity threshold: 55dBZ) for the MUC-19 hailstorm on 10 June.

and Social Research (Wirtschafts- und Sozialwissenschaftliches Institut, WSI) of the Hans Böckler foundation documented that people in the administrative districts of Munich and its neighbours have an above-average available income (German average 2016: EUR 21 952 per capita; WSI, 2019). Munich is leading among the 15 most populous cities in Germany (EUR 29 685 per capita), and the district of Starnberg southwest of Munich – site of many hail reports on 10 June – is actually number one of all 401 German districts (EUR 34 987). Property assets (money and real estates) in Bavaria (2013: EUR 72 622, median) are around 88% higher than the German median (EUR 38 689). Within the area covered by the MUC-19 hailstorm derived from radar data (cf. Figure 10) capital stock amounts to approximately EUR 123 billion. Thereof, EUR 75 billion are concentrated within the 100km² with highest capital stock values. These numbers substantiate that the expected financial damage from a hailstorm is higher in the Munich region than in most other parts of Germany. On 11 and 12 June, hail damage was significantly lower because large hail did not fall as widely spread and mainly hit regions with lower asset concentrations (not shown).

Summary and discussion

During the period from 10 to 12 June 2019, convection-favouring atmospheric conditions across parts of Germany and neighbouring countries were the consequence of a combined Scandinavian and Greenland blocking situation. High (potential) instability and moisture content were complemented by suitable trigger mechanisms: large-scale lifting downstream of a pronounced upper-level trough with an enclosed cut-off over southwestern Europe on 10 and 11 June; vertical lifting associated with a low-level convergence line at the German-Polish border on 11 and 12 June; and additional lifting by the advancing cold front of the low-pressure system Klaus on 12 June. Several convective cells formed east of the initially stationary cold front of Klaus, producing hailstones of various sizes. Several meteorological stations registered new monthly or seasonal records of daily rain totals or maximum wind gusts.

(Large) hail occurs frequently during the summer half year in Germany and Europe (e.g. Punge and Kunz, 2016). In Germany, hail can be observed at a fixed place on about 1–4 days per year, varying yearly and regionally. Hail hot spots exist, especially in central and southern Germany (e.g. Schmidberger, 2018): the regions around Munich, Stuttgart and Frankfurt/Main as well as parts of Saxony show the highest number of hail days. Most hail reports from 10 to 12 June originate from the two hot spots around Munich and central Saxony. Nevertheless, hailstones up to golf ball size also occurred across several regions in northeastern Germany. However, the excellent atmospheric setting on these days would generally have allowed the development of SCs producing even larger hail as happened in western Poland. Remarkably, the largest hailstones in Germany during the 3-day period were from the MUC-19 hailstorm on 10 June, although instability, moisture content and SHIP were higher on the following two days in (northeast)ern Germany.

Steep mid-tropospheric lapse rates caused by EML advection characterised the period from 10 to 12 June. Thus, this event joins a list of similar meteorologically exceptional and costly hailstorm events in
central Europe, where plumes of well-mixed subtropical, mid-tropospheric air complemented an ideal convection-favouring setting. Examples comprise the hailstorms on 27/28 July 2013 around Wolfsburg (east of Hannover) and in southwest Germany with hailstones up to 10cm diameter (depression Andreas; Kunz et al., 2018) – one of the costliest natural hazard events in Germany with total economic (insured) losses at EUR 3.6 (2.8) billion, ranking first in the list of European hail-related loss events since 1980 (Püschl et al., 2019). Further examples include the famous Munich hailstorm on 12 July 1984, which entitled the highest number of injuries (400 in total) and losses of a similar amount, or the Villingen-Schwenningen hailstorm on 28 June 2006. Although no reliable data are available to account for consumption assets, it appears likely that the MUC-19 hailstorm on 10 June would not have caused such high losses in other regions. In turn, considerably higher losses seem – from a meteorological perspective – also possible elsewhere in the event of a high number of large to giant hail-producing storms and a perfect match of these storms with a high asset concentration.

Acknowledgements

The authors thank the German Weather Service (DWD) for providing data of weather stations, radars and RADOLAN precipitation, radiosondes and COSMO-D2 assimilation analyses. Furthermore, we thank the European Severe Storms Laboratory (ESSL) for providing severe weather report and the European Centre for Medium-Range Weather Forecasts (ECMWF) for providing ERA5 reanalysis data. We thank the University of Wisconsin Space Science and Engineering Center and the EUMETSAT Data Centre for providing the MeteoSat Second Generation satellite imagery analysed in this study. In addition, many thanks to the lightning information service of Siemens (Blitz-Informationsdienst, BLIDS; namely Stephan Thern). Also, many thanks to Marco Kaschuba for providing Figure 1. Moreover, the authors thank the Federal Agency for Cartography and Geodesy (Bundesamt für Kartographie und Geodäsie, BKG) as well as Natural Earth for making use of geodata possible. We also thank the German Federal Statistical Office (Destatis) for providing investment (capital formation) data. Thanks to Jan Wandel (KIT) for preparing Figure 6(a) and Christian Ehmann (DWD) for sharing the high-resolution analysis map for Figure 6(b). Jannik Wilhelm thanks Ulrich Blahak (DWD) for sharing a programming library modified for the plots in Figure 8, and Florian Ehmele (KIT) and Tino Degenhardt (KIT) for an additional proofread of the manuscript. This research has been supported by the German Research Foundation (DFG) – Project-ID 257899354 – TRR 165 (Waves to Weather) within the subproject B1 (Michael Kunz).

Competing interests

The authors declare that they have no conflict of interest.

References

Baldau M, Gebhardt C, Theis S et al. 2018. Beschreibung des operationellen Kürzungstiefvorhersagemodells COSMO-D2 und COSMO-D2-EPS und seiner Ausgabe in die Datenbanken des DWD. Deutscher Wetterdienst. https://www.dwd.de/DE/leistungen/modellvorhersagedaten/cosmo_d2_eps_documentation.pdf?__blob=publicationFile&v=2 [accessed 28 September 2020].

Bedka KM. 2011. Overshooting cloud top detection using MSVIR SEVIRI infrared brightness temperatures and their relationship to severe weather over Europe. Atmos. Res. 99(2): 175–189.

Bedka KM, Khlopenkov K. 2016. A probabilistic multispectral pattern recognition method for detection of overshooting cloud tops using passive satellite imager observations. J. Appl. Meteorol. Climatol. 55(9): 1983–2005.

BMEL. 2018. Daten und Fakten – Land-, Forst- und Ernährungswirtschaft mit Fischerei und Wein- und Gartenbau, Bundesministerium für Ernährung und Landwirtschaft, Berlin, Germany. https://www.bmel.de/SharedDocs/Downloads/DE/Broschueren/Daten-und-Fakten-Landwirtschaft.pdf?__blob=publicationFile&v=6 [accessed 28 September 2020].

Carlson T, Benjamin S, Forbes G et al. 1983. Elevated mixed layers in the regional severe storms environment: Conceptual model and case studies. Mon. Weather Rev. 111: 1453–1474.

Daniell JE. 2014. Development of Socio-economic Fragility Functions for Use in Worldwide Rapid Earthquake Loss Estimation Procedures. KIT: Karlsruhe, Germany.

Dotzek N, Groenemeijer P, Feuerstein B et al. 2009. Overview of ESSL’s severe convective storms research using the European Severe Weather Database ESWD. Atmos. Res. 93: 375–386.

ESSL. 2014, ESWD Event reporting criteria. https://www.esrl.noaa.gov/psd/wp-content/uploads/20140509-ESWD_criteria.pdf [accessed 28 September 2020].

ESSL. 2020. Severe weather season 2019: summary. https://www.esrl.noaa.gov/cms/severe-weather-season-2019-summary/ [accessed 28 September 2020].

GDV. 2019. Medieninformationen – Pfiffigstunwetter, Gesamtverband der Deutschen Versicherungswirtschaft e. V., Berlin, Germany. https://www.gdv.de/de/medien/aktuell/versicherer-zahlen-mehr-als-eine-halbe-milliard-euro-48960 [accessed 28 September 2020].

GDV. 2020. Naturgefahrenerport 2020, Gesamtverband der Deutschen Versicherungswirtschaft e. V., Berlin, Germany. https://www.gdv.de/resource/blob/63610/9f7d9d95a0874f312a8e71363310fa/naturgefahrenerport-2020-schadenchronik-data.pdf [accessed 9 October 2020].

Grams CM, Beerli R, Pfenninger S et al. 2017. Balancing Europe’s wind-power output through spatial deployment informed by weather regimes. Nat. Clim. Chang. 7: 557–562.

Heimann D, Kurz M. 1985. The Munich hailstorm of July 12, 1984. A discussion of the synoptic situation. Beitr. Phys. Atmos. 58: 528–544.

Kaschuba M. 2019. Superzelle mit Hagelsturm – Ammersee bis München – 10. Juni 2019. Youtube. https://www.youtube.com/watch?v=gD7YtMQioQ [accessed 28 September 2020].

Kunz M, Blahak U, Handwerker J et al. 2018. The severe hailstorm in SW Germany on 28 July 2013: Characteristics, impacts, and meteorological conditions. J. R. Meteorol. Soc. 145(724): 3040–3056.

Mahr M, Kunz M, Richter A et al. 2017. Statistical characteristics of convective wind gusts in Germany. Nat. Hazards Earth Syst. Sci. 17: 957–969.

Mohr S, Kunz M, Richter A et al. 2019. Relationship between blocking and warm season thunderstorms in western and central Europe. J. R. Meteorol. Soc. 145(724): 325–348.

Morris RM. 1986. The Spanish plume – testing the forecaster’s nerve. Meteor. Mag. 115: 349–357.

Munich Re. 2020. Medieninformationen, Münchener Rückversicherungs- Gesellschaft, Munich, Germany. https://www.munichre.de/de/unternehmen/ media-media/medieninformationen-und-unternehmensnachrichten/ medieninformationen/2020/milliarden-schaden-preagen-bilanz-naturkatastrophen-2019.html [accessed 28 September 2020].

NOAA SPC. 2014. Significant Hail Parameter, Storm Prediction Center, National Oceanic and Atmospheric Administration, Norman OK, USA. https://www.spc.noaa.gov/exper/mesoanaly sis/help/help_sigh.html [accessed 28 September 2020].

Püschl T, Castellano C, Groenemeijer P et al. 2019. Large hail incidence and its economic and societal impacts across Europe. Mon. Weather Rev. 147(11): 3901–3916.

Punge HJ, Kunz M. 2016. Hail observations and hailstorm characteristics in Europe: a review. Atmos. Res. 176–177: 159–184.

Schmidberger M. 2018. Hagelgefährdung und Hagelrisiko in Deutschland basierend auf einer Kombination von Radaradaten und Versicherungsdaten. Wissenschaftliche Berichte des Instituts für Meteorologie und Klimaforschung des Karlsruher Instituts für Technologie (KIT) 78. KIT Scientific Publishing: Karlsruhe, Germany.

Pfeiffer G, Kunz M, Richter A et al. 2018. The meteorological conditions and impact of the severe hailstorm in SW Germany on 28 July 2013. Beitr. Phys. Atmos. 91: 891–906.

Püschl T, Castellano C, Groenemeijer P et al. 2019. Large hail incidence and its economic and societal impacts across Europe. Mon. Weather Rev. 147: 3901–3916.

Punge HJ, Kunz M. 2016. Hail observations and hailstorm characteristics in Europe: a review. Atmos. Res. 176–177: 159–184.
Severe thunderstorm, Jersey, 25 June 2020

Matt Winter and Jim Galvin
Jersey Met, St Helier, Jersey

Introduction
A combination of very warm air, high surface temperatures and an upper trough/surface cold front advancing slowly eastwards late on 25 June 2020 (Figures 1 and 2), triggered severe thunderstorms across northern France and the Channel Islands between 1700 utc and 2300 utc. This setup can generally be described as a ‘Spanish Plume’ event, where strong poleward advection of warm air from Iberia occurs ahead of a slow, eastward-moving amplified upper trough and approaching cold front during the summer (Morris, 1986; Lewis & Gray, 2010; Holley et al., 2014). The thunderstorms were most pronounced in Jersey and were accompanied by torrential rain which led to localised surface water flooding, strong gusts and reports of large hail (>5mm diameter).

In this report we look at when, where and how the storms developed, also examining the particular features and impacts which helped to categorise this as a severe storm. False colour satellite imagery at 1800 utc from Meteosat (Figure 3) highlights the trough which affected Jersey, stretching northwest to Ireland and eastwards into France, with deep convection (pink cloud tops are predominantly ice) over northern France and the Channel Islands. The storm cells produced pronounced shadows to the east, which are cast by high cumulonimbus anvils with a low evening sun angle. The layer cloud associated with the trough appears white and these cloud...