Case studies of severe thunderstorms

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1. Introduction

This paper discusses the use of different radar derived parameters to describe and evaluate the 4-dimensional development of isolated severe thunderstorms. We concentrate especially on the development of some bulk properties. Besides 'often' used properties like the total volume, the maximum reflectivity, the velocity of a storms' reference point, the total liquid water content and others, we define also some abstract properties like a 'reflectivity mass' as a reflectivity weighted volume, the height of the center of gravity of the thunderstorms' volume and reflectivity mass and some special ratios. These last parameters are also evaluated in relation to some specific, the convective environment representing heights like the level of free convection (LFC), the 0°C and the -10°C level.

We present results from one multicell storm we tracked on 20 August 2009. This storm shows a clear oscillation. A cross correlation analysis furthermore reveals some interesting patterns, which could be brought in line with the regular conceptual models for the development of a multicell storm. Especially the different development pulses in the life cycle of a multicell system are clearly visible. Additionally a relation between the parameter values in comparison to the specific heights (LFC, 0°C and -10°) and the storms' strength is given.

2. Short description of the methods

In order to separate the reflectivity data of the investigated thunderstorm from the background and to retrieve this data in subsequent datasets a modified version of the tracking algorithm TRACE3D (Handwerker 2002) is used. This version of TRACE3D identifies thunderstorms as continuous regions of strong reflectivities above 40 dBZ and tracks them in time. Setting the threshold to 40 dBZ is taken as a compromise. Smaller thresholds lead to very large identified convective cells, which partly contain less relevant parts of the cell, e.g. the anvil-blowoff. On the other hand we found that higher thresholds subdivide the individual cell into smaller disjunct parts.

To shortly summarize: Up to this point the investigated storm is represented as a time series of a discrete number of beam volume elements (voxel) with each voxel being allocated with a specific volume, specific location and a specific radar reflectivity factor value Z.

For our study we introduce further parameters to describe the life cycle of the thunderstorm:

- The **speed** and **direction** of the storms' reference point $\vec{r}_s$ (Fig.2). The reference point of the storm is given as the center of mass of the logarithmic reflectivity.
- The **volume** of the storm (Fig.1-left). To this end we have to take into account that each voxel represents not only the 3dB width, but the area between the middle of two adjusting elevations to the middle of the next two adjusting elevations.
- The **reflectivity mass** (Fig.1-left). In addition of calculating just the volume, one can also weight the volume of every voxel with its reflectivity value. We have to admit that we had some difficulties to find a for this parameter. Anyway, the unit of this parameter is mm^6.
- The height above ground of the volumes' centre of gravity $\mathbf{z_V}$ and the height of the reflectivity mass' centre of gravity $\mathbf{z_M}$ (Fig.4-left). In this study these two parameters are compared to the LFC, the 0°C and the -10°C levels. The idea to use these parameters evolves from the rough estimation that a strong updraft - which is a prerequisite for a strong thunderstorm - produces a strong radar echo high above the ground. Thus a high z_V and z_M is taken as a criterion for a strong updraft. With the z_V and z_M one can also claim, whether a storm is still top-heavy or whether the volume or the mass is concentrated near the base and a pronounced "rain foot" exits.
- The ratio of the volume above a specific level to the total volume (Fig.3). As the specific levels the LFC, the 0°C and the -10°C level are used. These levels are situation sensitive, in which the -10°C level represents roughly the beginning of the zone of optimized hailstone growth (Grenier et al. 1983)). These parameters are in the

following called the **LFC-, 0°C** and **-10°C-volume-ratio** resp. **Relectivity mass-ratios** are defined in the same way.

- The total liquid water content (**LWC**) (Fig.1-left) based on $Z = 3.47 \times 10^4\ W^{1.73}$ (Bertram 2004)
- The **40 dBZ Echotop** and the **55 dBZ Echotop** (Fig.4-right). The first threshold (40 dBZ) represents the top of the cell defined by the tracking algorithm.
- The ratio of the volume with an allocated reflectivity of at least 55 dBZ to the total volume is called the **55dBZ-ratio** (Fig.1-left). A reflectivity value of 55 dBZ is often used as a rough estimate for the occurrence of hail (Holleman 2001 and Hohl et al. 2002). Thus the 55dBZ-ratio can serve as a rough estimate of the strength of the cell.
- The **maximum reflectivity** value and the **95th percentile** (Fig.1-right). Since the maximum reflectivity is prone to errors we recommend the use oft the 95th percentile, which seem to be more robust.

In the following we want to demonstrate that these parameters are helpful.

3. Input data and synoptic setup

Input data

The measurements were performed with the C-Band Doppler radar of the KIT. The radar is located in the upper Rhine valley in Southwestern Germany. The region is characterized by a pronounced orographical structure with the radar site surrounded by the Black Forest to the east and southeast (up to 1200 m a.s.l) the Vogeses to the southwest (up to 1000 m a.s.l), the Palatinatian Forest to the west (up to 670 m. a.s.l) and the Odenwald to the northwest (up to 630 m a.s.l). We expect that the growth, evolution and decay of thunderstorms are strongly affected by the orographic structures.

The used radar data compasses a 14-elevation volume scan of reflectivity with a range of 120 km, a range gate of 500 m and an azimuthal resolution of 1°. The time distance between two consecutive volume scans is 5 Minutes.

The temperature and convection data are extracted from data of operational rawind sounding (Stuttgart-Schnarrenberg, WMO-ID: 10739) with a horizontal distance to the radar site of roughly 80 km. Surface temperature values come from a synoptic weather station in Karlsruhe.

Synoptic setup

The synoptic environment of the investigated multicell storm was characterized by a migrating ridge to the east and an advancing trough. In between a southerly wind brought a warm and humid air into the area. During the day the temperature reached a maximum value of 35.9°C. The sounding data of 12:00 UTC showed some instability with a MLCAPE of 292 J/kg, a Lifted Index of -1.44 K, a Total Totals Index of 45.2. A CIN of -289 J/kg helped to suppress a premature release of the instability, leading to higher potential buoyant energy later in the day. The Low Level Shear reached values of 3.0 m/s and the Deep Level Shear of 12.1 m/s. This shear then also dominates the Bulk Richardson Number (BRN) in that way that the observed BRN of 21.3 pointed towards a highly sheared environment capable to lead to a specific organization of thunderstorms. The deduced LFC had a height of 3740 m, the 0°C isotherm of 4130 m, the -10°C isotherm of 5710 m and the equilibrium level of 10950 m above the ground.

4. Development of the multicell storm

The studied storm was tracked for 130 min. with the storms path covering a distance of 65 km. Thus the mean speed is 8.3 m/s with a mean direction of 31°, which is from SSW to NNE (Fig.2). Comparing the storm motion vector with the wind field (from VVP and rawinsondes) shows that the storm motion could not only be described by advection. Instead, when one accounts for internal dynamics by constructing the Bunkers storm motion vector (Bunkers et al. 2000) the motion of the storm is described considerably better. This result shows on the one hand that the observed storm exhibits some kind of organization (which in turn is to be expected when one looks at the observed shear values). On the other hand it is interesting that the best description of the storm motion is achieved when the 0 to 10 km wind values are used, in contrast to the usage of the 0 to 6 km wind values which seem to be the best fit for the storm in the Midwest of the United States (Bunkers et al. 2000). Also it is interesting that the motion of the storm is to the left of the mean wind.

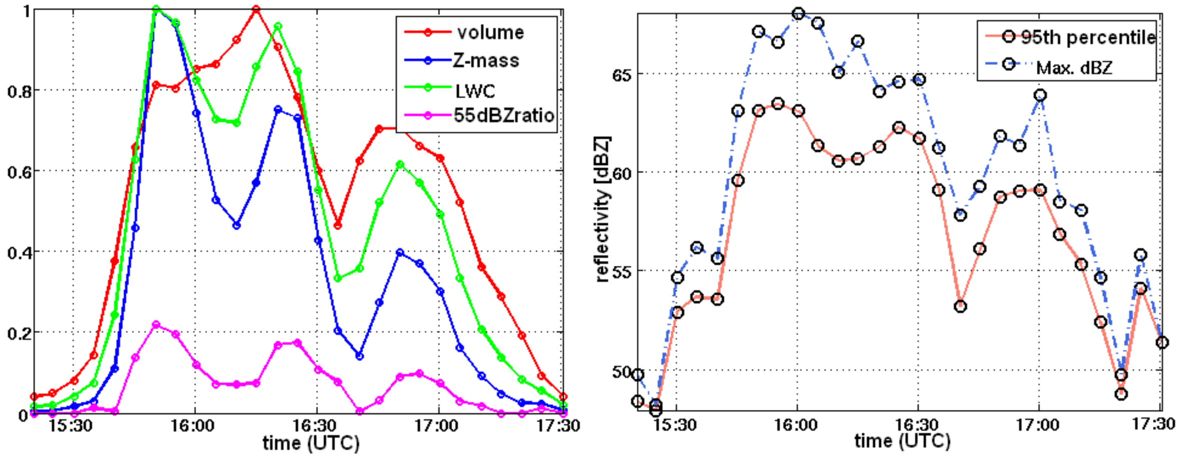

***Fig.1:** - **left**: time series of the volume (red) , the reflectivity mass (blue) and the LWC (green) (all normalized by the maximum of the specific time series), and 55dBZ-ratio ;**right:** time series of the 95th percentile and the absolute maximum value of the reflectivities..*

The sequence of the storms' volume, reflectivity mass, the LWC and the 55dBZ-ratio (Fig.1-left) show a distinct oscillation, which is also visible when one watches just a sequence of the radar images. Moreover, the oscillation is noticeable in the time series of the storms' speed and the direction the storm moves (Fig.2), the time series of the LFC-, 0°C- and -10°C-volume-ratio and the LFC-, 0°C- and -10°C-reflectivity mass-ratio (Fig.3), the time series of the different center of gravity heights (Fig.4-left) and to a lesser extend in the time series of the 95th percentile (Fig.1-right).

Besides the common oscillating pattern, the different time series show also some distinct differences in the number of oscillations or maxima and minima and in the timing of the maxima and minima. These are the features, which now seem to be capable to reveal some interesting features of the development or even explain some processes.

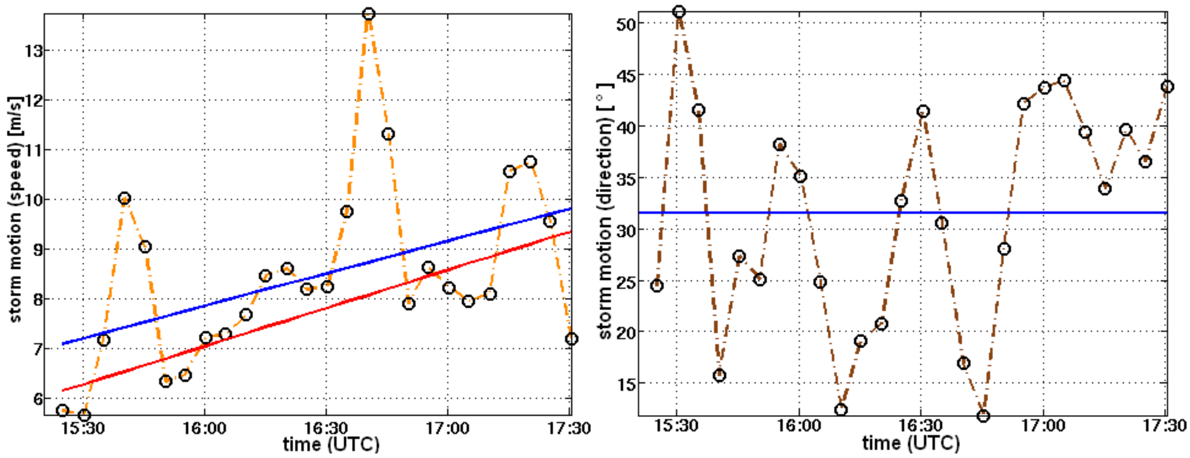

***Fig.2:** - **left:** time series of the storms' speed (orange) - with the regression lines for all data points (blue) and for all data points except the ones at 15:40, 15:45, 16:35, 16:40, 16:45, 17:15 and 17:20 UTC (red).**; right:** sequence of the storms' direction (brown) with the mean direction (blue).*

As a "lead parameter" of the further investigation we use the time series of the storms' speed and direction. These parameters are in the first hand independent of the extent of the reflectivities and thus of the strength of the storm. The significant peaks of the time series indicate internal shifts of the storms reference point. These shifts may be caused by a new development of a daughter cell within the life cycle of a classic multicell development. A shift represents the decay of the old mature cell and the growth of the next daughter cell to the new mature cell. This should be accomplished by a new updraft pulse, which then also should be discernible in the time series of the other parameters or in a time shift between the maxima and minima between the different time series among each other, respectively.

In order to reveal a statistic significant time shift between the different time series or the between the maxima of the different time series, a cross correlation analysis between all time series among each other shows following pattern:

1) a.) First (i) the local maximum of the center of gravity height z_M and (ii) of the -10°C-reflectivity mass ratio and probably also already (iii) the 0°C- reflectivity mass ratio is attained.

   b.) Then one can observe (i) a distinct increase of the storms' speed (by an internal shift of the storms' reference point), (ii) a distinct shift in the storms' direction, (iii) a local maximum of the center of gravity height z_V and (iv – vi) the LFC- , 0°C- and -10°C-volume-ratio and (vii) the LFC-reflectivity mass-ratio.

2) Then – even later – (i) the total volume, (ii) the total reflectivity mass, (iii) the LWC and (iv) the 55dBZ-ratio reach a local maximum.

This finding is consistent with a rough conceptional model of the development of convection:

A new updraft pulse in the life cycle of the storm leads first to an increase in the number and/or in the size of detectable hydrometeors in the higher regions of the storm. This is especially marked in heights above the -10°C level. Casually speaking: With a new updraft pulse hydrometeors are first brought above the -10°C level.

Afterwards the LFC-reflectivity mass-ratio, the 0°C-reflectivity mass-ratio, the LFC-volume-ratio and 0°C-volume-ratio reach their largest value. This is explainable as a further growth of the hydrometeors by means of drop size and amount and their beginning sedimentation to lower levels. Nevertheless, the cell stays top-heavy.

Next, the fall down and further growth of the hydrometeors (with respect to size and amount) continues. From now on the largest amount of the reflectivity mass and of the cell volume is found more and more in the lower part of the cell. z_M and z_V ascend already and the different volume-ratios and reflectivity mass-ratio decrease.

In other words: At this point the cell in the current development cycle has apparently reached its peak with most of its reflectivity mass concentrated near the base. Probably the proportion of large hydrometeors also reaches its maximum.

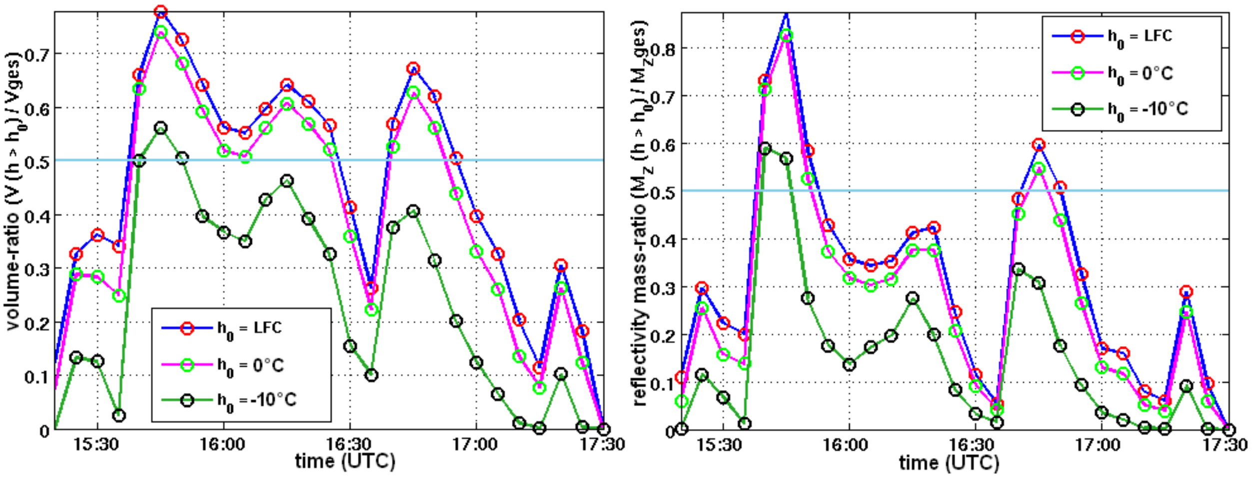

***Fig.3:** - **left:** time series of the LFC-, 0°C- and -10°C-volume-ratio; **right:** chronological sequence of the LFC-, 0°C- and -10°C-reflectivity mass-ratio.*

During the next time step all here examined parameters decrease. There is for example a descent of z_M and z_V, which is linked to a simultaneous decrease of the reflectivity mass. One reason for this combination might be the fact that the hydrometeor formation or the mean hydrometeor growth is lower than the sedimentation of hydrometeors, and/or there is a reduction of the mean hydrometeor size by a burst of the big hydrometeors after they had e.g. been water coated hailstones (with maximized reflectivities). At least there is rain present which falls to the ground.

In the further course (with a further, but decreased reduction of the various parameters) the transition into a decay phase sets in. Afterwards a new updraft pulse at the northern edge of the complex may initiate a new development into a new stage of maturity and the described sequence maybe starts all over again.

On the possibility to forecast the further storm development

Comparing the development of z_M and z_V (Fig 4-left) to the storm strength indicated by the 95th percentile of the reflectivity (Fig. 1-right) motivates the assumption that z_M and z_V can be used as indicator of the further storm development, especially when one sets z_M and z_V in relation to the LFC and the 0°C and -10°C level. Comparable results can be stated for the different volume-ratios and reflectivity mass-ratios (Fig .3).

In case of the z_M and z_V in relation to the different levels this means that if the z_V ascends over the 0°C level or z_M ascends at least over the LFC, then the next mature stage of the multicell will be "stronger". For example during the next mature stage the 95th percentile of the reflectivity values will then exceed 58 dBZ or the (albeit in radar measurements sensitive) maximum reflectivity will exceed 60 dBZ (see Fig. 1 – right). These values are in the range of the ones, which can be used as a first, rough signature of a strong thunderstorm development.

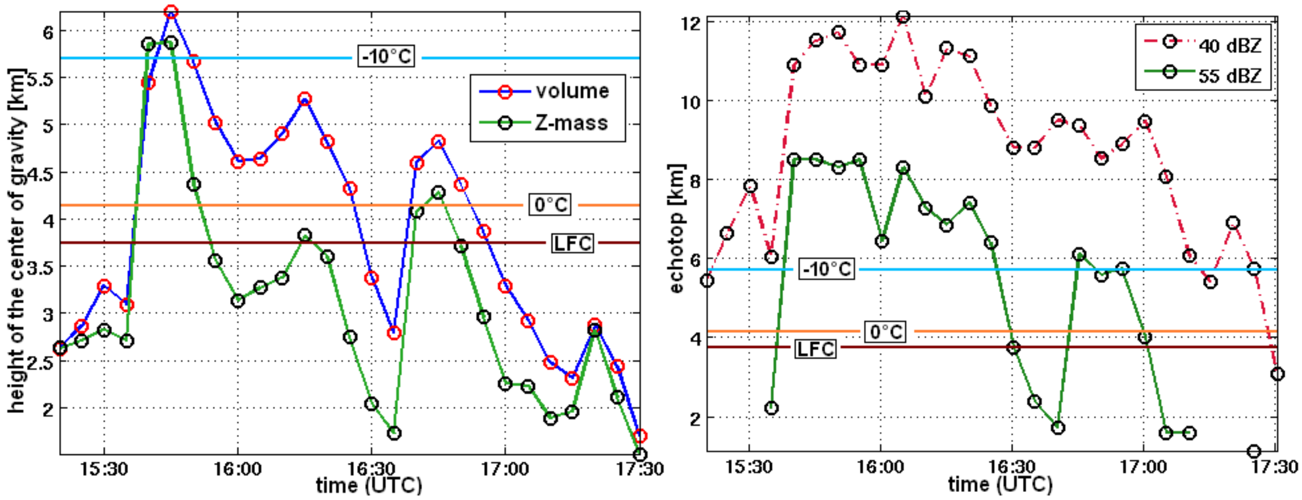

***Fig.4:** - **left:** time series of the center of gravity height of the volume and of the reflectivity mass, also shown the height of the LFC, the 0°C and the -10°C level; **right:** chronological sequence of the 40 dBZ echotop and the 55 dBZ echotop.*

In terms of the level-related ratios, it is especially the level-related volume-ratio, which seems to have a prognostic value. For this examined case one can claim, that if the LFC-volume-ratio and the 0°C-volume-ratio reaches at least 0.5 and the -10°C-volume-ratio reaches at least 0.3, than the next mature stage will be stronger. If those values are not reached (as in the last cycle (17:15/17:20 UTC) and maybe in a first cycle (15:25/15:30 UTC)), then the following mature stage remains “weaker”, as e.g. the 95th percentile of reflectivities stays below 55 dBZ. According to a simple storm model, this means that enough reflectivity mass has to be lifted above the convective relevant levels (particularly above the LFC or close to the zone of optimal hail growth starting with the -10 ° C isotherm) first, in order to initiate a stronger development.

Furthermore one can possibly claim that if the level related volume-ratios and z_M and z_V stay below the stated values during a mature stage, but have reached higher values in earlier mature stages, then the present cycle will be the last one in the total life of the multicell storm. The multicell now finally decays.

Within a conceptional frame this means: the cold pool / shear interactions, which have earlier led to a new cycle within the total multicell-development and partly have accounted for its self-preservation, are no longer strong enough to create a distinctive new development cycle. In other words: The body of cold air which is built in this mature stage by precipitation/downdraft processes now is too weak to produce an adequate horizontal vorticity.

Short evaluation of the oscillation frequency

The most striking pattern of the chronological sequence of the different parameter in this case study is an oscillation, which in turn also characterizes to a certain extend the multicell character of the examined storm. A rough estimation of the mean cycle period by a visual analysis shows a period of 25 minutes, if one analyses 5 cycles, and a period of 32.5 minutes, if one analyses 4 cycles.

For a further, sound statistical determination of the period the amount of data (the time series consists of 27 data points) is principally not sufficient. But on the other hand only rare observations of longer lasting events are available.

A calculation of an one-sided amplitude spectrum using a Fourier transform for the time rows of the different parameters (see Fig. 4 as an example) shows - in addition to the natural maximum at the frequency of the total life cycle - a significant secondary maximum at a frequency of 0.031 min^{-1}. This corresponds to a period of 32 minutes, a value which is – by the way - close to the value found by Chisholm and Renick (1972) for a multicell storm in Alberta, Canada.

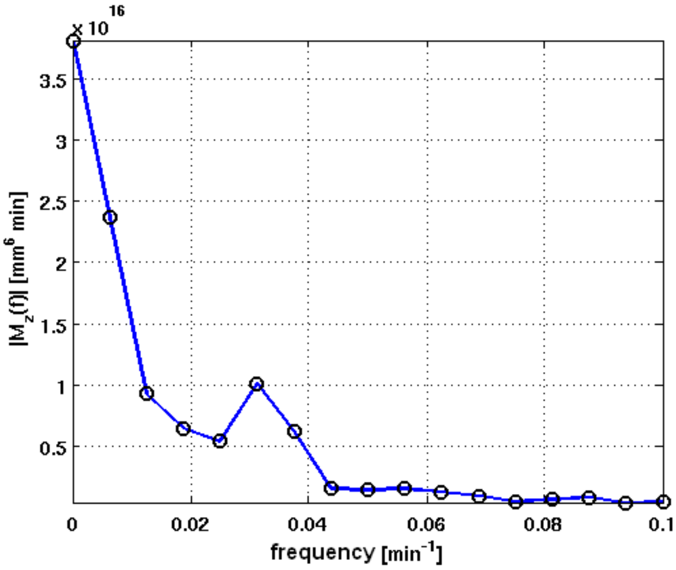

Fig.5: *one sided amplitude spectrum of the total reflectivity mass.*

4. Conclusion and annotations

By tracking a thunderstorm cell with a tracking algorithm and evaluating the time series of the reflectivity data by forming some specific parameters some meaningful patterns of a multicell storm have been revealed. For this specific multicell storm a reasonable time shift between different parameters, which were calculated out of the time series of the radar data of a storm, seems to exist. The time shift between the developments of the different parameters fits to a rough conceptional model and can be explained by some physical processes. Furthermore, using z_M and z_V and the different volume- and reflectivity mass-ratios seems to be promising to evaluate the strength of the storm.

In comparison to other (her not shown) cases of a supercell storm and three single cell storms, it also seems to be possible to distinct between single cell storms, multicell storms and supercell storms by the usage of these parameters. E.g. in a supercell storm z_M stays well above the 0°C level most of the time and z_V stays even above the -10°C level for a long period of time. In the shown example of the multicell storm on the other hand a more pronounced oscillation of z_M and z_V around the different convective levels is observed, with a mean cycle period of roughly 32 minutes.

We want to point out that these results stated were based on isolated thunderstorms. There are no interactions with other convective activities. Such interactions may cause more complicated storm behavior. More studies are needed to reveal the benefit oft the usage of the here presented parameters. First results for a cell splitting seem to be very promising concerning the question which splitting partner will be the dominant.

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