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RESEARCH ARTICLE

Intensification of single cell storms prior to lightning onset

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Single cell storms in the United Kingdom can produce lightning, despite apparently only having developed to towering cumulus rather than cumulonimbus. Such marginal thunderstorms still present severe weather hazards but are difficult to identify and predict and therefore provide a warning. Observations from the Met Office radar mosaic and ATDNet (Arrival Time Difference Network) show that these single cell storms demonstrate a characteristic increase in the area of high reflectivity storm core during the 15 min prior to the first lightning. By using the Met Office Unified Model to investigate reflectivity development in modelled storms, a micro-physical explanation for the observed reflectivity increase is identified. During a rapid reflectivity increase, the updraft area at the melting layer, the peak updraft velocity and the storm graupel mass increase. The three quantities examined are linked to each other and to the generation of charge within the storm. The production of graupel is promoted by the increase in updraft area and charge separation is enhanced by the faster peak updraft velocity. This explains some of the physical differences between single cell storms that produce lightning and apparently similar storm systems which do not. It also provides a new basis with which to predict lightning hazard for marginal storms.

KEYWORDS

radar, Thunderstorm evolution

1 | INTRODUCTION

Within the United Kingdom, marginal storms are developed single cell convective storms that either produce a small number of lightning strikes or produce no lightning themselves but appear similar to storms that do produce lightning. Therefore, marginal thunderstorms can be difficult to identify early in their lifetime, before they produce lightning. However, these marginal thunderstorms can still be destructive, for example Elsom *et al.* (2016) report that the first lightning strikes from a short-lived thunderstorm killed two men near the peak of Pen-y-fan in Wales. On days with marginal storms, therefore, it is especially important to accurately predict which storms will and will not produce

lightning and to predict when storms might become electrically active.

Numerous studies have examined multicellular thunderstorms (e.g., Carey and Rutledge, 1996; 1998; Bruning *et al.*, 2007) or mesoscale convective systems (e.g., Cifelli *et al.*, 2002; Wang and Liao, 2006; Ely *et al.*, 2008) in the United States or tropical regions and some have studied lightning in supercells (e.g., Wiens *et al.*, 2005; Stough *et al.*, 2017) or within tropical cyclones (e.g., Lyons and Keen, 1994; Black and Hallett, 1999; Cecil *et al.*, 2002). There have, however, been comparatively few studies on simple single cell thunderstorms (e.g., Dye *et al.*, 1986). Single cell thunderstorms should be the simplest version of convection as there are no influences on a storm and its

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structure from competing storm cores and updrafts. It is hoped that observations of single cell storms will be informative for and applicable to more complex convection.

The primary process by which thunderstorms initially become charged is broadly accepted to be through relative diffusional growth (Baker *et al.*, 1987; Saunders, 2008; Emersic and Saunders, 2010), which is a version of the non-inductive charging (NIC) process. Dash *et al.* (2001) explain that differences in the growth of ice crystals and graupel cause differences in the magnitude and the sign of charge contained at the surface of the particles. When ice crystals and graupel particles collide, resulting in a small amount of melted ice, charge can freely flow through the liquid equalising across the temporarily joined particles. As the particles separate again the liquid (and thus charge) is separated equally across the two particles creating a net unequal charge in both particles.

Previous studies examining the onset of lightning using radar data have focused on reflectivity at certain isotherms (see Mosier *et al.*, 2011, table 1). However, frequently, thunderstorms in the United Kingdom do not reach these high levels of intensity even when electrically active. Indeed, in the United Kingdom, lightning can be observed in thunderstorms with a maximum reflectivity of less than 40 dBZ. These low reflectivity thunderstorms mean that the thresholds referenced in Mosier *et al.* (2011) would regularly not capture the onset of lightning.

This less intense nature of the convection in the United Kingdom leads to weaker updrafts and to less graupel routinely present in the convective clouds, and therefore fewer electrified storms. This is exemplified by the storm tracks and lightning strikes shown in Figure 1. There is only one storm which produces more than 10 lightning strikes over its lifetime. Instead, the majority of the storms produce one or

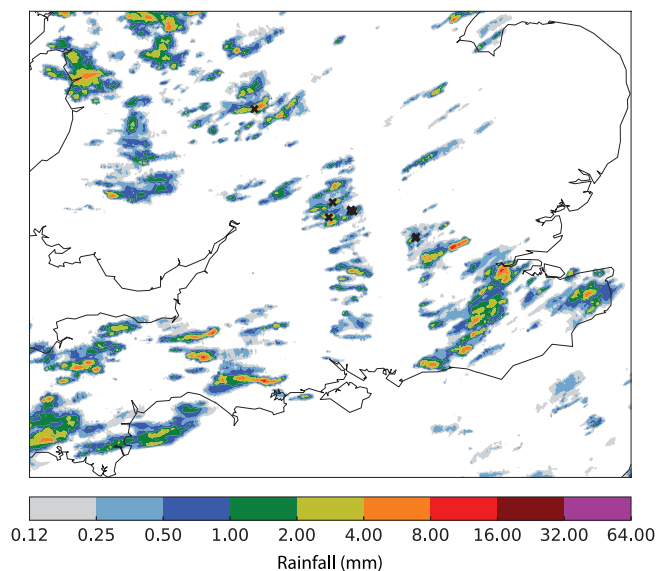


FIGURE 1 The accumulated rainfall from the radar composite on August 31, 2017 from 1200 to 1300, black crosses show the location of lightning strikes

two strikes, while some storms that initially appear similar to the lightning producing storms, produce no lightning at all. The difference between the storms that produce a small number of lightning strikes and those that appear similar in track intensity and length but with no lightning presents a challenge to forecast.

In order to investigate the differences between “low lightning” and “no lightning” convective storms, the Met Office radar network was used in conjunction with the Met Office Arrival Time Difference Network lightning observations to examine storms (especially the mixed phase region) prior to their producing lightning. Subsequently, model data from the Met Office UKV model was used to analyse the physical causes and consequences of the observed intensifications.

2 | DATA AND METHOD

The domain is focused on the south of the United Kingdom (specifically the Heathrow domain from Scovell and Al-Sakka, 2016). This is the part of the United Kingdom that most frequently experiences thunderstorms (Cecil *et al.*, 2014). Two days of observations (August 6, 2012 and August 31, 2017) are used in total in this analysis.

2.1 | Radar composite

The Met Office 3D radar composite is compiled from the 15 operational C-band radars in the Met Office network. It has a 1 km resolution in the horizontal and 500 m resolution in the vertical, extending to an altitude of 12 km (Scovell and Al-Sakka, 2016). Especially across the south of the United Kingdom, the coverage of this radar network is comprehensive with as many as four radars observing individual pixels. The mosaic has a temporal resolution of 5 min allowing for the representation of the evolution of thunderstorms. Currently the only radar parameter included in the composite is radar reflectivity. The composite was used to track storms (see section 2.2) and storm cores and to examine the 3D structure of lightning producing storms.

2.2 | Storm tracking

To allow for tracking of storms within the 3D mosaic, the composite was condensed to a 2D composite. Each column was represented by the 75th percentile of reflectivity above 2.5 km. As shown in Figure 2, using the 75th percentile reduces the variability inherent to the maximum value in a column while retaining the relevant information about the most intense parts of the storm. Also the 75th percentile retains information about the storm even if the convection is relatively shallow, whereas the median must have a storm of at least 6 km depth before showing a signal. Ignoring the data below 2.5 km eliminates the potentially misleading

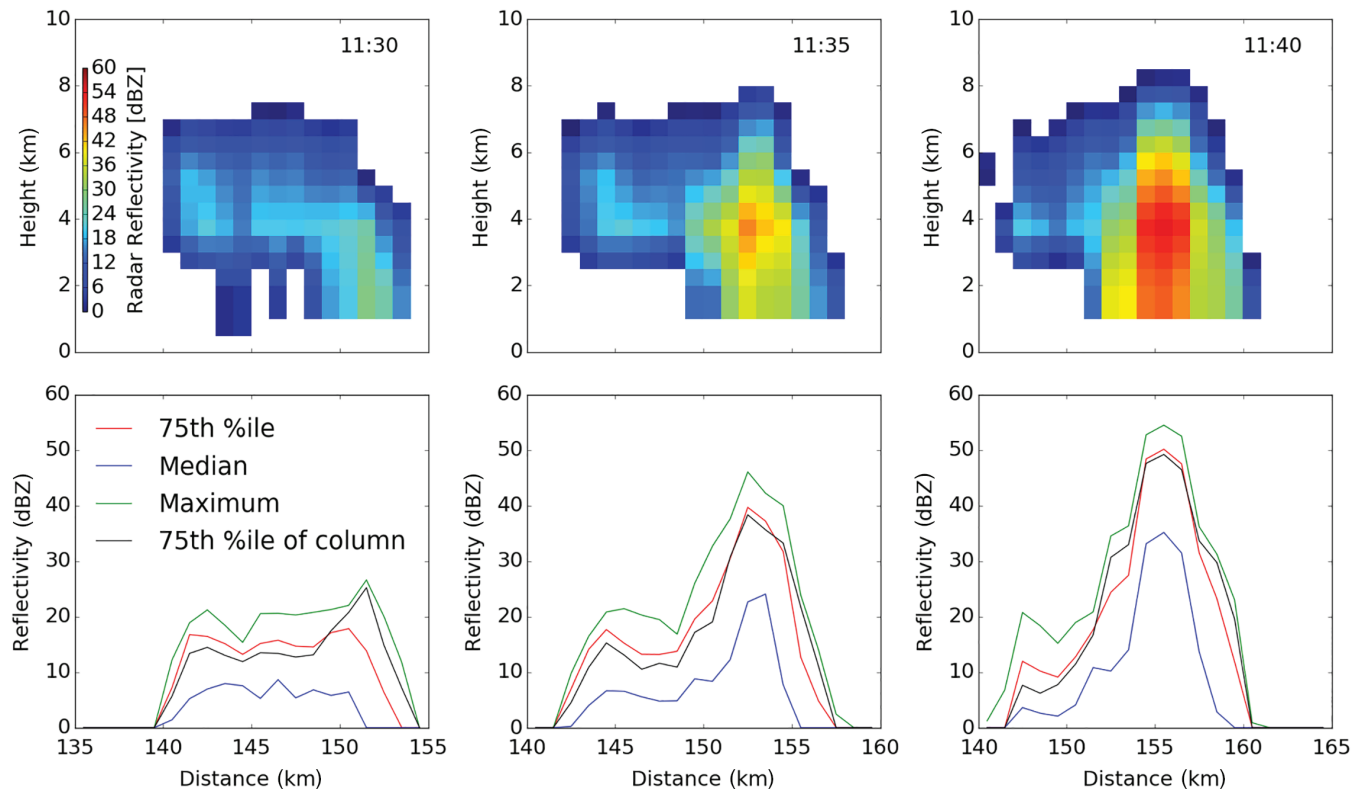


FIGURE 2 Top row shows radar cross sections through the most intense area of a single cell thunderstorm at the times indicated on August 6, 2012. Bottom row shows methods of reducing the cross section to individual points. The median, maximum and 75th percentile (in red) only consider data above 2.5 km (2.5–12 km) whereas the 75th percentile of column (in black) uses the entire column of data (0–12 km)

intensification of the melting layer (e.g., at 153 km in the top right panel of Figure 2) which contains little information about the microphysics of a thunderstorm (Mattos *et al.*, 2016). It can be seen in Figure 2 that the more convective (1135 and 1140) timestamps have a smaller difference between the entire column method (the black line) and the above the melting layer method (the red line) than the more stratiform timestamp (1130).

Storms were tracked in this 2D composite using the tracking method from Stein *et al.* (2015); in this case the storm edge was defined as the 5 dBZ contour (using the 75th percentile above 2.5 km) and the minimum storm area was 5 km². In addition to the 5 dBZ contour to mark the cloud edge, a 25 dBZ contour was used to mark a storm core and used to calculate a storm core area. The storms were then limited to single cell storms in order to reduce the impact of multiple storm cores interacting and thereby confusing the interpretation of the microphysics within the storm.

The lower limit for the storm size was chosen as no storms with an area smaller than 9 km² were observed to produce a lightning strike (see Supporting Information S1). The 5 dBZ contour was chosen arbitrarily as a small enough reflectivity to include all of the cloud information while not including noise. The 25 dBZ contour for the storm core maximised the skill of using the intensification of the storm core to predict lightning (see Supporting Information S2).

2.3 | Lightning data

The lightning data were also provided by the Met Office, via the Arrival Time Difference Network (ATDNet). This is a VLF detection network based on locating vertically polarised sferics in the 10–14 kHz range (Lee, 1989). The polarisation gives the network less sensitivity to intra-cloud (IC) or cloud–cloud (CC) strikes compared to cloud to ground (CG) strikes which tend to have stronger signals in the vertical.

Lightning strikes were co-located with the radar composite using latitude and longitude to match to the Cartesian radar grid, each strike was situated in a gridbox by finding the nearest grid box centre. Lightning strikes that occurred within a storm area and within the previous 5 min (to match the radar interval) were associated with that storm. If a strike could not be co-located with a storm or if, due to its location error (location error is specified for each individual strike, it is typically 1–3 km), a strike was co-located with multiple storms, the strike was discarded and ignored.

2.4 | Model data

The UKV is the Met Office convection-permitting implementation of the Unified Model (UM), run operationally over the United Kingdom (Tang *et al.*, 2013). It is a variable resolution model with a horizontal grid-length of 1.5 km in the interior, extending to 4 km at the edges, with variable

height levels and a time step of 1 min. As a convection permitting model it includes microphysics relevant to convection such as having three cloud ice species: crystals, aggregates and graupel. The model can also output forward modelled radar reflectivity as an output diagnostic; this enables the model output to be used in the storm tracking method used above for the radar observations.

For the UKV simulations used here, the model was run with the 0400 UTC operational analysis as initial conditions, with lateral boundary conditions provided by the 0000 UTC global model forecast. The model was run for 16 hr. The model data used were forward modelled reflectivity, graupel mass mixing ratio and vertical wind speed. These were all output on the native model grid, with a 15-min temporal resolution.

The radar shows lighter rain rates over larger areas and less intense heavy rain rates than the model. The model also appears to be more clustered than the observations (see Supporting Information S3).

3 | RESULTS

Figure 3 shows the area of the storm core prior to the first lightning strike of a storm. Each line represents the evolution of a separate thunderstorm core from first detection until the time of first lightning strike (at time 0). The chart includes 55 single cell thunderstorms, across 2 days of thunderstorm activity. Of these thunderstorms, only three had no change or a decrease in storm core area before the lightning strike. Each of these three storms had no storm core per our definition and maintained no core until producing lightning. Of the storms that increased in core are 39 out of 52 increased by 10 km^2 or more, the most explosive storm increased from a core area of 6 km^2 to a core area of 58 km^2 in just 25 min.

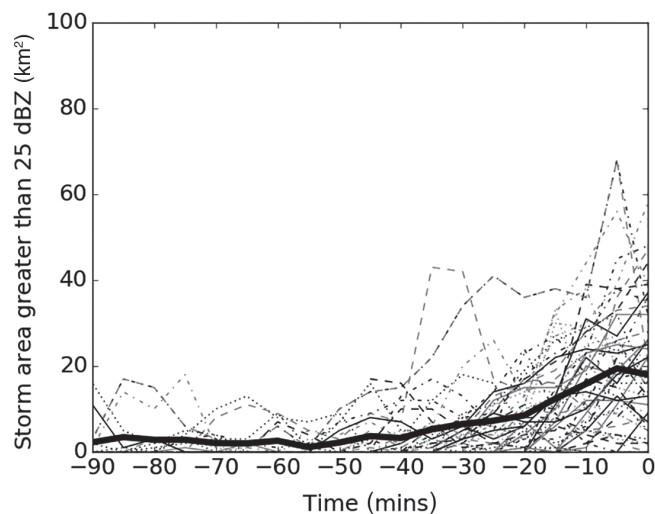


FIGURE 3 Lines showing the increase in storm core area for all single cell thunderstorms in the time before the onset of lightning at time 0, the bold line shows the mean

Half the number of storms that intensified before the onset of lightning did so by $10\text{--}25 \text{ km}^2$.

As the only radar parameter available within the composite at the time of writing was radar reflectivity, more detailed microphysical information than that already shown could not be obtained from observations. Therefore the Met Office convection permitting UKV model was used to investigate the microphysics. The forward modelled reflectivity that is output from the UKV was compatible with the tracking algorithm used for the radar data, and so the same algorithm was used to track storms in the model.

From the model, these isolated storms were found to undergo a similar rapid intensification. Figure 4a shows the evolution of the storm core, from radar observations, until it undergoes a rapid intensification (an increase of 10 km^2 in storm core area in 15 min or less), rather than until a lightning strike as in Figure 3. There is some overlap between the lines in Figures 3 and 4a, 34 of the 55 lines in Figure 3 are also included in 4a together with 37 other intensifying storms. The intensification of the storm core was used, as this measure could be replicated in the model (shown in Figure 4b). The two means in Figure 4b, while slightly offset in absolute storm core area, show similar increases in core area within the final 15 min of the plots. The model plot shows an increase in core area from a mean of 7.6 km^2 to a mean of 23.5 km^2 , within 15 min. The observations show an increase in core area from a mean of 3.2 km^2 to a mean of 17.4 km^2 in 15 min, although the majority of this change occurs within the final 5 min of the intensification. The range of magnitudes of the intensifications was smaller than that in Figure 3, because by definition the intensifications were larger than 10 km^2 . About 95 and 90% of the intensifications were between 10 and 25 km^2 for the radar observations and model, respectively.

In Figure 4a the mean area of storm core in both panels follows a similar path. The difference in temporal resolution between the observations and the model means that the observations appear to have more variability than the model and appear to intensify slightly later than the model. However, the magnitude of the intensification is very similar within the final 15 min and the final core area is approximately similar in both the model and the observations. Therefore we, now investigate the simulated microphysical properties to understand potential physical mechanisms occurring during the observed intensifications.

Within the model, the graupel mass, the updraft area greater than 1 m/s at the melting layer and maximum updraft velocity in the storm core were measured before and after the model intensifications. The differences across the intensification for all parameters were plotted in boxplots in Figure 5. Each boxplot shows that approximately 75% of the storms increase in their respective parameter across an intensification. Each boxplot also shows that the distributions are slightly positively skewed. Although in each parameter the

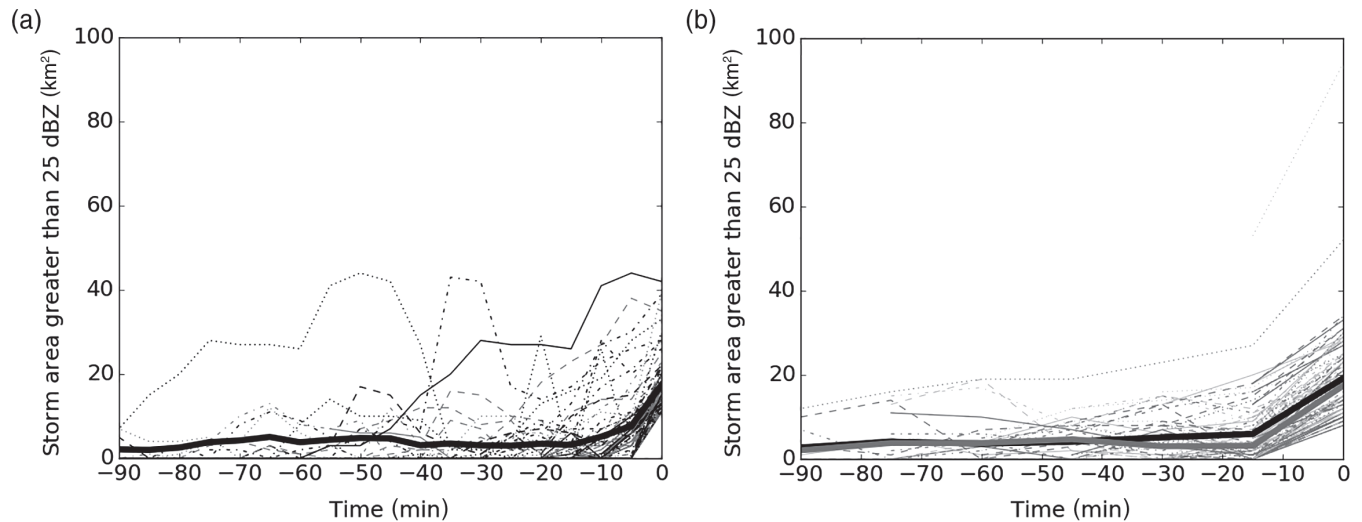


FIGURE 4 Lines showing the storm core area before an intensification (defined as an increase of 10 km^2 in storm core area in 15 min or less) for (a) radar observations; and (b) the forward modelled radar output from the model. In both plots the black bold line shows the mean, in (b) the grey bold line shows the mean from (a) at the same temporal resolution as the mean in (b)

lower quartile value is near 0, there is still a portion of the distribution that shows a decrease across an intensification.

The boxplots in Figure 5 show, on average, for all of the parameters examined in the model, an increase across an intensification. This follows the expectation that as reflectivity is increased and high reflectivity is observed over a larger area there must be more and/or larger particles present in the cloud. The decreases shown in each variable may relate to

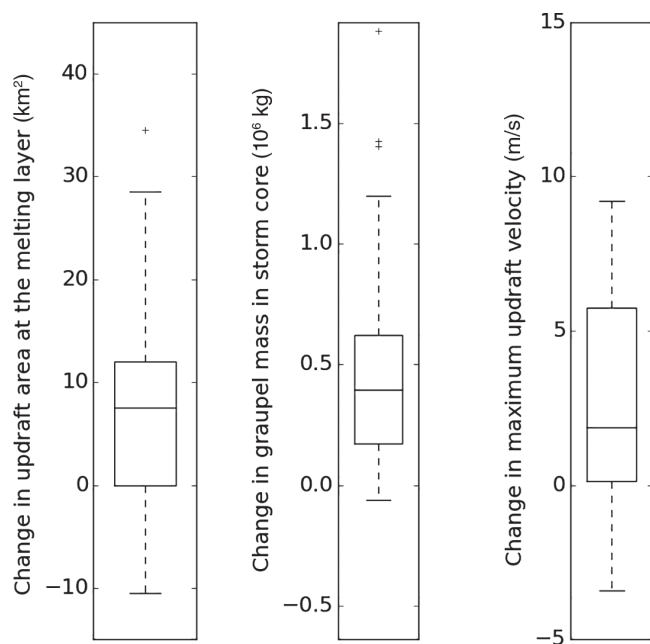


FIGURE 5 Boxplots showing the change in microphysical parameters across the intensifications (defined as an increase of 10 km^2 in storm core area in 15 min or less) observed in the model (as shown in Figure 4b). The whiskers show the highest (lowest) datum within upper quartile +1.5 IQR (lower quartile -1.5 IQR): (a) shows the change in updraft area within the storm at the level of the melting layer (2.5 km); (b) shows the change in graupel mass within the storm core, above the melting layer; (c) shows the change in maximum updraft velocity within the storm core, above the melting layer

the fact that (as shown in Figures 3 and 4a) not all intensifications lead to the onset of lightning. Figure 5b tells us that at least a part of this increase in reflectivity is due to an increase in graupel mass within the storm core. Linked to this is an increase in both updraft area and peak updraft velocity. These are again linked to the formation of graupel as supercooled liquid (lifted above the melting layer by the updraft) is required to rime ice and thereby create graupel. The riming process can feedback to the updraft through releasing latent heat, thereby increasing buoyancy and the updraft velocity. It can be surmised that during the process of an intensification the increase in updraft area (causing an increase in riming) creates an increase in graupel mass and therefore an observable increase in radar reflectivity.

4 | DISCUSSION

4.1 | Thunderstorm electrification through rapid intensifications

The rapid intensifications are important for thunderstorm charging in particular because of the increase in graupel mass and maximum updraft velocity shown in Figure 5. The graupel is the most obviously necessary as (according to the NIC theory) graupel and ice crystals must be present to separate charge. The increase in graupel mass in the majority of storms allows for the creation and storage of an increased amount of charge within the storm. This is especially important for single cell storms as frequently before the storm underwent an intensification the mass of graupel present in the storm was too small to allow enough charge for a lightning strike (see Supporting Information S4). It is therefore hypothesised that graupel mass is a limiting factor of thunderstorm charging in the United Kingdom and therefore lightning production within single cell storms.

The updraft velocity is also important for the charging process, not just in the creation of graupel. A strong updraft is necessary to suspend large graupel particles after collisional charging and to separate the graupel and ice crystals through the lofting of ice crystals to the top of the cloud. Further to this, Bruning and MacGorman (2013) speculate that the turbulence created due to the shear at the edge of the updraft can help to cause charge separation through mixing of particles in turbulent eddies. This could be another mechanism by which the increase in updraft strength shown in Figure 5 promotes thunderstorm charging.

Therefore, both an increase in updraft area and in updraft strength are important for storm charging and therefore the onset of lightning. With just a broad weak updraft there may be a large amount of graupel formed, but no strength to suspend it while charge separation occurs and to allow separation of the graupel from the cloud ice. However, equally, if there is just a narrow strong updraft there may not be enough graupel generation to allow for a significant amount of charge to be generated within the storm.

4.2 | Low or zero lightning convective storms

It is suggested that this intensification process is of such importance in the UK because of the limiting factor that graupel mass appears to present to storm electrification. Figure 1 shows that there are storms that produce one or two lightning strikes, and some storms that look similar in reflectivity but produce no lightning. The low lightning convective storms and zero lightning convective storms are a unique challenge to forecast due to their marginality. However, the results of this study suggest that there is a possibility to at least nowcast the onset of lightning in these storms with a lead of time of around 30 min.

In Figure 3 some storms can be observed to exist for 90 min before eventually intensifying and then producing lightning, this further suggests that the intensification is vital for storm electrification. However, in Figure 4a there are also many storms that can be observed to intensify in a similar way to the lightning producing storms, without producing lightning (37 of 71 intensifications do not result in lightning). Therefore, it is suggested that the intensification (while necessary itself) is not the only process that is required to produce lightning in single cell storms. It is possible that in observing storm intensifications we are only observing one part of the entire lightning generation process (i.e., the generation of the microphysical ingredients necessary for electrification) and missing other steps, such as the charge separation and the triggering of lightning.

5 | CONCLUSIONS

This work shows that marginal single cell storms in the UK undergo a rapid intensification and increase in storm core

size prior to the onset of lightning. Closer examination of the microphysics of similar intensifications simulated in the Met Office UKV model show that the observed intensifications may be due to an increase in the graupel mass in the storm core, this in turn is likely related to an increase in the updraft area at the melting layer. Further, during the intensification, there is also an increase in the peak updraft velocity which can cause turbulent mixing of graupel and cloud ice and aids the charging and charge separation processes. However, although almost all observations of lightning from single cell thunderstorms were preceded by an intensification, not all intensifications led to lightning. Therefore, it is assumed that there are other ingredients to the production of lightning from a small convective storm. Further work is needed to identify the other processes that are necessary for lightning production.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

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