THE MESOCYCLONE DETECTION ALGORITHM OF DWD

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I. INTRODUCTION

Observations by weather radar networks offer the possibility of scanning the low- and mid-level atmosphere in high spatial and temporal resolution providing the means for detecting and tracking rapidly developing, small scale severe weather phenomena in an operational environment. A mesocyclone, defined as a vortex of rotating air within a thunderstorm, is such a dynamic feature that can be captured by Doppler radar networks. Mesocyclones are frequently found as rotating updrafts in supercells and often occur in connection with severe weather events like heavy rain, hail, strong surface winds and tornadoes. Therefore, the detection of mesocyclonic shear regions in Doppler radar data gives valuable information for issuing nowcasts and severe weather warnings.

The approach of mesocyclonic shear detection as implemented at Deutscher Wetterdienst (DWD) can be divided into a preprocessing, a processing (the actual algorithm) and a postprocessing part. During preprocessing, dual-PRF unfolding errors are corrected, which otherwise would produce spurious high shear regions and corrupt real mesocyclone vortices. The algorithm uses the pattern vector approach to identify the regions of high shear within the centre of mesocyclonic rotation and provides 3D mesocyclone objects. An unique planned aspect of the DWD algorithm is the merging of 2D mesocyclone features from multiple network radars in overlapping regions to create a single 3D detection. During postprocessing these mesocyclone objects are validated using secondary features such as VIL. A severity metric is created using mesocylcone object properties (shear, momentum) and the secondary features and the various mesocyclone objects are then ranked and issued to the forecaster as guidance

II. THE DOPPLER RADAR DATA AND QUALITY ISSUES

The German Weather Service operates a network of 16 radar stations delivering radar scans in five (precipitation scan) and fifteen minute intervals (Doppler- and intensity volume scans).

The Doppler scan (dual PRF, 800/1200 Hz, maximum range 128 km) is comprised of single sweeps with elevation angles extending from 0.5° to 37° while the long-range intensity scan (600 Hz, max. range 256 km) merely covers the lower elevations (0.5°-4.5°). In this context a sweep is a complete antenna revolution at constant elevation angle, which geometrically corresponds to a cone.

The precipitation scan (600 Hz, max. range 125 km) is a terrain-following scan: in order to observe close-to-ground precipitation, the radar beam closely follows the radar horizon with an elevation offset large enough to minimize beam blockage and suppress clutter from orographic obstacles. Here, a sweep is again a complete antenna revolution. However, the elevation angle may change as a function of azimuthal direction.

The preprocessed data of all the described scans is called basic data. In the preprocessing procedure, which is performed at the radar site itself (within the radar device's signal processor) a first quality control is achieved by means of a set of filters and thresholds (e.g. Doppler Filter for removing stationary clutter, for details see Seltmann 2000). The basic data from all German radar stations are gathered at the DWD central office Offenbach in real-time by means of an automated file distribution system (AFD) and are available for follow-up applications, the MDA being one of these. The radar basic data as well as all products are visualized in the meteorological workstation system NinJo where a so-called SCIT-Layer (**S**torm **C**ell **I**dentification and **T**racking) optionally shows the MDA detections (Joe et al., 2005).

The essential input for the MDA is comprised of the Doppler scan data. This scan, as introduced above, is configured in such a way as to achieve both an adequate unambiguous Doppler velocity interval and a suitable maximum range. The dual-PRF scan with 800/1200 Hz permits a measurement of radial velocities within -32 to +32 m/s (+/-V_{Nyq}). The maximum range is determined by the high PRF (1200 Hz) and amounts to 124 km, which ensures a (nearly) complete coverage of Germany with the 16 radar stations of DWD.

Unfortunately the dual PRF unfolding technique relies on the assumption, that adjacent range-bins show the same true radial velocity within a tolerance of 5.3 m/s (for the 800/1200 HZ mode taking into account a radar wavelength of 5.3 cm). This tolerance can be exceeded due to ubiquitous noise fluctuations on top of the true velocity values and appear as randomly scattered points. In high shear regions, the tolerance can be exceeded due to the real shear. 'The distribution of these velocity errors is discrete, as the errors are multiples of twice $V_{Nyq,800}$ or $V_{Nyq,1200}$. In practice this most commonly results in errors of +/-V_{Nyq}' (citation from (May, 2000) with adapted PRFs). These quality errors are not removed by the on-site pre-processing quality assurance.

However, these dual PRF are corrected by means of a detection-correction filtering algorithm. In the pre-processing of the Mesocyclone Detection Algorithm of DWD a Laplacian operator technique based on (Joe and May, 2001) is used. This method applies a 'discrete filtering' taking into account the affected range-bin's PRF, which counteracts an over-smoothing.

III. THE MESOCYCLONE DETECTION ALGORITHM (MDA)

As outlined in the last section the Doppler data are quality controlled by means of a filtering algorithm which mitigates the occurrence of dual PRF unfolding errors, which otherwise would lead to spurious values of azimuthal shear.

The next step is the calculation of the azimuthal shear for each sweep of the Doppler volume. Here, insignificant shear values < 2 m/s (adapted to the data's noise level) are set to 'missing value'. It should be noted that the MDA in its current configuration performs a search for cyclonic rotation, which is the dominant 'mode' of mesocyclonic rotation on the earth's northern hemisphere. Cyclonic rotation corresponds to positive values of azimuthal shear (the radial velocity is increasing in direction of increasing azimuth). Treating negative shear as noise reduces the influence of remaining dual PRF unfolding errors in regions of positive, cyclonic shear since dual PRF unfolding errors are often associated with a change of sign in the spurious velocity estimate.

The MDA can be devided into three main parts, each of which is based on the precursor part: The Detection of pattern vectors, the grouping of pattern vectors to features and, finally, the combination of features to 3D-mesocyclone objects. The MDA approach basically follows (Zrnic, Burgess, Hennington, 1985).

A pattern vector is a sequence of positive azimuthal shear at constant range. Figure 1 shows a Doppler rotation signature (typical dipole) and the series of pattern vectors that can ideally be found within the area of rotation. The pattern vector search accepts interruptions of one range-bin within a pattern vector. Each pattern vector is filtered with respect to Doppler momentum and shear. The Doppler momentum is a specific or relative physical quantity since the air mass is unknown. First, low thresholds t_{low} must be passed (momentum > $t_{low,\ momentum}$ and shear > $t_{low,shear}$), so that only shear regions above noise threshold are accepted for further analysis. Second, high shear and momentum thresholds are applied (moment > $t_{high,\ momentum}$ or shear > $t_{high,shear}$). Here, the idea is to pick up high shear, small-scale rotations (late, mature stage of mesocyclone development) as well as high momentum, large scale rotations (early stage of mesocyclone development).

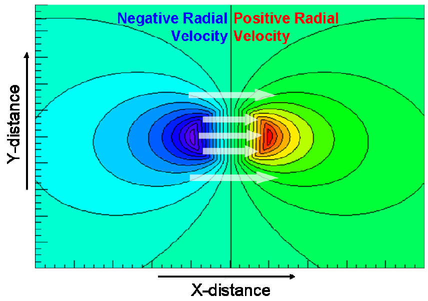

FIG. 1: Typical mesocyclone vortex as it appears in Doppler radar velocity data (here assumed: distance to radar much larger than Mesocyclone diameter, infinite resolution of radar). The wind field can be described by the Rankine Combined Vortex Model and consists of an inner part (rigid rotation) and an outer part where the vortex wind field is embedded into the environmental wind field. Pattern vectors are shown as thick white arrows. The group of pattern vectors resembles a feature.

The MDA proceeds by grouping the pattern vectors to features. In the ideal case, a feature corresponds to a complete rotation signature within a sweep and is build up by several pattern vectors adjacent in range. However, in reality, there is always some noise present (remaining dual PRF unfolding errors, missing data due to signal filters). Thus, the following criteria are used to extract only meaningful features and, at the same time, allow for imperfect data:

- First, the number of detected pattern vectors must exceed a certain threshold that depends on the range resolution and on the minimum assumed vortex spatial extent.
- Second, symmetry criteria (spatial extension of feature should be roughly equal in azimuth and range direction) must be passed (gaps of one range bin between pattern vectors are allowed).

Finally, the Doppler volume with its sweeps and related features (2D-objects within a sweep) are combined to 3-dimensional, vertically aligned mesocyclone objects (see figure 2).

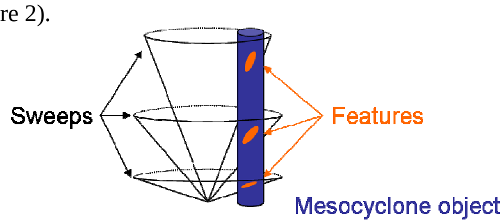

FIG. 2: Schematic showing a 3D mesocyclone object consisting of three features that are detected in 3 consecutive sweeps.

The condition of vertical alignment (overlap) between two features is fulfilled if the offset of the feature centers is less than the sum of the features radii. For each detected mesocyclone object, maximum and mean shear, maximum and mean momentum as well as the properties shown in table 1 are calculated taking also into account the reflectivity information from the Doppler volume.

Severity-Level		**1**	**2**	**3**	**4**	**5**
Max. reflectivity [dBZ]	≥	10	30	40	50	55
Avg. reflectivity [dBZ]	≥	10	20	25	35	40
Height above ground [km]	≤	5	3	2.5	2	1.5
Meso-Height [km]	>	0	0	2	4	6
VIL [kg m^{-2}]	>	2	2	5	20	30
Echo top height [km]	>	1	3	4	5	7
VIL density [g cm-3]	>	0	1	1.5	2.	2.5

TABLE I: Thresholds for severity calculation (connected by logical AND). The severity color coding is the same as in figure 3.

A definition of VIL and VIL density can be found in (Greene, Clark, 1972) and (Graham, Struthwolf, 1999). In the latter publication cell-based VIL, which is used for the MDA, is described in some detail. As a last step, a severity ranking is computed. Table 1 shows a first, preliminary set of thresholds used for severity calculation.

IV. WEATHER CASES

In the convective season 2010-2011 in Germany, more than 10 very strong severe weather events, where supercells, identified by experienced meteorologists and partly supported by eye-witness reports of funnels or wall clouds and were correctly detected by the MDA were documented. The locations and tracks of the supercells visible as pronounced KONRAD cells (see Joe et al., 2005 and references therein) identified in the precipitation scan reflectivity data could be linked to the MDA detections in the Doppler scan velocity data. In the following, two particular weather cases will shortly be introduced.

The most outstanding weather event of the convective season 2010 in Germany was the tornadic supercell of 24.05.2010 in Saxony (Pentecost Monday F3-tornado). The supercell with its rotating updraft is clearly visible in both reflectivity (hook echo) and Doppler wind data (see figure 3).

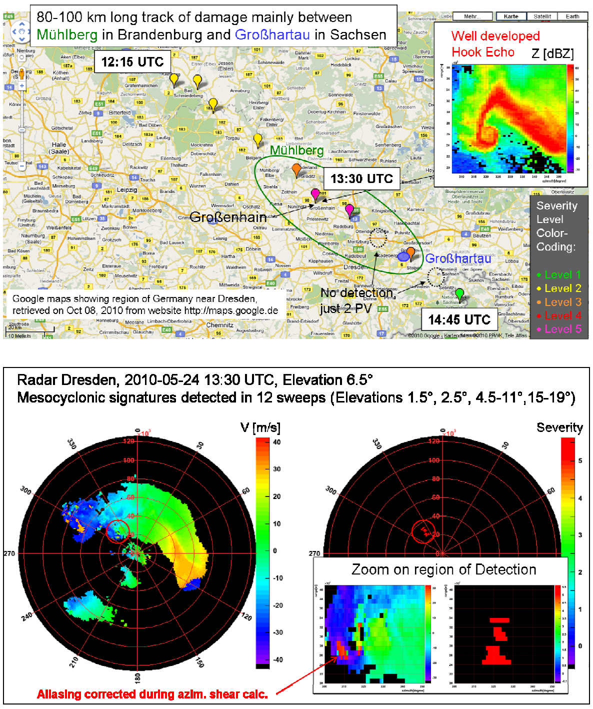

FIG. 3: Top: Track of detections of the Mesocyclone Detection Algorithm in an offline analysis of the 'pentecost Monday supercell' near Dresden, Saxony (map retrieved on Oct 8, 2010 from website http://maps.google.de). Bottom: Doppler wind PPI-scan at reference time 13:30 UTC (time of start of Volume scan). The typical dipole structure can clearly be seen (together with aliasing artefacts, which, however, can be corrected during calculation of azimuthal shear).

A further example is the supercell of 13.07.2011 in south Bavaria leading to the F2 tornado near Sautorn, Plattlingen (the supercell could be visually tracked from a region east of Munich up to the Bavarian Forest and produced high severity MDA-detections along this track). Figure 4 shows the Doppler wind PPI scan with rotation signature at a time when the F2 tornado was reported in the mesocyclone's direct vicinity.

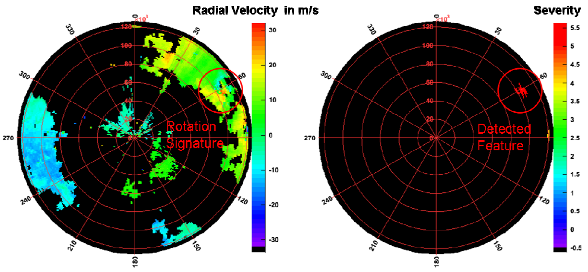

FIG. 4: Left: Doppler wind PPI-Scan, July 13 2011, Radar Munich. A rotation signature in north-east direction (close to Bavarian Forest) can be seen. Right: The feature as detected by the MDA.

V. SUMMARY AND OUTLOOK

The MDA with preceeding quality assurance as described in the previous sections is running in pre-operational mode with the severe weather forecasting tools (Joe et al., 2005) at the central office of DWD. A preliminary validation has started; examples are given in the last section. The severity scale is still being tuned. At the current stage it can be stated that the overall results look very promising. As mentioned above, a lot of supercells identified by experienced meteorologists have been correctly detected. A more quantified validation on the basis of the convective seasons 2010 and 2011 is in work.

Within the DWD-project RADSYS-E (Mammen et al., 2010), an upgrade of the whole DWD radar network is under way, providing state-of-the-art dual-polarization radars and extending the available moments beyond reflectivity and radial wind towards differential reflectivity, correlation coefficient and phase shift between horizontal and vertical polarized waves, just to mention a few. In order to fully exploit the possibilities of the new radar network, a change of the scan strategy towards volume scans with higher time resolution is under consideration. Further developments will include a 3D-cell detection and tracking as well as dual polarimetric algorithms (e.g. hydrometeor classification). The mesocyclone detection will be integrated into a common software framework where the implemented algorithms can benefit from each other. Furthermore, this software framework will be designed in such a way as to synchronize the arrival of the the radar data. Thus, the merging of 2D mesocyclone features from multiple network radars in overlapping regions to create a single 3D detection becomes feasible.

VI. REFERENCES

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