Lightning characteristics of extreme weather events

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Abstract: Lightning characteristics of extreme weather events are reviewed by first introducing the variety of thunderstorm types and large scale weather systems with embedded thunderstorms which may cause extreme events. In a description of charge separation processes, we identify the non-inductive charging mechanism as the most relevant and outline the resulting basic charge layer distribution, the normal (or inverted) polarity dipoles and tripoles. Several case studies serve to illustrate and exemplify the concepts of the introductory part and relate the lightning evolution characteristics to hail storms, tornadoes, mesoscale convective systems, derechos or tropical and extratropical cyclones. There is compelling evidence that severe weather from thundering convection is often correlated to anomalous lightning activity, for instance signified by unusual values of lightning frequency or polarity. We also identify areas in which further research is needed, like the causes of the land-ocean contrast in lightning activity or the interrelation between recently discovered cold-ring cloud top structures and the storms' total lighting evolution (cloud-to-ground and intracloud flashes). Due to recently improved total lighting discrimination capabilities of lighting detection networks, we are confident that significant progress can be achieved in clarifying these open issues in the near future.

Keywords: Severe Convective Storms; Electrification; Lightning; Hail; Flash Floods; Tornadoes; Straight-line Winds; Derechos; Mesoscale Convective Systems; Tropical and Extratropical Cyclones

1 Introduction

Extreme weather events are increasingly being investigated over the last years due to a growing concern that they might become more frequent, more extended or more intense in the course of natural and anthropogenic climate change (cf. Brooks and Dotzek, 2008 or Price, 2008, this volume). Among all such extreme events, those that produce lightning are normally found on the mesoscale (Fujita, 1981) and range from tropical cyclones with embedded thunderstorms in their rain-bands, mesoscale convective complexes (MCC), linear mesoscale convective systems (MCS) down to individual thunderstorms which by themselves cover a spectrum of sizes, intensity and internal organisation. This is one of the reasons why exploring the lightning characteristics of these extreme events is at the same time a difficult task and a fascinating scientific challenge.

A number of authors have taken this challenge in recent years, and comprehensive treatments of lightning in severe storms were given by MacGorman (1993), Houze (1993), MacGorman and Rust (1998), Williams (2001) and Rakov and Uman (2003). Nevertheless, they all had to acknowledge the complexity and intricacies of severe thunderstorm electrification. Not only do these arise from the range of scales covered by thunderstorms, but also from the multi-parameter phase-space created by the relevant cloud microphysical effects. First, the charge separation in developing convective clouds is influenced by the particle types and size spectra contained in the storm and by the interaction of these various hydrometeors. Second, the amount of liquid water is relevant, also in supercooled form above the freezing layer, as well as the temperature level at which the interaction of liquid and frozen hydrometeors occurs. Third, the relative motion of hydrometeors inside the cloud depends on the updraft speeds which are directly related to the vertical profile of convective available potential energy (CAPE), cf. Blanchard (1998).

It is here where the notion of “storm severity” enters the scene. So far, we had only referred to electrification processes which apply to all kinds of deep moist convection. To deal with lightning in severe storms additionally requires analysing the thermodynamic environments that may lead to severe storms in the first place, and what aspects of these environments or the internal storm dynamics can influence their electrical behaviour. One factor that is commonly tied to the development of storm severity is their longevity. Long-lived storms in a quasi-steady state will necessarily have a higher chance of developing certain dynamic and electrical characteristics which may distinguish them from shorter-lived convection which cannot evolve into a well-defined convective mode.

In that sense, severe storms can display more distinct lightning characteristics than ordinary storms, and their often destructive and disorganising effects at the ground are a result of their high degree of organisation aloft. This internal organisation is also promising for the development of improved nowcasting or early warning algorithms: Severe thunderstorms present a significant hazard, both at the ground and for aircraft (e.g., Roach and Findlater, 1983; Pike, 2000). Higher understanding of the reasons behind the evolution of lightning in severe storms may help to forecast the severe weather phenomena that result at or near the ground later on.

In this Chapter, we will explore the various extreme events which display thundering convection and identify what aspects of their structures and life-cycles bear relevance for their electrical activity. A number of illustrative case studies will serve to point the reader to the relevant literature before we draw our conclusions and outline open research questions.

2 Electrification mechanisms in deep moist convection

2.1 Severe convective storms and hurricanes

This introductory section serves as a brief overview of the various storm types relevant for our subject. Readers interested in more thorough treatments are referred to the monographs by Cotton and Anthes (1989), Houze (1993), Emanuel (1994) or Doswell (2001). These references and e.g. Doviak and Zrnić (1993) or MacGorman and Rust (1998) further contain information on the relation between lightning activity and radar characteristics, an extensive topic by itself, treated also by Dombai (2008, this volume) and many of the references cited in this Chapter.

2.1.1 Single-cell thunderstorms

The single-cell storm forms the archetype concept for any kind of deep moist convection. It is the most frequently observed thunderstorm variety and also that with the least potential of becoming severe. Its life-cycle begins with a convective cloud forming from a rising moist and warm air mass. If its vertical development is not limited by stably stratified atmospheric layers, significant precipitation formation and charge separation can take place in the cumuliform cloud.

In mid-latitudes, this requires that the cloud tops reach well above the 0°C isotherm, and that the updraft persists for at least half an hour, such that precipitation-sized hydrometeors can form in the cloud. Aside from this typical lifetime, the dimension of a single-cell storm is roughly 10 km in both the vertical and horizontal. This also puts a limit to the horizontal extent of flashes in these storms, and cloud-to-ground (CG) flashes will mainly be observed from the lower part of the cloud. The total numbers of lightning discharges as well as the CG density (per unit time and per unit area) at the ground are unlikely to attain very large values.

As the typical setting for single-cell thunderstorms is characterised by weak vertical wind shear, the storm updraft remains essentially vertical, such that any precipitation from the cloud will fall into the main updraft region and cut off the cloud from its feeding boundary layer airmass. This marks the decay of the thundercloud. Severe events from this type of storm are rare, as its short life-cycle would not support formation of sustained heavy rain, large hail or excessive lightning activity. Given the right stratification below cloud base, weak downbursts may form or occasionally a brief and weak non-mesocyclonic tornado (cf. Dotzek et al., 2005b), especially if the thunderstorm developed at a pre-existing boundary layer convergence line. Such lines are an example of thunderstorms “breeding zones” which can often trigger several nearby single cell storms simultaneously or successively. This may eventually lead to their clustering and thus the formation of a multicell storm.

2.1.2 Multicell thunderstorms

Multicell storms are larger clusters of convective entities which by themselves may follow the single-cell storm life-cycle, but which have as an important additional feature the interaction between the individual cells. Multicells can be either a more or less randomly arranged group of individual cells in various stages of their life-cycles, or they can develop as a succession of cells from the front to the rear side of a propagating storm system. The latter type requires higher vertical wind shear to develop its greater degree of internal organisation, and in turn, its likelihood to spawn severe weather phenomena is enhanced.

Typical severe weather hazards from multicells are heavy precipitation or even flash-flooding, large hail and also damaging straight-line winds. Tornadoes are not a main hazard, but possible as well. The higher likelihood of severe weather from multicell storms comes from their increased size and lifespan compared to single-cell storms. Higher amounts of precipitation and large numbers of lightning flashes can be formed from these larger storms. Due to the larger horizontal dimension of the multicell storm, intracloud (IC) lightning discharges can bridge larger distances in the cloud’s upper portion. The presence and interaction of several cells at a time also leads to higher CG flash densities at the ground. The increased longevity of multicells further enables a more efficient formation and growth of hailstones, as well as the development of precipitation-cooled downdrafts which may reach the ground as damaging winds.

2.1.3 Supercell thunderstorms

Supercell or mesocyclonic thunderstorms are the least frequent, but also most dangerous type of thunderstorms. Under very special environmental conditions, these storms can form and attain the highest degree of internal organisation of all convective storms. Among other things, supercell formation requires both favourable amounts of vertical wind shear and CAPE to develop their main discriminating feature: a single, deep, persistent, rotating updraft called the mesocyclone.

Note that the size of the storm is not a criterion for the presence of a supercell. Rotating, mesocyclonic storms have been observed over a wide range of scales, from barely the size of a single-cell storm (sometimes referred to as "mini-supercells") to very large entities with cloud tops protruding into the lower stratosphere and horizontal dimensions of over 20 km. The term "persistent" in the definition of the mesocyclone refers to the timescale of an ascending airmass from the base to the top of the storm, and "deep" means that the mesocyclone should extend vertically through a significant portion of the whole cloud depth.

Due to the high wind-shear in supercell environments, the main updraft will be tilted downshear, so precipitation from the supercell will not interfere with its boundary layer inflow region. Together with the stabilising effect of the large helicity in its mesocyclone, this can lead to a quasi-steady state of the storm and to its longevity, as long as the storm environment continues to provide the necessary essential ingredients.

Supercells are capable of causing any severe weather phenomenon, from copious amounts of rain to large (and very large) hail, as well as downburst up to F3 intensity and tornadoes up to F5 intensity on the Fujita scale (e.g., Fujita, 1981). Depending on the amount of liquid precipitation at the ground, three types of supercells are distinguished: the classic supercell, the low-precipitation (LP) and high-precipitation (HP) supercell. Despite little or no rain at the ground, LP supercells are known to be reliable producers of very large hail.

Severe thunderstorms, in particular supercells, are often marked by U- or V–shaped radar cores or cloud-top overshoots (Maddox, 1981; McCann, 1983; Adler et al., 1985; Heymsfield and Blackmer, 1988). Due to their long lifetime of several (up to 12) hours, either CG or IC lightning activity in these storms can be high (cf. Steiger et al., 2007a) and itself present a significant hazard at the ground or to aviation. On the one hand, CG numbers and densities can be very large, and CG lightning may also occur from higher regions of the cloud, for instance the anvil of the storm. On the other hand, one impetus for investigating the lightning flashes in supercells has been the observation that the evolution of their total lightning activity can display certain characteristics (cf. Williams et al., 1999) that may facilitate early detection and warning of other impending severe phenomena, like downbursts, hail or tornadoes.

2.1.4 Mesoscale convective systems

We follow the broad mesoscale convective system (MCS) definition given by MacGorman and Morgenstern (1998) which includes linear systems (like squall lines) and is not restricted to circular–shaped cumulonimbus clusters below the size of a mesoscale convective complex (MCC): "*A mesoscale convective system* *is a group of storms which interacts with and modifies the environment and subsequent storm evolution in such a way that it produces a long–lived storm system having dimensions much larger than individual storms*".

One important type of these systems is the linear MCS, often manifesting itself by a leading line of convective cells (which may display either multicell or supercell characteristics) and a horizontally extended trailing stratiform region. Consequently, these systems have been dubbed leading-line, trailing stratiform MCS. Their lightning activity is split up between the distinct convective and stratiform regions, with a relatively small intermediate zone in between. The most notable severe events from these MCSs are flash-flooding, large hail and damaging winds. Tornadoes are less frequent in mature linear MCSs, but pose a higher threat during the early stages of MCS formation, before the initial thunderstorms have fully merged to establish the MCS.

Like with multicell or supercell storms, the lightning activity in MCSs may be high and encompass also very long IC flashes. Due to the complex internal structure of MCSs, affecting also their internal charge distribution, lightning initiation and evolution reflect this complex structure (cf. Steiger et al., 2007b; Ely et al, 2008). In addition, several studies, among them Toracinta and Zipser (2001) and Zipser et al. (2006), noted a significant difference of about one order of magnitude in lightning activity of MCSs over land compared to those over oceans. Despite some candidate cloud-microphysical charge separation processes which may respond to the land-ocean contrast (cf. Zipser, 1994), a generally accepted theory for the observed difference in electrical activity is not yet at hand.

2.1.5 Tropical cyclones

Tropical storms and tropical cyclones are storms that have lifetimes of days to weeks as they cross the tropical oceans. Over the Atlantic, they are called hurricanes, over the Pacific typhoons, and over the Indian Ocean, they are referred to as cyclons. Unlike the storms discussed in previous sections, hurricanes spend most of their lifetime over the warm tropical oceans (sea surface temperatures greater than 27°C), and their impacts are felt mainly when they approach coastlines, islands, or enter continental regions. Hurricanes start off as atmospheric tropical waves that can develop into tropical depressions, later developing into tropical storms, and then hurricanes. Only about 10% of the waves develop all the way into hurricanes.

The damage from hurricanes is threefold: Extensive coastline flooding due to the storm surge as the hurricane crosses the coastline; extensive wind damage due to the horizontal hurricane-force winds (up to 200 km h^{-1}) that remain sustained for hours at a time, changing direction as the eye passes over; and inland flooding due to heavy sustained precipitation. Once over land, embedded thunderstorms in hurricanes often result in other types of severe weather such as tornadoes. Hurricanes passing over islands will re-intensify as they move back over the warm ocean waters.

The electrification of hurricanes has not received much attention over the years, mainly due to the fact that hurricanes spend most of their lifetime over the oceans, while lightning observations were mainly available over land. However, there is significant evidence for the existence of convective cells within the eye-wall of the hurricanes, and within the outer spiral rain bands. Recent observations confirm significant lightning activity in hurricanes (Black and Hallett, 1999 Shao et al., 2005). As these lightning discharges come from embedded thunderstorms, their flash characteristics will most likely correspond to that of the individual storm types described above.

2.1.5 Extratropical cyclones

Contrary to their tropical counterpart, extratropical cyclones pose a multitude of major severe weather threats in mid-latitudes mainly in the cool season from autumn to spring. These threats encompass the large-scale field of high winds, resulting storm surges along the affected coastlines, large amounts of precipitation and, finally, embedded thunderstorms which may occur more isolated in the cyclone's warm sector or more widespread along the cold front of the storm. In Europe, individual cases of extratropical cyclones have caused losses of about 10 billion Euros, and Ulbrich et al. (2001) have analysed three high-impact events of December 1999. Like for hurricanes over the North Atlantic, the question of trends in extratropical cyclone activity in Europe under the influence of climate change is an area of intensive research (e.g., Ulbrich et al., 2008).

The dominant cause of damage by these cyclones is the interaction of the large-scale wind field with structures at the surface. However, on a smaller scale, the warm-sector or cold-frontal thunderstorms in these systems may be responsible for the highest observed loss densities in the cyclone damage track. The lightning activity in these storms will in principle correspond to the description given above for isolated and potentially supercellular thunderstorms or linear MCSs, but due to the coupling of the extratropical cyclones to the cold season, peculiarities of winter thunderstorms as discussed by Brook et al. (1982) will also be found, like low cloud base and cloud top and a high-shear environment supportive of strongly tilted updrafts. In passing, we note that low cloud base and high low-level shear are also factors which favour tornado genesis in the presence of strong convection. Therefore, embedded electrical activity in extratropical cyclones should be an especially alarming signal for operational forecasters.

2.2 Charge separation and lightning polarity

Charge separation mechanisms and lightning physics are treated in detail by Saunders (1993), MacGorman and Rust (1998), Uman (1986, 2001) and Rakov and Uman (2003). The topic of lightning initiation and hence predictability of the lightning hazard was treated, for instance, by Zipser (1994), Lang and Rutledge (2002) and Clements and Orville (2008). Here, we focus primarily on the charge separation process which is likely the most relevant for convective storms: the non-inductive charging mechanism.

The non-inductive charging (NIC) is based on the interaction of graupel or hail with small ice crystals in the cloud, given the side constraint that supercooled droplets are also present and riming of the graupel particles can occur. Due to differential fall speeds (cf. Berdeklis and List, 2001), these hydrometeors experience collisions by which charge is being transferred from the surface of the small particles to that of the large ones. Under the influence of differential convective updraft speeds, the charged particles of different sizes are separated vertically, with the ice crystals lifted to the upper cloud regions and the macroscopic particles remaining at mid- or low cloud levels.

The sign of the charge transfer between graupel and ice crystals is mainly determined by the ambient temperature, relative humidity and liquid water content. Takahashi (1978) and Jayaratne et al. (1983) were able to show that the graupel particles acquire negative charge if the graupel-ice collisions occur below a temperature of about -20°C, and charged positively above this reversal temperature T_R. Similarly, high liquid water contents and larger updraft size and intensity favour positive charging of graupel, while low or moderate liquid water content and less vigorous updrafts lead to negatively charged graupel (e.g., Carey and Buffalo, 2007).

As a result of the NIC mechanism, most ordinary thunderstorms are characterised by a main dipole in the cumulonimbus cell's main updraft region, with positively charged small ice crystals in the upper part of the cloud and negatively charged larger hydrometeors at intermediate levels. If the graupel-ice collisions occur above T_R and liquid water contents are high, an inverted dipole can form, with positive charge at mid-levels and a negatively charged cloud top region. This becomes more likely for storms with a low cloud base and hence a larger cloud portion below the freezing layer.

The conceptual model of the main charge layers and cloud-to-ground (CG) or intracloud (IC) flash polarity based on the NIC mechanism is summarised in Fig. 1 and has gained widespread acceptance (cf. Lang and Rutledge, 2002; Hamlin et al., 2003): There are two dominant charge regions present within the storms, one between -10 and -20 °C (negative in a normal polarity dipole), and another region higher up, close to the -40 °C temperature level (positive in a standard dipole). Aside from this main dipole structure, there may be other, less pronounced charge layers in the thundercloud. For instance, a smaller positive charge region is often found near the freezing level, leading to a tripole setup (Williams, 1989). Fig. 1 depicts these main layers within schematic thunderstorms and shows the possible consequences for CG and IC discharges. The left- and rightmost sketches show negative CG and IC flashes, respectively, for a normal polarity dipole storm with a main positive charge centre above the negative main charge centre.

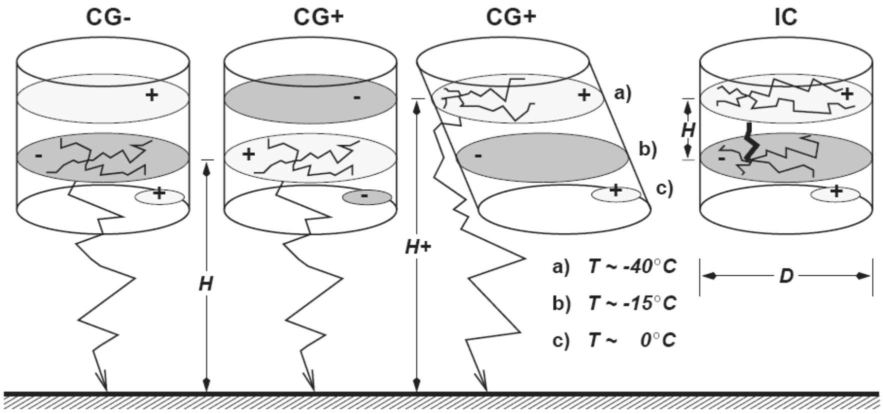

Figure 1: Conceptual model of lightning types, main charge layers (light grey=positive, medium grey=negative) and their typical in-cloud temperature levels. Note two options for CG+ flashes: (i) inverted dipole, with negative charge above positive charge; (ii) normal polarity, tilted dipole in strongly sheared environments, unshielding the upper positive charge region. The tilted dipole setup could also lead to stronger CG- flashes from an inverted polarity storm.

For the positive CG flash, however, there are two different candidate processes. The first of these, favoured by Carey and Buffalo (2007), is the inverted dipole in which the charge layering inside the cloud is reversed compared to the normal polarity setup. The second alternative is the tilted dipole, a special case of a normal polarity storm. In a strongly sheared environment that favours development of supercell storms, the upper positive charge centre will be shifted downshear from the lower, negative charge region. In this way, the negative charge layer does not shield the positive charge overhead from the ground anymore, so CG+ flashes can occur (cf. Brook et al., 1982; Reap and MacGorman, 1989; Curran and Rust, 1992). These originate from a much greater altitude and are thus likely to have higher return stroke currents (say, above ~100 kA) than positive discharges from an inverted polarity dipole.

CG+ flashes from a tilted dipole are often thought to provide evidence for presence of a supercell storm. However, if an inverted dipole could be verified in the course of CG+ lightning detection or electric field measurements, the non-inductive cloud electrification theory might be related to its microphysical observables (Saunders et al., 1991; Saunders, 1993) and allow making judgments on the significance of the NIC mechanism compared to other charge separation processes. For these reasons, CG+ flashes are a focal point of thunderstorm research.

When using total lightning detection, it is possible to discriminate between the two possible dipole types. Aside from several studies (e.g., Hamlin et al., 2003) in the USA, Dotzek et al. (2001) showed an example of an inverted dipolar structure in a supercell hailstorm in southern Germany. In addition, Carey and Buffalo (2007) strongly questioned the relevance of the tilted dipole concept based on a review of recent evidence.

Due to a relative lack of three-dimensional lightning observations in mature MCSs, there are no similar conceptual models of in-cloud lightning structure in the trailing stratiform region of MCSs. Several balloon studies (e.g., Marshall and Rust, 1993; Stolzenburg et al., 1994) of electric fields in the stratiform region of MCSs have inferred multi-layered charge structures there, but few studies have examined in-cloud lightning behaviour. Mazur and Rust (1983) as well as Dotzek et al. (2005a) found that significantly more IC lightning occurred in the convective as compared to the stratiform region, where long (>20 km) flashes tended to occur preferentially.

3 Case studies

The purpose of the case studies chosen here is to illustrate the concepts from Sec. 2 and to point the reader to persisting open questions which are active fields of research presently. Due to their potential longevity and their tendency to approach a quasi-steady state during much of their lifetime, our discussion will focus on supercell thunderstorms, mesoscale convective systems as well as tropical and extratropical cyclones.

3.1 Hail Storms

Changnon (1992) studied the spatial and temporal relationship between damaging hail and CG lightning. Lightning activity was always closely coupled to the presence of hail (Fig. 2), with the peak lightning activity generally associated with the start of the hail falling on the ground. In addition, the thunderstorm cells in which CG flashes were closely linked to hail typically developed 9 min before the hail was observed, and at a point 5 km upstorm from first hail, suggesting that CG flashes began as the hailstones were developing aloft. The hailstorm's severity was also found to be well correlated to the rate of flashing during the hailfall.

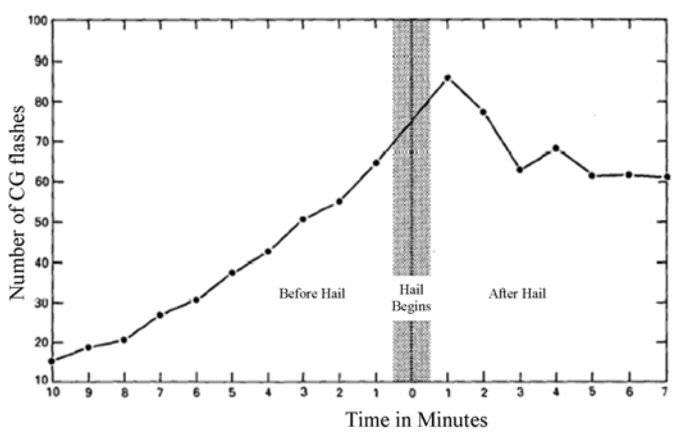

Figure 2. The temporal evolution of lightning activity associate with 48 hail events in the United States (adapted from Changnon, 1992).

Carey and Rutledge (1998) found an extremely high IC-to-CG flash ratio (IC/CG ~ 20-70, cf. Boccippio et al., 2001) and predominantly CG+ lightning (over 74%) when storms are producing large hail and weak tornadoes. Similar results were found during the STEPS project in the United States (Kyle et al., 2005) and observations in central and southern Europe (Dotzek et al., 2001; Soula et al., 2004).

3.2 Flash floods

Many studies show a positive correlation between lightning and precipitation amounts (Piepgrass et al., 1982; Tapia et al., 1998; Petersen and Rutledge, 1998; Zhou et al., 2002, Price and Federmesser, 2006; Gungle and Krider, 2006), some of which can produce flash floods with dramatic consequences to loss of life and damage to infrastructure and property. Soula et al. (1998) showed that in a flash flood that killed more than 80 persons, the CG flash density was exceptionally high, and the peak flash rate averaged over 5-min periods reached 11.6 min^{-1} within the cell area. The evolution of the CG flash rate and the radar reflectivity were closely correlated, with a very good agreement between the location of the intense rain at the ground and the high CG flash density. More importantly, the flash rate reached high values before the arrival of the precipitation at the ground, which provides hope that lightning could possibly be used for early warnings of flash floods.

3.3 Tornadoes

Anomalous lightning activity associated with tornadoes has been observed in many studies. The anomalous activity is frequently observed in the polarity of the CG lightning activity, being mostly of positive polarity at the time of the tornadoes (Carey et al., 2003; Seimon, 1993). In addition, the lightning activity often peaks just before the onset of tornadic activity (Kane, 1991; Perez et al., 1997). Fig. 3 shows the intensification of lightning activity shortly before the occurrence of a tornado, and the decrease in lightning activity commonly observed during the tornado lifetime. These results were further corroborated in an extensive study by Williams et al. (1999) using total lightning observations.

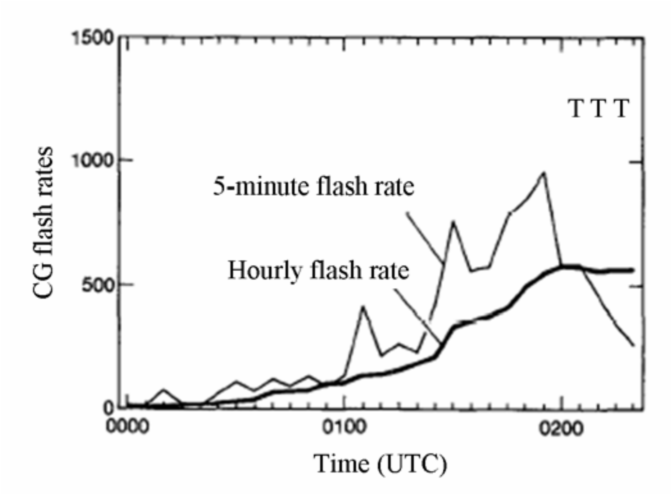

Figure 3. The 5-min and hourly CG lightning flash rates prior to a tornado (T) in the USA (adapted from Kane, 1991).

Analysis of a tornadic supercell by Dotzek et al. (2005a) showed that most ground flashes occurred in the south-eastern sector of the anvil, and most CG+ were found below the coldest cloud tops. Eight minutes before the long-lived tornado formed, the majority of CG+ lightning flashes were under a V-shaped cumulonimbus overshoot (cf. Heymsfield and Blackmer, 1988). This cold-V coincided with many NLDN (Cummins et al., 1998; Orville, 2008) CG strike locations. Just 1 min before tornado formation, there was significant CG+ activity north of the tornado, with two southern tips of concentrated CG– flashes (cf. Keighton et al., 1991). This pointed towards presence of a tilted dipole (cf. Fig. 1). About halfway through tornado lifetime, the CG activity attained a minimum.

Remarkable in the storms around the tornado were the high CG+ percentage prior to the tornado and few, but strong CG+ strokes near the end of tornado lifetime. Furthermore, CG- flash multiplicity was low, yet persistent and very regular

15-min oscillations of CG flash multiplicity were seen, especially for the CG+ discharges; see Dotzek et al. (2005a).

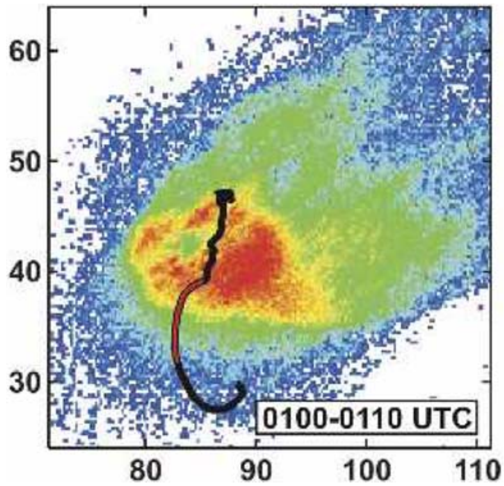

Figure 4. A lightning hole is visible in the 10-min total lightning flash density of a STEPS supercell on 6 July 2000. Axis labels denote kilometres east and north of the observation network centre, while the coloured line gives the ascent track of a measuring balloon (adapted from MacGorman et al., 2005).

Following the initial observation by Krehbiel et al. (2000), several groups have found "lightning holes" in the total lightning (IC and CG) density of supercell storms (not exclusively tornadic). Fig. 4 shows an example from MacGorman et al. (2005); additional examples were given by Murphy and Demetriades (2005) and Wiens et al. (2005). Comparison with simultaneous radar data has revealed that the lightning holes correspond to the bounded weak echo region (BWER) of the supercell storms. The BWER is formed by the supercell's main updraft in which the vertical transport is too rapid to enable hydrometeor formation – and in turn charge separation by the NIC mechanism. As the BWER or the mesocyclone themselves, the lightning holes usually have diameters of 5-10 km and lifetimes of 10-20 min.

3.4 MCS with "cold-ring" cloud top signatures

Dotzek et al. (2005a) studied the life cycle of a long-lived MCS. Fig. 5 marks its transition from individual cells on a surface boundary to a line of severe thunderstorms. Near the northern tip of the linear MCS, there is the tornadic storm discussed in Sec. 3.3 with its V-shaped cloud-top signature. Fig. 5 further shows the impressively large anvil of a separate strong storm in the Dallas–Ft. Worth region.

Its CG lightning activity is mostly confined to the regions of highest cloud tops at that time.

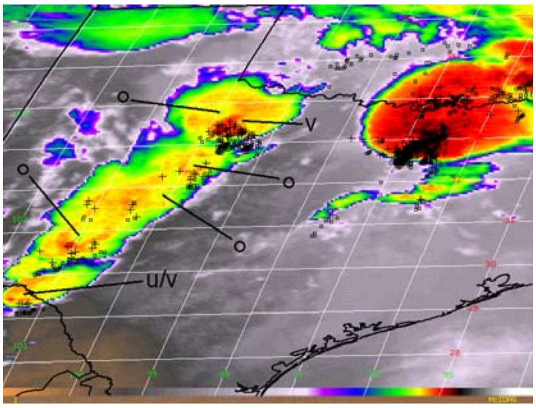

Figure 5: GOES 8 channel 4 enhanced images of the early stage of a leading-line, trailing stratiform MCS over Texas on 7 April 2002, 2025 UTC. NLDN flash overlay (+=CG+, □=CG-) 10 min before to 5 min after image time (cf. Dotzek et al., 2005a). Cold-ring signatures are marked by o-symbols, and cold-U, cold-V are indicated as well.

Yet, the most striking features of Fig. 5 are several cold-ring cloud top structures of 50 to 100 km diameter along the forming leading-line, trailing-stratiform MCS. These are also found in the non-tornadic regions of the line and are much larger in size than the lighting holes of individual supercells discussed above, but they seem to be similarly transient phenomena: For the northern portion of the MCS, the cold-ring started to vanish from the northwest shortly before tornado formation and had broken up completely 15 min later. Only CG lightning data were available for the MCS at that stage, so the total lightning behaviour in the cold-ring regions had to remain unexplored.

Such cold-ring cloud top structures during MCS formation had rarely been depicted before (the exceptions being, e.g. Heymsfield et al., 1983a,b; Höller and Reinhardt, 1986). Adler and Fenn (1979a,b) showed similar but smaller structures. Bartels and Maddox (1991) discuss smaller circular, but not ring–like, clusters of storm cells and the later formation of mid–level cyclonic vortices.

Dotzek et al. (2005a) stressed the need to clarify if the cold-ring cloud tops are relatively regular phenomena which might have distinct total lightning characteristics – and in turn potential for severe weather warnings. Indeed, Setvák et al. (2007) have noted a number of cold-ring cloud top storm cases over Europe. Their total lightning activity is currently under investigation.

3.5 Derechos

Derechos (e.g., Fujita and Wakimoto, 1981; Johns and Hirt, 1987) are spatially extended straight-line wind storms (unlike a tornado with spiralling winds) that occur with large linear MCSs under very specific meteorological conditions. Contrary to general gust fronts often preceding lines of thunderstorms over their full length, derechos form when storm cells in a certain segment of the linear MCS persistently produce series of downbursts with much higher wind speeds than generally observed along the MCS. Thus, while the MCS progresses during its life cycle, the series of downbursts lead to a swath of maximum wind damage which is aligned roughly perpendicular to the major axis of the MCS. By convention (Johns and Hirt, 1987), such events are only classified as derechos if the length of the damage swath is at least 450 km and there are at least three F1 wind reports separated by at least 75 km and no more than 3 h apart in time.

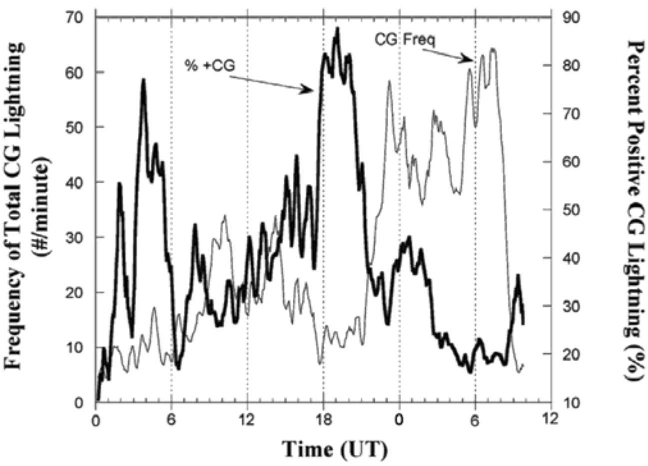

Figure 6: Time series (0000 UTC, 4 July to 1000 UTC, 5 July 1999) of CG activity of the Superior derecho. Bold line gives number of CG flashes per minute, thin grey line shows the CG+ percentage (from Price and Murphy, 2002).

Recent derecho cases from Europe were analysed by Gatzen (2004); López (2007) and Punkka et al. (2007). Price and Murphy (2002) studied a derecho in the USA, during which 12.5 million trees were destroyed in a national park along the US-Canada border within a few hours. While normally the majority of CG lightning has negative polarity (CG-), during this derecho the positive fraction of lightning (CG+) rose to 80% for more than 2 hours (Fig. 6). López (2007) also reported a relatively high CG+ percentage of about 50% in their derecho case over a period of about 2 hours.

3.6 Tropical cyclones

Although it was believed for many years that hurricanes were only weakly electrified, recent evidence has shown that the eye-wall and the rain-bands of hurricanes can have significant amounts of lightning (Molinari et al., 1994; Molinari et al., 1999, Shao et al., 2005). As shown in Fig. 7, the lightning activity in hurricanes may therefore be a useful tool in detecting the intensification of these damaging storms.

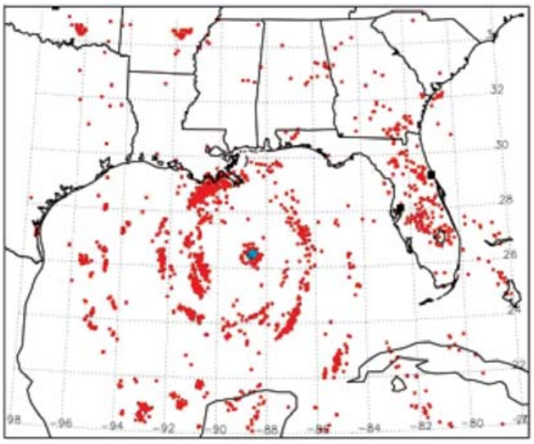

Figure 7: Lightning observations (red dots) of Hurricane Katrina on 28 August 2005, between 1730-1930 UTC (from Shao et al., 2005).

In addition to lightning within hurricanes, it has recently been shown that the genesis of hurricanes in the Atlantic Ocean is related to lightning activity in thunderstorms over the African continent (Price et al., 2007; Chronis et al., 2007). Hence, the nature of normal MCSs over the tropical African continent (in tropical easterly waves) may determine the likelihood of these storms developing into hurricanes as they move from the African continent into the Atlantic Ocean.

3.6 Extratropical cyclones

Among the recent severe winter storms in Europe, locally highest damage levels at the ground were often coupled to the passage of the cyclone's cold front (cf. Ulbrich et al., 2001). The convection along these cold fronts can be vigorous enough to enable and sustain thunderstorm formation. In the case of winter storm "Kyrill" on 18 January 2007, frontal thunderstorms caused damaging wind gusts and hail, and also several tornadoes of up to F3-intensity. Aside from nonzero prefrontal CAPE and abundant low-level wind shear conducive to tornado formation, the large propagation speed of the cold front contributed to the high intensity of the tornadoes.

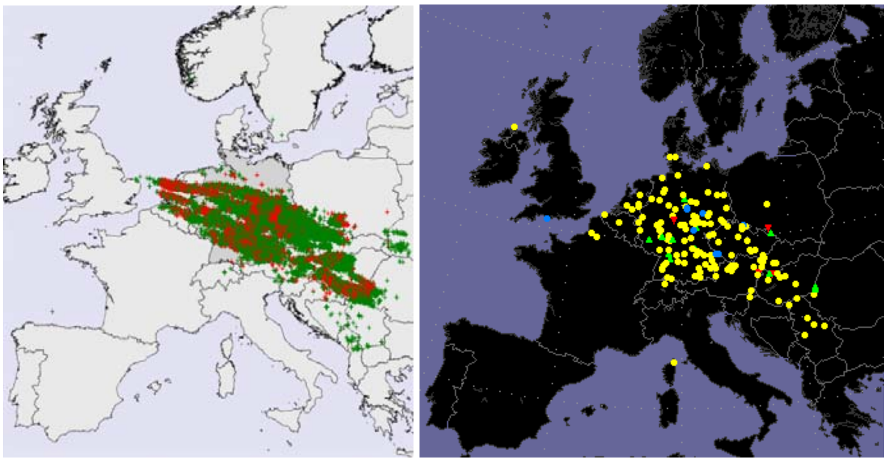

Figure 8: Traces of embedded severe thunderstorms in the cold front of extratropical cyclone "Emma" on 1 March 2008, 000-2400 UTC. Left: 67811 LINET flashes (red: IC, green: CG). Right: 162 ESWD severe weather reports (yellow: damaging wind, red: tornado, green: large hail, blue: heavy precipitation).

Another case of thunderstorms along the cold front of a winter cyclone in Europe is shown in Fig. 8: cyclone "Emma" of 1 March 2008. The one-day record of LINET total lightning discharges (Betz et al., 2004, 2007) on this day illustrates the sustained electrical activity along the NW-SE moving front. The corresponding 162 severe storm reports from the European Severe Weather Database ESWD (www.essl.org/ESWD/, cf. Brooks and Dotzek, 2008) reveal that the extreme weather phenomena at the ground were confined to a region which corresponds remarkably well to the swath of cold-frontal lightning activity. Aside from hail, heavy precipitation and some tornadoes, the most remarkable wind event on this day was an F3-downburst in Austria.

4 Conclusions

We have assessed the lightning characteristics of extreme weather events. Our main conclusions with respect to the present state of knowledge and open research questions are:

- Severe weather appears to be characterised by anomalous lightning activity, whether through lightning frequencies, lightning polarity, multiplicity, peak currents or spatial patterns.

- The increasing availability of total lightning detection networks around the globe has led to improved insights on lightning activity in severe storms over the past ten years;
- The majority of recent studies acknowledge the primary role of the non-inductive charging mechanism for (severe) thunderstorm electrification;
- The non-inductive charging process can consistently explain both negative (normal polarity) and positive (anomalous) CG flashes and thus help to quantify what environmental factors likely contributed to a dominance of either polarity;
- Lightning holes in total lightning data of supercell storms are collocated to the supercell BWER and provide further evidence for the role of the NIC mechanism for severe thunderstorm electrification;
- Severe convective storms are often characterised by a high CG+ percentage above 50% or even 75%, at least during significant parts of their lifetime. The corresponding candidate prototype thunderstorms are the inverted dipole or the tilted dipole;
- To clarify the relative role of the tilted dipole versus the inverted dipole for causing high CG+ ratios is an active area of research;
- Large-range lightning detection ability may help to improve early warning of the most hazardous regions in tropical cyclones before they make landfall;
- The contrast in lightning activity between thunderstorms and MCSs over land and over the ocean still awaits a firm explanation;
- Storm dynamics may both lead to certain lightning characteristics as well as to typical features observable by radar or satellite. For the recently discovered cold-ring cloud top structures, a through analysis of their related (total) lightning activity has just started.

The most relevant application of a more thorough understanding of lightning behaviour in severe storms will be the improvement of nowcasting and warning decision procedures for protecting human lives and property.

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