Severe thunderstorms with large hail across Germany in June 2019

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Jannik Wilhelm[1], Susanna Mohr[1,2], Heinz Jürgen Punge[1], Bernhard Mühr[2,3], Manuel Schmidberger[1], James E. Daniell[2,4], Kristopher M. Bedka[5] and Michael Kunz[1,2]

[1] *Institute of Meteorology and Climate Research (IMK), Karlsruhe Institute of Technology, Karlsruhe, Germany*

[2] *Center for Disaster Management and Risk Reduction Technology (CEDIM), Karlsruhe Institute of Technology, Karlsruhe, Germany*

[3] *EWB Wetterberatung, Karlsruhe, Germany*

[4] *Geophysical Institute (GPI), Karlsruhe Institute of Technology, Karlsruhe, Germany*

[5] *NASA 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. Púčik *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 inter alia 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 in eastern Germany, one caused considerable damage to 30 to 40 houses (Tornadoliste, 2019).

In this article, we used 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.

Figure 1. Hailstones near Inning am Ammersee (Bavaria) on 10 June 2019 (© 2019 Marco Kaschuba).

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 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 minimum 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 (92) from eastern Germany; and on 12 June (43) exclusively from northeastern Germany.

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 the German border in a northeasterly direc-

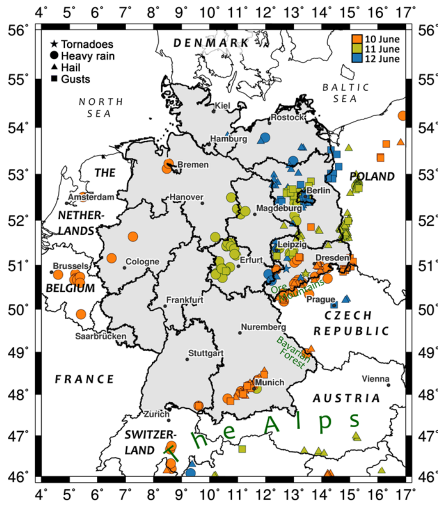

Figure 2. Overview map of central European countries and the federal states of Germany (in grey). In addition, relevant orographic features are displayed. The map is supplemented by ESWD reports (quality control level QC0+ and higher; 336 in the domain) from 10 to 12 June 2019 for hail (▲), heavy precipitation (●), convective wind gusts (■) and tornadoes (★). The colouring indicates the respective report day.

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tion and dissipated northeast of Stuttgart 4 hours later (Figure 3(a)). 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 4(a)). The broad storm track suggested an expanding squall line. However, a rotating supercell formed at its southeastern flank, as confirmed by reports from storm chasers (e.g. M. Kaschuba, pers. commun., 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 32.9ms^{-1} was measured. Satellite image detections of overshooting

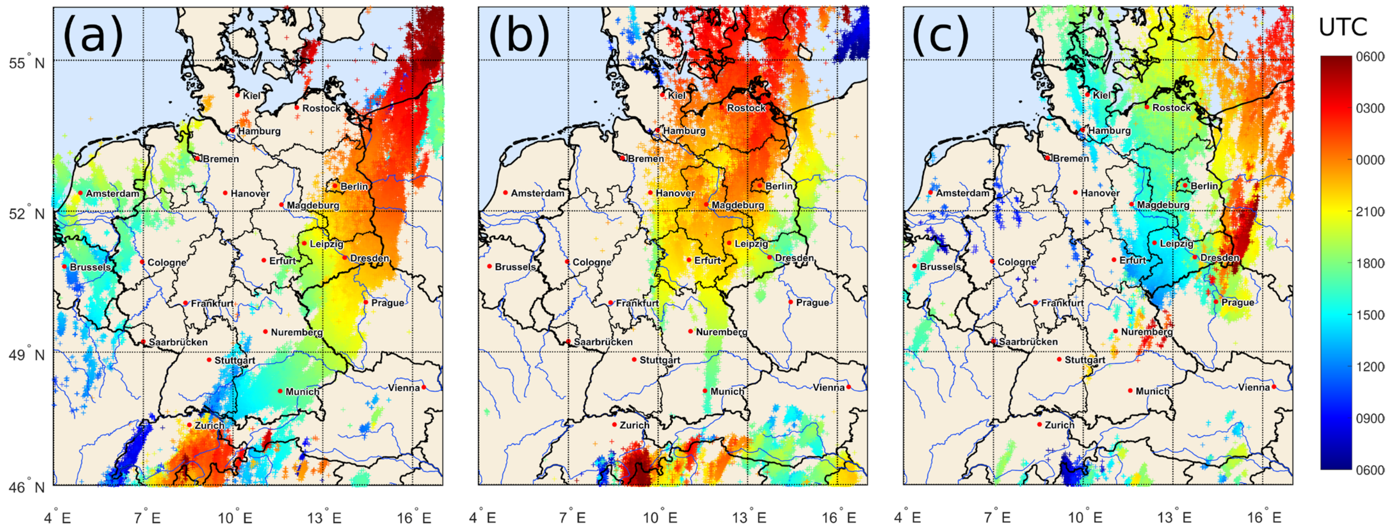

Figure 3. Lightning maps of central Europe for the timespan (a) 10/11 June 2019; (b) 11/12 June 2019; (c) 12/13 June 2019 (0600 UTC in each case). The colouring indicates the relative time of day (EUCLID/BLIDS).

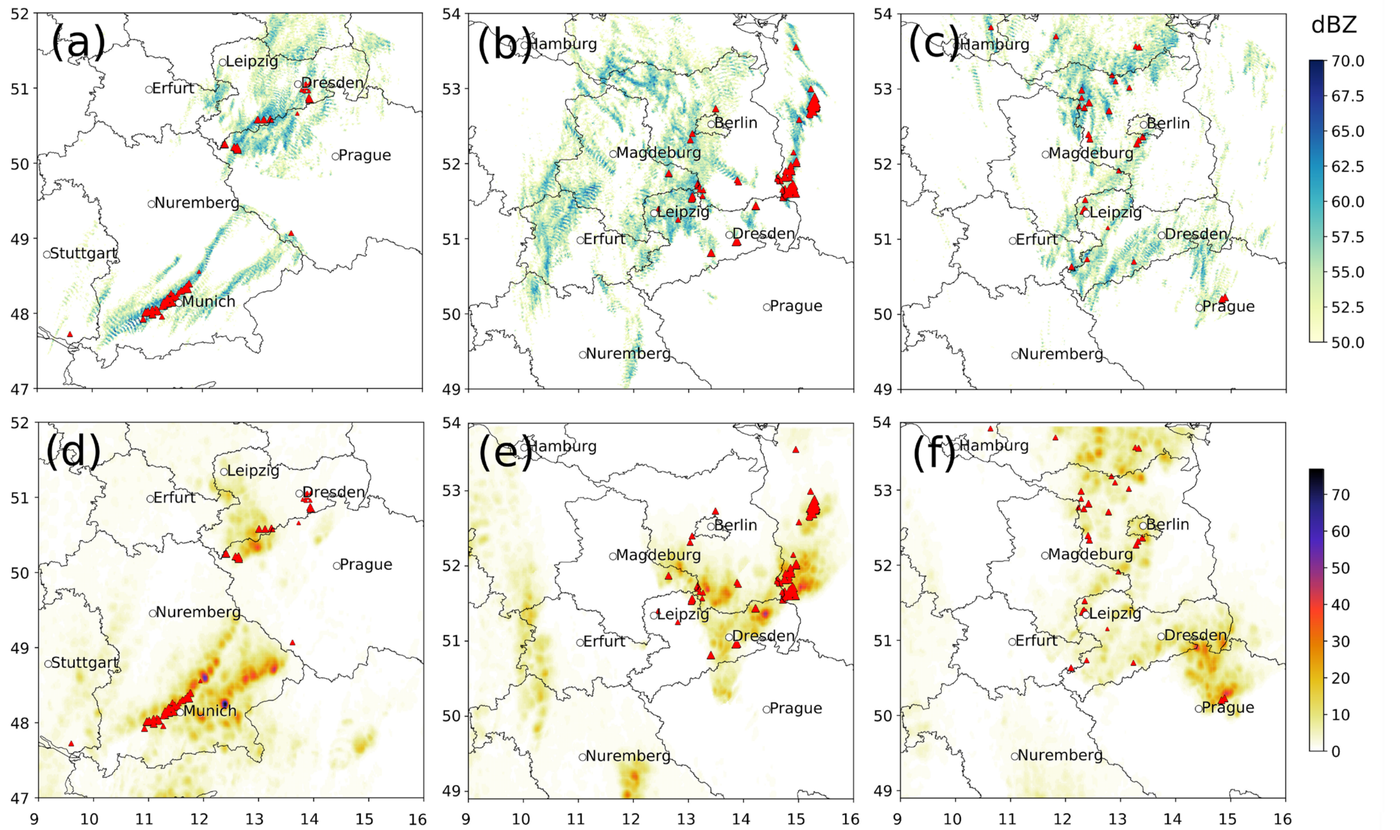

Figure 4. Radar-derived maps of maximum reflectivity factor (in dBZ; a–c) and satellite-derived maps of overshooting top detections based on observations of Meteosat Second Generation (MSG; d–f) for different parts of Germany on 10 June (left column), 11 June (middle) and 12 June (right). The corresponding 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 shown product does not capture nocturnal overshooting tops as for example from the storms and the MCC around Berlin and in northeastern Germany during the night from 11 to 12 June.

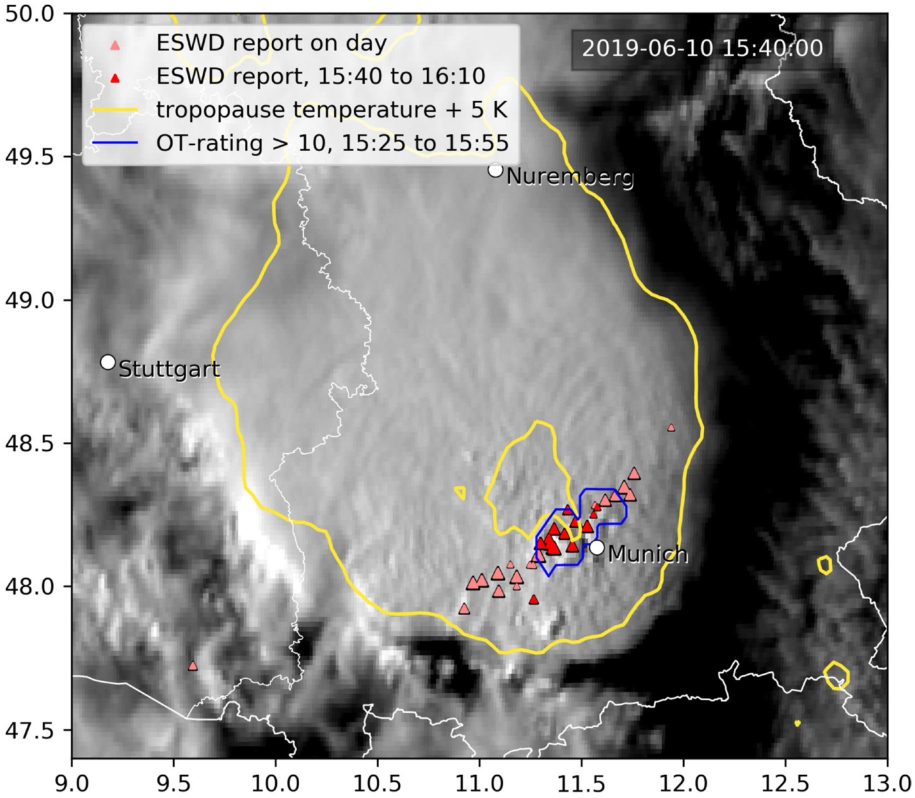

Figure 5. High-resolution visible satellite image of the MUC-19 hailstorm at 1540 UTC *on 10 June 2019. The yellow lines indicate cloud top temperatures 5K warmer than at the tropopause (based on GEOS-FP model data). The blue line indicates regions of overshooting top detections within a half-hourly period around 1540* UTC *(cf. Figure 4(d)). As in Figure 4, red triangles mark hail reports from the ESWD. Reports registered in a half-hourly period after 1540* UTC *are displayed in normal red, the others in a lighter shade.*

tops, which represent a local intrusion of convective clouds into the lower stratosphere associated with an intense updraft, accurately reflect the track of the MUC-19 hailstorm around 1540 UTC (Figures 4(d) and 5; cf. Table 1). The prominence of texture in visible wavelength imagery (Bedka and Khlopenkov, 2016) is a proxy for overshooting and updraft intensity and thus the likelihood of large hail (Bedka, 2011). The entire track stretched across southern Bavaria with a length of about 200–250km. However, most of the related hail reports originate from a narrow stretch of about 100km length near Munich. Many eyewitnesses reported hailstones with diameters between 3cm and 5cm. The largest stones were found in Gilching 20km west of Munich with diameters of up to 6cm that strongly indicate a supercell as well (Table 1).

From 1700 UTC onwards, several SCSs formed over the eastern lower mountain ranges (Bavarian Forest and Ore Mountains; cf. Figures 2 and 3(a)). Only the cells originating in the Ore Mountains produced large hail with reported diameters reaching 5cm (e.g. Bad Gottleuba 25km south of Dresden). These storms subsequently crossed Saxony and the northeast of Germany, approaching Berlin around midnight. In total, more than 220 000 lightning discharges (strokes) 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 4(b) and (e)). First isolated thunderstorms appeared between 1500 and 1600 UTC over the Bavarian Alps and over Saxony (Figure 3(b)), 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 later evening hours, 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 entailed 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 3(c)). 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 SCSs 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 moderate overshooting top indicator (Figures 4(c) 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 night-time, the SCSs 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 averaged 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 centred over Brittany in France with its axis spanning from northern England to Gibraltar; the second upstream south of Greenland; and the third centred over western Turkey (Figure 6(a)). 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 Grams *et al.* (2017): the Scandinavian and the 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 northeastward, 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

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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. Pilsensee*	48.03	11.18	10 June 1526	5.0
Unterpfaffenhofen*	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 SCSs. 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 6(b)). Most SCSs 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 north-east to southeast of Germany, providing ideal conditions for strong lifting and SCS development (not shown).

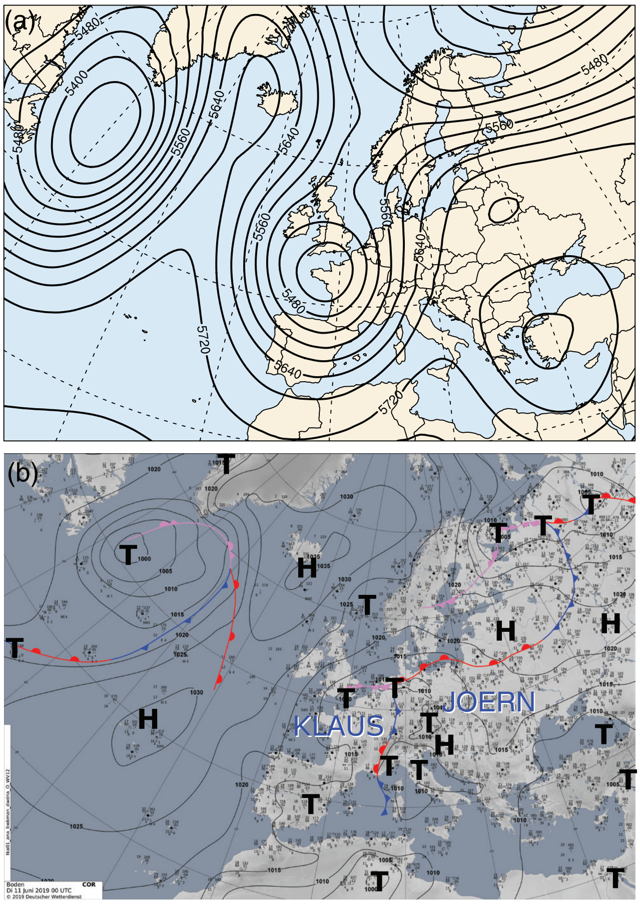

Figure 6. (a) Three-day average of the 500hPa geopotential height for the period 10 to 12 June 2019 (ERA5 reanalysis). (b) Analysis of mean sea level pressure at 0000 UTC on 11 June 2019 (FU Berlin naming; pers. commun. by Christian Ehmann, DWD).

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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 of 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 35kgm^{-2} in central Europe. Instability is estimated by the Surface Lifted Index (SLI), defined as the temperature difference at 500hPa between the environment and an air parcel rising (pseudo-)adiabatically from the ground. Negative values indicate unstable stratification, values below −8K 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) 3km 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: 500hPa temperature; 700–500hPa 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 6km height. SHIP can distinguish between environments supporting the formation of small and large hail (>2 in ≈5cm) with SHIP = 1.0 as dimensionless threshold.

On 10 June, IWV already reached values between 30 and 35kgm^{-2} across Germany, including the western parts (Figure 7(a)).

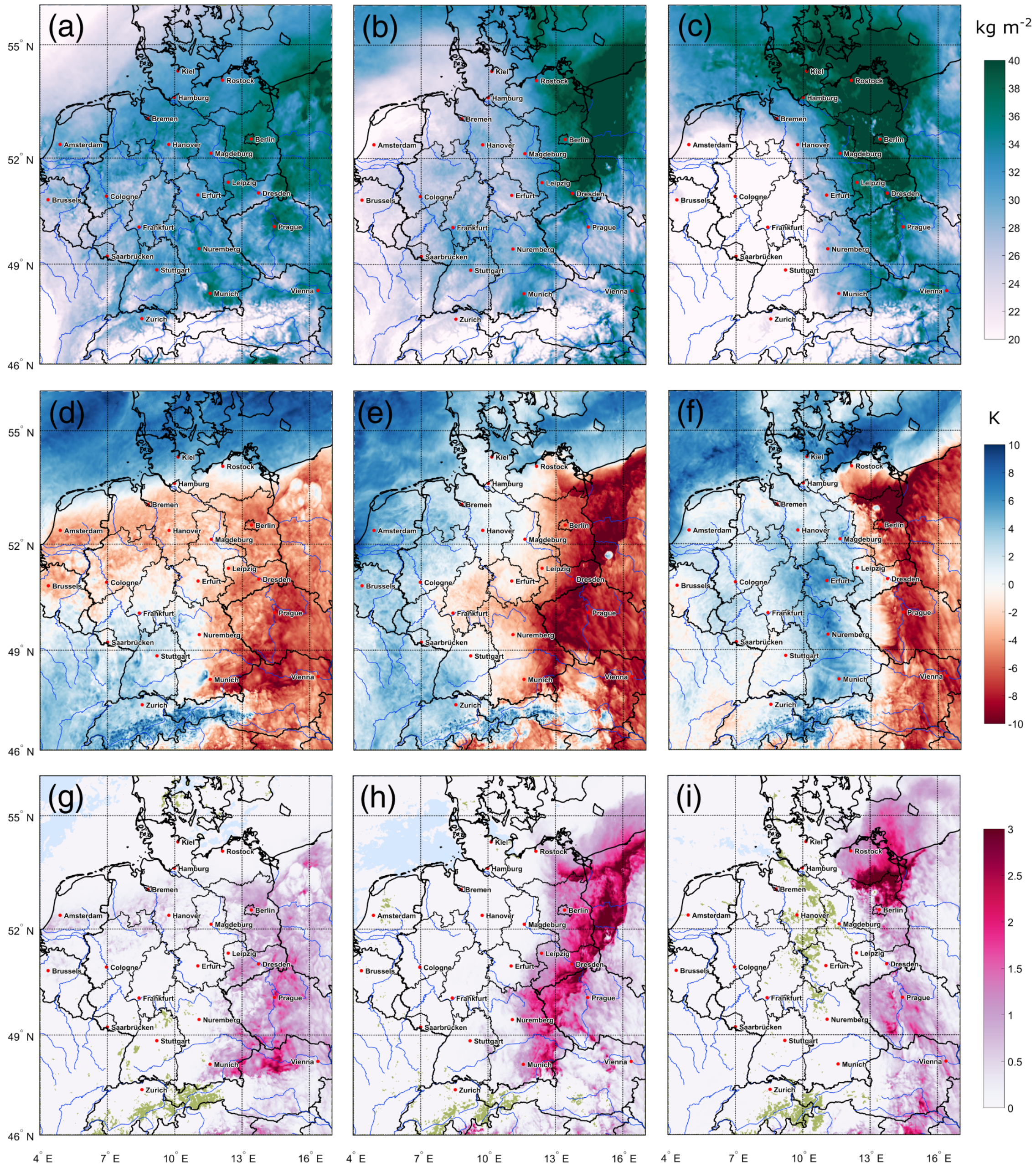

Figure 7. Vertically integrated water vapour (IWV in kgm^{-2}; a–c), Surface Lifted Index (SLI in K; d–f) and Significant Hail Parameter (SHIP; g–i) over central Europe at 1600 UTC on 10 June 2019 (left column), 11 June 2019 (middle) and 12 June 2019 (right; COSMO-D2 assimilation analyses, DWD). Note that SHIP has no value, if the lifting condensation level cannot be computed (green and light blue areas).

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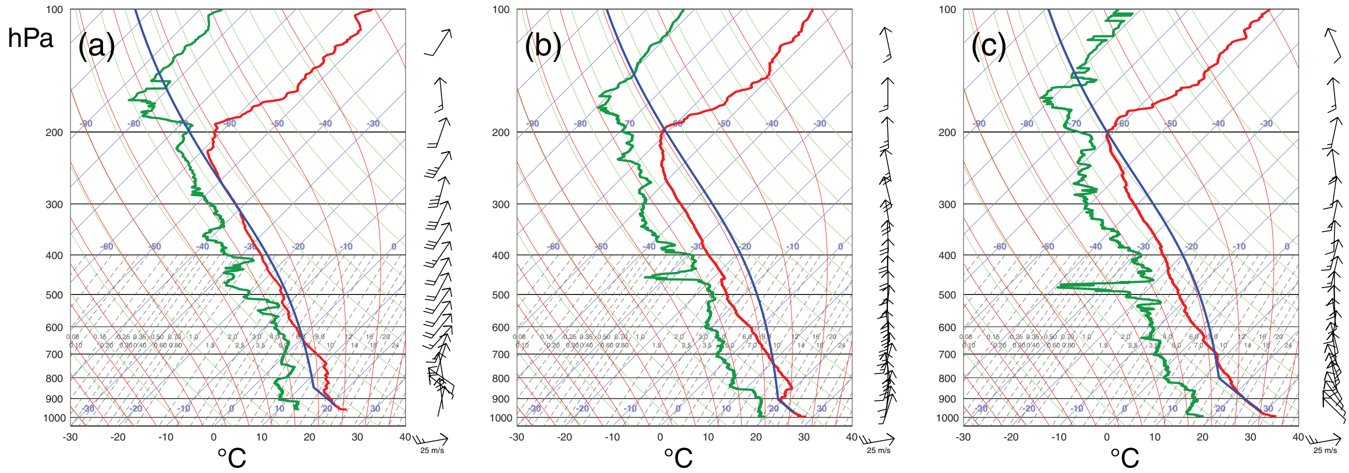

Figure 8. Atmospheric vertical soundings measured by radiosondes launched at 1200 UTC (a) on 10 June 2019 in Oberschleissheim (WMO: 10868) close to Munich; (b) on 11 June in Lindenberg (10393) close to Berlin; (c) on 12 June in Lindenberg. The bold red (green) line represents virtual temperature (dew point) values. Pseudo-adiabatic mixed-layer ascent curves based on virtual temperature are drawn in blue.

SLI was widely negative (Figure 7(d)), 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 7(g)), which is well in line with the observed hailstone sizes of 3–5cm in these regions. The EML advection caused a quite strong convective inhibition at 1200 UTC at the sounding station of Oberschleissheim – located within the track of the MUC-19 hailstorm (Figure 8(a)). However, due to diurnal boundary layer heating, sufficient CAPE of around 1500Jkg^{-1} developed in southern Bavaria during the afternoon, providing excellent conditions for supercell development in combination with high DLS values of 25–30ms^{-1} and SRH values of 300–400m^{2}s^{-2}, 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 45kgm^{-2} over eastern Germany and western Poland with the highest values along the convergence line (Figures 7(b) and (c)). SLI fell to extraordinarily low values of −8K, regionally even −10 or −11K (Figures 7(e) and (f)). Mixed-layer CAPE reached 2500Jkg^{-1} across large areas, and 4000Jkg^{-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 8(b)) illustrates a very thick layer of well-mixed air between 850 and 550hPa, capping the moist boundary layer until the evening hours. At 1800 UTC, mixed-layer CAPE exceeded 3100Jkg^{-1}. SHIP values widely exceeded 2.0, locally even 3.0, reflecting very good conditions for large hail (>5cm; Figure 7(h)). Despite these high values, the reported hailstone sizes in Germany were only 3–5cm. However, one SCS in western Poland indicates that the conditions allowed for the formation of even larger hail: in Gorzów-Wielkopolski, 125km east of Berlin, eyewitnesses reported giant hailstones with diameters up to 12cm (ESSL, 2020; Figure 2). SHIP values exceeded 3.0, SLI was below −10K, mixed-layer CAPE above 3500Jkg^{-1} and IWV above 40kgm^{-2}. DLS and SRH reached values of 15–20ms^{-1} and 200–300m^{2}s^{-2}, 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 7(c), (f), and (i)). Mid-tropospheric lapse rates flattened slightly (Figure 8(c)), whereas DLS increased moderately. Reported hailstone diameters were below 5cm. 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, 75km east of Munich (in operation since 1953), registered the strongest gust during the 3-day period with 33.3ms^{-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 32.9ms^{-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 the beginning of recording: Angermuende (since 1947), 75km northeast of Berlin, with a peak gust of 26.3ms^{-1} and Heckelberg (since 2007), 35km northeast of Berlin, with 24.7ms^{-1}. Both were hit by the same storm as Berlin-Schoenefeld (30.5ms^{-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 79.7mm, the highest value ever observed on a day in June at that site. The daily totals of Annaburg (92.4mm; since 1901) and Jueterbog (95.9mm; 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 46.2mm (Table 3). Note that the highest 1-hour precipitation sum during the 3-day period was measured at Hude, 25km west of Bremen, in northwestern Germany on 10 June. The 69.1mm precipitation total was caused by a back-building isolated cell that moved very slowly (cf. Figure 9(a)). 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

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. Further EUR 300 million loss corresponds to 120 000 reports about damage to buildings, household effects, commercial and industrial premises (GDV, 2019, 2020). Thereof, 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).

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

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% (0.6%) of the cropland (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

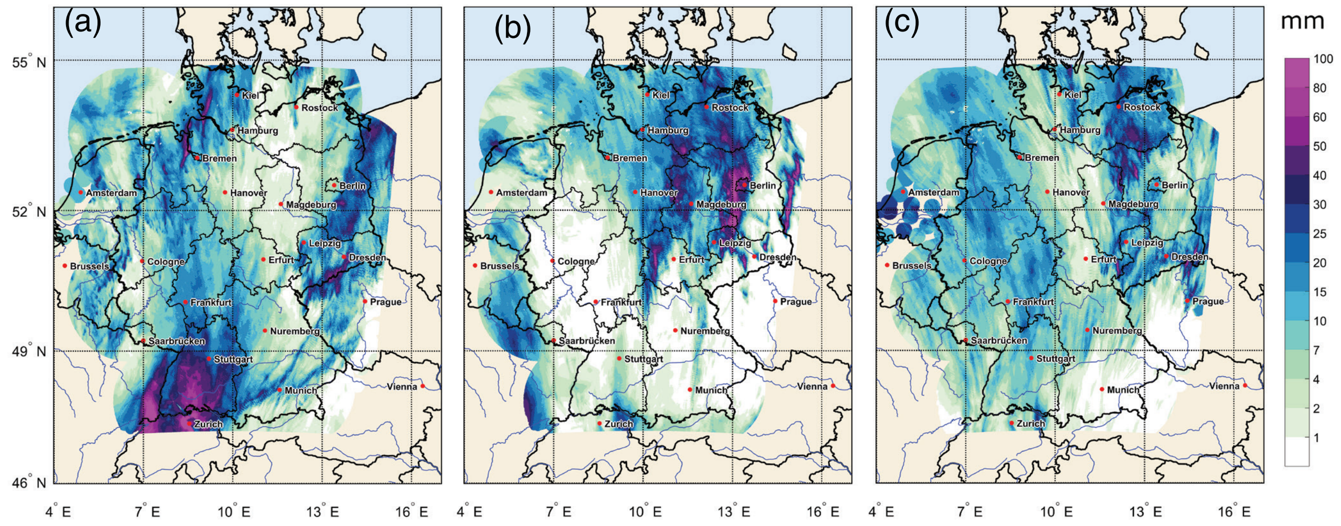

Figure 9. As Figure 3, but for 24h precipitation totals based on a combination of in situ and radar-derived observations (RADOLAN, DWD).

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 100km^2 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).

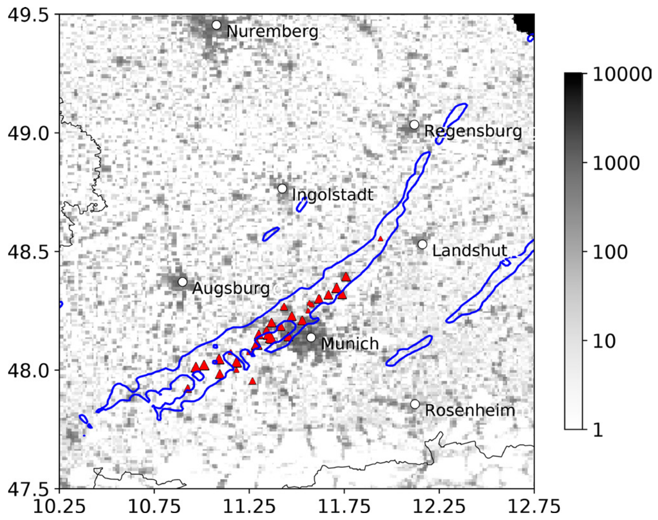

Figure 10. Asset map of capital stock (in million EUR per km^2; reference year 2019, Destatis; cf. Daniell, 2014), overlaid by the smoothed radar-derived storm-affected area (reflectivity threshold: 55dBZ) for the MUC-19 hailstorm on 10 June.

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; 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 SCSs 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 (north)eastern Germany.

Steep mid-tropospheric lapse rates caused by an EML advection characterised the period from 10 to 12 June. Thus, this event joins a queue 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 Hanover) and in south-west 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 (Púčik *et al*., 2019). Further examples include the famous Munich hailstorm on 12 July 1984, which entailed 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 case of (a) a high number of large to giant hail-producing storms and (b) a perfect match of these storms with a high asset concentration.

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Competing interests

The authors declare that they have no conflict of interest.

References

Baldauf M, **Gebhardt C**, **Theis S *et al***. 2018. *Beschreibung des operationellen Kürzestfristvorhersagemodells 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 detections using MSG 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 storm 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**: 575–586.

ESSL. 2014. *ESWD Event reporting criteria*. https://www.essl.org/cms/wp-content/uploads/20140509-ESWD_criteria.pdf (accessed 28 September 2020).

ESSL 2020. *Severe weather season 2019: summary*. https://www.essl.org/cms/severe-weather-season-2019-summary/ (accessed 28 September 2020).

GDV. 2019. *Medieninformationen – Pfingstunwetter, Gesamtverband der Deutschen Versicherungswirtschaft e. V.*, Berlin, Germany. https://www.gdv.de/de/medien/aktuell/versicherer-zahlen-mehr-als-eine-halbe-milliarde-euro--48960 (accessed 28 September 2020).

GDV. 2020. *Naturgefahrenreport 2020, Gesamtverband der Deutschen Versicherungswirtschaft e. V.*, Berlin, Germany. https://www.gdv.de/resource/blob/63610/9fb7d9d95fa0874f312ae871363310fa/naturgefahrenreport-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=gD7YitnMQao (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. *Q. J. R. Meteorol. Soc.* **144**: 231–250.

Mohr S, **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, **Wandel J**, **Lenggenhager S *et al***. 2019. Relationship between blocking and warm season thunderstorms in western and central Europe. *Q. J. R. Meteorol. Soc.* **145**(724): 3040–3056.

Mohr S, **Wilhelm J**, **Wandel J *et al***. 2020. The role of large-scale dynamics in an exceptional sequence of severe thunderstorms in Europe May/June 2018. *Weather Clim. Dynam.* **1**: 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.com/de/unternehmen/media-relations/medieninformationen-und-unternehmensnachrichten/medieninformationen/2020/milliarden-schaeden-praegen-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/mesoanalysis/help/help_sigh.html (accessed 28 September 2020).

Púčik 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 Radardaten und Versicherungsdaten*. Wissenschaftliche Berichte des Instituts für Meteorologie und Klimaforschung des Karlsruher Instituts für Technologie (KIT) 78. KIT Scientific Publishing: Karlsruhe, Germany.

Tornadoliste. 2019. *Tornadoliste Deutschland*. https://tornadoliste.de/2019 (accessed 28 September 2020).

Vereinigte Hagel. 2019. *Vereinigte Hagelversicherung VVag, Gießen, Germany*. https://www.vereinigte-hagel.net/de/2019/06/erschreckende-unwetter-zwischenbilanz-zum-17-juni-2019/ (accessed 28 September 2020).

VKB. 2019. *Pressemitteilungen, Versicherungskammer Bayern*, Munich, Germany. https://www.vkb.de/content/ueber-uns/presse/pressemitteilungen/pressearchiv/2019-pressemitteilungen/20190710-status-pfingstunwetter/index.html (accessed 28 September 2020).

WSI. 2019. *WSI Verteilungsmonitor, Wirtschaft- und Sozialwissenschaftliches Institut,* Hans Böckler Stiftung, Düsseldorf, Germany. https://www.boeckler.de/pdf/wsi_vm_verfuegbare_einkommen.pdf (accessed 28 September 2020).

Correspondence to: J. Wilhelm

jannik.wilhelm@kit.edu

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