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# TEMPORAL AND SPATIAL DISTRIBUTION OF TOTAL LIGHTNING DENSITIES IN THUNDERSTORMS IN CONJUNCTION WITH OVERSHOOTING TOPS

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#### Abstract

Lightning density and lightning density tracks are introduced. Due to the strong link between lightning activity of a convective storm and its updraft strength, monitoring lightning characteristics of convective storms help to assess storm intensity and potential severity, and thus may support weather warning operations.

The lightning characteristics of severe thunderstorms in Germany and neighbouring areas measured by the LIghtning detection NETwork (LINET) are analysed. The lightning data are analysed in conjunction with measurements from MSG satellite and precipitation radar, as well as information from automated cell detection algorithms based on ground-based radar measurements which are combined with severe weather reports. Lightning characteristics of storms with overshooting tops have been analysed in detail for 20 June 2013 based on 2.5-minute rapid scan HRV data showing that the lightning density of thunderstorms with overshooting tops is much larger compared to thunderstorms without overshooting tops.

### **1. INTRODUCTION**

Lightning pose a significant threat to life, property and economy. Hence, the detailed knowledge of the occurrence of lightning and its characteristics is important. Furthermore, the knowledge of lightning characteristic of thunderstorms can support the warning of further accompanying convective phenomena.

Based on the analysis of several hundred hailstorms in Central Europe in a multi-year period, Wapler (2017) showed that on average hailstorms have higher lightning densities than ordinary thunderstorms. The local lightning density is higher for hail events with larger observed hail diameter. The higher lightning density was observed on the left flank of the hail streak.

A feature that has been shown to occur in many severe convective storms is the lightning jump, i.e., a rapid increase in the total lightning density (e.g. Schultz et al. 2009, Chronis et al. 2015, Farnell et al. 2017, Wapler 2017). It often occurs well before the observed severe weather phenomena (e.g. large hail) and has thus a great potential to increase the lead time of warnings of severe weather events. Analysis by Wapler (2017) also revealed that half of the analysed hailstorms show a pulsating lightning activity.

Several ground-based lightning localisation networks (e.g. Betz et. al. 2009, Cummins et al. 2009, Mäkelä et al. 2010, Schulz et. al. 2016, Poelman et al. 2016) exist around the world, which provide lightning measurements essential for weather warning operations. Furthermore, lightning measurements on-board geostationary meteorological satellites will provide useful additional information: total lightning (cloud-to-ground and intra-cloud) observations with high temporal resolution and relatively continuous detection efficiencies across the field of view nearly covering the full Earth disc. The Geostationary Lightning Mapper (GLM) on Geostationary Operational Environmental Satelllite R-series (GOES-R; Goodman et al. 2013) is planned to become fully operational soon (Stano et al. 2018). The Meteosat Third Generation Lightning Imager (MTG-LI; Grandell et al. 2009) will complement the GLM in the future.

Due to the strong link between lightning activity and the updraft strength, lightning density / lightning rate is used in automatic nowcasting systems, e.g. ProbSevere (Cintineo et al. 2018) and NowCastMIX (James et al. 218) to support estimating the severity of ongoing convective storms in conjunction with other data sources. Wapler et al. (2018) provide an overview of the current status of nowcasting systems applied at several European National Meteorological Services. They summarise that nowcasting approaches will benefit from a multiple data approach and the provision of life-cycle information, e.g. strengthening and weakening of convective weather events.

# 2. LIGHTNING DENSITY

The lightning density is the number of lightning strokes or flashes per chosen spatial area (e.g. km<sup>2</sup>) and time interval (e.g. min). It can be derived using measurements from ground-based lightning location networks or lightning imagers / mappers on-board meteorological satellites. Typically total lightning (intra-cloud and cloud-to-ground lightning) is considered.

Currently, the lightning densities are calculated mostly on national level. Lightning density products will come available for the new Lightning Imager on board MTG via NWCSAF (Calbert et al. 2018).

Fig. 1 shows an example of the lightning density, overlaid on a high-resolution visible (HRV) image, of a hailstorm that occurred in Slovenia on 5 July 2018. The lightning density was calculated on a 3km\*3km grid with a 5-min time interval using lightning stroke measurements (both, intra-cloud and cloud-to-ground) from the LIghtning localisation NETwork (LINET; Betz et al. 2009, Wapler 2013). Along this storm track, heavy rain was reported in the European Severe Weather Database (ESWD; Dotzek et al. 2009) at 1645 UTC +/-15 min and hail with a diameter of 3 cm at 1745 UTC +/-5 min.



Figure 1: Hailstorm in Slovenia on 5 July 2018 between 1530 UTC and 1800 UTC. MET 10 HRV (grey), 5-min lightning density (logarithmic colour bar) with 3\*3km<sup>2</sup> horizontal resolution. © ESSL, EUMETSAT, DWD

A so-called lightning density track is created by accumulating the lightning density products from a certain interval, e.g. 3 hours. Each pixel of the lightning density track product is assigned the total of all strokes / flashes observed during the given time interval. The lightning density track product is useful for depicting paths of moving cells. In case of cell splits two divergent lightning density paths can be observed. Also, lightning density track allows visualising the temporal evolution of lightning activity along the storm track as an alternative to an animation of the lightning density at subsequent times.

The lightning density track of a hailstorm that occurred on 27 May 2016 in southern Germany is shown in Fig. 2. Hail was reported in the ESWD at 1445 UTC after a lightning jump between 1410 UTC and 1420 UTC.



Figure 2: Hailstorm in southern Germany on 27 May 2016. HRV (grey), 3-h lightning density track (logarithmic colour bar) with 1\*1km<sup>2</sup> horizontal resolution and ESWD hail reports (triangle) at 1410 UTC, 1420 UTC, 1430 UTC, 1440 UTC and 1450 UTC. © ESSL, EUMETSAT, DWD

Lightning density and lightning density track products based on LINET measurements were evaluated by forecasters from various European countries during the European Severe Storms Laboratory (ESSL; Groenemeijer et al. 2017) testbed 2016 and 2017. The overall feedback was positive. Forecasters' feedback include the following: "*It is fine, easy and straightforward.*" "*For monitoring storm severity is useful.*" "*There is a correlation between lightning frequency and reports.*" "*In messy convective situations, the lightning density is very beneficial in helping a forecaster triage the threat.*" "Suggestion to use it in combination with satellite products." Various discussions were concerned with the aggregation time interval and the spatial resolution. Some participants preferred a high spatial resolution while others asked for lower resolutions (resulting in larger pixels on the display). The optimal choice might - amongst other things - depend on the size of the domain one is working with or the option to zoom in easily and even factors such as the size of the monitor the product is displayed on.

While lightning densities can be calculated using any type of lightning detection sensor, caution has to be applied when directly comparing lightning density values based on measurements from different sensors. Lightning Mapping Arrays, Lightning Location Systems and space-borne Lightning Imagers measure different properties of lightning (electrical breakdown vs. optical energy). Information is either provided for specific point(s) or for a pixel affected by illumination. Also, the geolocation of satellite-based lightning measurement depends on the parallax correction assuming a certain cloud height. Certainly, the field of view / network coverage differs from one system to the other as well as their detection efficiency and its spatial homogeneity. Thus, knowledge of the underlying measurements is important when interpreting different lightning density products.

# 3. CASE STUDY 20 JUNE 2013: MAJOR CONVECTION IN CENTRAL EUROPE

On 20 June 213, a long-wave trough approaching from the north-eastern Atlantic merged with the south-west-European cut-off low and propagated northwards as negatively-tilted short-wave trough (Fig.3 left). With the ridge extending from the Mediterranean to the Baltic Sea very warm, moist and unstable air has been advected to Central Europe.

The surface weather chart (Fig. 3 right) shows a convergence zone between the hot air mass across western Germany and a humid and slightly cooler air mass across north-eastern Germany as well as a cold front that moved across southern Germany during the day.

ESTOFEX (European STOrm Forecast EXperiment; Brooks et al. 2011) issued a level 2 for southwest and central Germany, the Netherlands, western Alps and surroundings mainly for severe wind gusts and to a lesser extend large or very large hail, excessive precipitation, and tornados; for northwestern Italy and south-eastern France mainly for large and very large hail. Furthermore a level 1 was issued for eastern France and Belgium for large hail and severe wind gusts; for southern Sweden and western Poland to northern Balkans mainly for large hail and excessive precipitation.



Figure 3: 500-hPa and surface analysis on 20 June 2013 at 0000 UTC. © Berliner Wetterkarte e.V.

Rapidly increasing convective activity developed along the convergence zones and crossed Central Europe during the course of the day (Fig. 4, 5). The high coverage of storms also resulted in MCSs moving north-eastward with high winds and excessive precipitation.

The ESWD collected 268 severe wind, 81 heavy rain and 100 hail reports on 20 June 2013. A map with the ESWD reports is given in Fig. 4. 24 h accumulated precipitation  $\geq$ 70 l/m<sup>2</sup> were measured at several SYNOP stations in Germany; wind gusts reached maximal wind speeds above 100 km/h (see Table 1). Numerous reports with hail diameter  $\geq$ 5 cm are documented. The storms inducing these severe weather phenomena had a high lightning activity (Fig. 4). During daytime overshooting tops were visible in HRV images along severe storm tracks (Fig. 4).



Figure 4: Overview of convective activity on 20 June 2013 in Germany. From left to right: overshooting tops (provided by M. Setvak / M. Radova, CHMI); ESWD reports (downloaded 10 Sept 2018; blue circle: precipitation, green triangle: hail, yellow square: wind gust, red triangle: tornado, pink triangle: gustnado); lightning strokes detected by LINET (colour: time) and 24h-lightning density on 1km\*1km grid. Red rectangle shows location of hailstorm shown in Fig. 6.

Location	RR [mm]	Location	FFx [km/h]
Deuselbach (RP)	100.7	Weinbiet (RP)	112.7
Hoyerswerda (SN)	77.7	Karlsruhe-Rheinstetten (BW)	112.7
Bochum (NRW)	73.9	Hoherodskopf (HE)	105.8
Wusterwitz (BB)	73.0	Bab Kissingen (BY)	103.7
Gevelsberg-Oberbroeking (NRW)	70.0	Berlin-Schoeneberg (BL)	100.4

 Table 1: Measurements at German SYNOP stations on 20 June 2013. Stations with the highest values were selected.

 Left: 24-h accumulated precipitation (RR; 06-06UTC); right: maximum wind gust (FFx; 00-00 UTC).



*Figure 5:* Convection on 20 June 2013 observed from space: Left: NOAA AVHRR IR channel noon overpass. © Berliner Wetterkarte e.V. Right: MSG SEVIRI-based sandwich product from the 1800 UTC scan: combination of HRV channel with colour-enhanced brightness temperature image (yellow and red colours show temperatures below -53°C).

#### 4. CASE STUDY 20 JUNE 2013: HAILSTORM IN THE MAIN VALLEY

Around 10:30 UTC a storm initiated near the Main River. Later on several storms initiated along a line north of this storm. The left panel of Fig. 5 shows the storm during its mature stage. Three-dimensional radar reflectivity measurements showed deep convective cores with high echotops and mesocyclonic rotation could be detected in radar radial velocity measurements at some stages of the storm (not shown).

The temporal evolution of the lightning activity is depicted in Fig. 6. The left panel shows all measured strokes coloured by the time of occurrence. Hail was observed along the storm track. The ESWD documented hail with a diameter of 6 cm at 1226 UTC +/-5 min (thick triangle). An alternative visualisation shows the 5-min lightning rate (color-coded) of the storm at consecutive

times (5-min interval) combining lightning measurements with a cell detection and tracking algorithm.



*Figure 6:* Hailstorm in the Main Valley (see rectangle in Fig. 2) on 20 June 2013: Left: lightning strokes detected by LINET (colour: time of occurrence) and hail reports (thin triangles; thick triangle: hail diameter 6 cm according to ESWD); middle: 5-min lightning rate per detected convective cell (number of strokes with +/-2.5 min and 15 km of detected cell) and location of overshooting tops (black circles); right: time series of 5-min lightning rate.

The lightning rate was calculated considering all strokes within 15 km of the convective cell detected in radar reflectivity data with the cell detection algorithm KONRAD (KONvektionsentwicklung in RADarprodukten, convection evolution in radar products, Lang, 2001). Within KONRAD, a cell is defined as an object with a continuous area of at least 15 km<sup>2</sup> with a radar reflectivity of 46 dBZ or more. Colorcoding the cell detected at consecutive times with its lightning rate allows for an easy assessment of the temporal evolution of the lightning activity of the storm, e.g. identifying lightning jumps. The location of the overshooting tops is also shown in the middle panel of Fig. 6. Overshooting tops were observed during the time of strongest lightning activity.

The time series of the 5-min lightning rate is shown in the right panel of Fig. 6. This visualisation also clearly shows the lightning jump as well as the pulsating lightning activity of this storm. Wapler (2017) found that half of the hailstorms in Germany have a pulsating lightning activity and lightning jumps preceded observed hail in many cases.

# 5. LIGHTNING CHARACTERISTICS IN CONJUNCTION WITH OVERSHOOTING TOPS

Overshooting tops (convective updraft regions penetrating through the local anvil cloud) are a wellknown feature of deep convective clouds with strong updrafts. Convective storms with overshooting tops have been shown to be often associated with hazardous weather, e.g. heavy rainfall, tornadoes, damaging winds, and large hail (Dworak et al. 2012).

Overshooting tops have been analysed and provided for 20 June 2013 based on the 2.5-minute rapid scan HRV data by M. Setvak / M. Radova (CHMI). The spatial distribution of strokes (measured by LINET within +/- 2.5 min) relative to the location of the overshooting top, calculated for each OT individually and averaged over all cases, is shown in Fig. 7. For comparison, the average 5-min lightning density of all thunderstorms (cells detected by KONRAD with at least one stroke) that occurred in June 2013 in the same domain of Central Europe are also shown. Most of the strokes occur in the convective core of the storm. The lightning density of thunderstorms with OT is much larger than thunderstorms without OT.



Figure 7: Average 5-min lightning density around all thunderstorms (at least one stroke and 15km<sup>2</sup>246dBZ) in June 2013 (left) and around all overshooting tops on 20 June 2013 (right).

#### 6. SUMMARY

The lightning activity of a convective storm is linked to the updraft strength. As shown for the strong convective day 20 June 2013, the lightning density of thunderstorms with overshooting tops is much larger compared to thunderstorms without overshooting tops. The overshooting tops occurred during the strongest lightning activity in the presented case study.

As supported by many studies, monitoring lightning characteristics of convective storms helps to assess storm intensity and potential severity. Lightning jumps, i.e. a rapid increase in lightning rate, have shown to be a precursor of reported severe weather in many cases. Thus, it may improve the lead time of severe weather warnings.

The lightning density as well as its temporal development should be easily visible to the forecasters for operational severe weather warning. Traditionally, lightning detections are presented to the weather forecaster on their meteorological workstation by displaying individual strokes or flashes with a symbol. In convectively active situations it can be difficult to distinguish cells with strong and weak lightning activity and to see whether lightning activity increases or decreases. Therefore, lightning visualisations such as lightning densities, object-based lightning rates or time series of lightning rates for individual storms should be provided. Lightning density and lightning density track products were evaluated at the European Severe Storms Laboratory Testbed with positive feedback by forecasters.

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