Atmospheric Research 213 (2018) 110–120

Contents lists available at ScienceDirect

Atmospheric Research

journal homepage: www.elsevier.com/locate/atmosres

A radar-based centroid tracking algorithm for severe weather surveillance: identifying split/merge processes in convective systems

Anna del Moral[a,c,*], Tomeu Rigo[b], Maria Carmen Llasat[a,c]

[a] GAMA, Department of Applied Physics, University of Barcelona, Barcelona, Spain
[b] Meteorological Service of Catalonia, Barcelona, Spain
[c] Water Research Institute, University of Barcelona, Barcelona, Spain

ARTICLE INFO

Keywords:
3D centroid-tracking algorithm
Nowcasting
Weather radar
Severe weather
Anomalous movements
Split
Merge
Convection

ABSTRACT

Nowcasting tools using radar data are essential when researching severe weather phenomena. Identifying thunderstorms and characterising their properties are usually the main steps to follow in order to make a good short-term forecast. These analyses are normally used to feed early warning systems in many countries, helping to reduce the impact of severe weather. Over the last few decades, research in this meteorological field has increased significantly, defining different methodologies that have worked well for many severe events. Most of these methodologies are based on a prior 3D identification of the thunderstorms in question, by applying intensity and size thresholds and obtaining their characteristics, allowing their centroids to be tracked. In some cases, the thresholds for identification and the distance established to track the centroid are too restrictive, which results in the incorrect identification of individual cells in multicell systems, or even means that the algorithm is unable to distinguish when an anomalous movement takes place. This paper presents a new type of 3D cell identification and tracking, based on the algorithm developed by Rigo and Llasat (2004). This last algorithm is currently used in the Meteorological Service of Catalonia (SMC), and consists of a nowcasting methodology based on centroid tracking. In the new version, a new two-step methodology to construct 3D radar cells has been proposed. A double reflectivity thresholding method plus an overlapping technique have been applied for a better definition of the convective structures. This makes it possible to identify possible changing processes such as splitting or merging within the same thunderstorm. Furthermore, a dynamic distance threshold technique has been adopted to correctly track cells with anomalous movements. An in-depth study has been carried out for a severe weather case in which a multicell system presented a complex merging and splitting process that was correctly forecasted using the proposed algorithm.

1. Introduction

Thunderstorm identification, tracking and short-range forecasting of the trajectories of future cells throughout their life cycle constitute the basis of severe weather warning operations (Roberts et al., 2006). According to the Meteorological Service of Catalonia (SMC) and other weather services around the world, a severe weather event is associated to a thunderstorm in which occurs at least one of the following meteorological phenomena: hailstones ≥ 2 cm in diameter, wind gusts $\geq 25\,\mathrm{m \cdot s^{-1}}$ and/or tornadoes. Besides these conditions, different meteorological services and the scientific community worldwide also include thunderstorms that produce excessive rainfall in short periods of time, or may vary slightly the previous thresholds based on their experience and climatology. In spite that some windstorms not associated to thunderstorms can overpass $25\,\mathrm{m \cdot s^{-1}}$, the term "severe weather" is usually associated to "severe thunderstorms" because these are the main source of this type of phenomena. For this reason, this paper is focused on identifying and tracking severe thunderstorm events.

These type of thunderstorms can present anomalous movements. According to Cotton et al. (2011), the displacement of a thunderstorm is basically composed by three types of movement: the translation (synoptic factors), the forced propagation (mesoscale factors) and the autopropagation (thunderstorm itself factors). These two last factors, from mesoscale and from the thunderstorm itself, may force an anomalous movement, this is, the movement performed by the thunderstorm could not be straight or, in other words, it could not follow the winds aloft at the level where the centroid is located (sharp changes of direction, stationarity, splitting, merging and trajectories opposite to the neighbour cells). The mesoscale factors include, for instance, orographic borders or convergence lines, which are easier to predict if the

* Corresponding author at: Water Research Institute, University of Barcelona, Barcelona, Spain.
E-mail address: adelmoral@meteo.ub.edu (A. del Moral).

https://doi.org/10.1016/j.atmosres.2018.05.030
Received 23 January 2018; Received in revised form 15 May 2018; Accepted 28 May 2018
Available online 29 May 2018
0169-8095/

forecaster knows the orography of the region or if accurate mesoscale weather forecasting models are available. However, the internal thunderstorm dynamics (autopropagation factors) are the most difficult to predict due to the local nature and the small spatial and temporal scale. The possible anomalous behaviour derived from the autopropagation factors can be seen analysing the entire volume of the thunderstorm through weather radar images, since it produces changes in the internal structure of it. In this sense, this paper is focused on identifying and tracking severe thunderstorm events with local anomalous movements that can be indirectly detected with radar that is, splitting and merging processes.

Over the last few decades, research on thunderstorms and severe weather has increased significantly, resulting in different radar-based nowcasting methodologies that have been very efficient in forecasting many events (Golding, 1998; Pierce et al., 2000; Mueller et al., 2003; Seed, 2003). According to Wilson et al. (1998, 2004), the historical treatment of thunderstorm extrapolation techniques can be divided into two main groups: assuming no change in motion, size and intensity (steady-state assumption), and allowing changes based on past trends. Furthermore, the steady-state assumption techniques can be divided into two further groups, depending on the way they track the thunderstorms: cross-correlation tracking (Rinehart and Garvey, 1978; Rineheart, 1981; Golding, 1998; Lai, 1999; Wolfson et al., 1999), and centroid tracking and matching (Crane, 1979; Rosenfeld, 1987; Dixon and Wiener, 1993; Johnson et al., 1998; Han et al., 2009).

The first methodology, cross correlation tracking, essentially uses correlated radar images to calculate the displacement vector, then extrapolates the cell area to future images over a period of time and takes the translation that gives the maximum correlation with the final echo displacement. This methodology is highly effective when applied to nowcasting for convective rainfall embedded in stratiform rain, usually found in frontal systems. It is capable of distinguishing between convective and stratiform rainfall, although it is not so efficient when identifying and tracking individual convective cells (defining a cell as a typically small area within a radar image that presents higher reflectivity than the surroundings, as suggested by Crane, 1979). The second methodology, centroid tracking, is based on identifying and tracking the centroid of every single cell within a convective system, obtaining other properties, such as the intensity, vertical integrated liquid (VIL), or top height, among others. However, it is unable to identify stratiform precipitation, mainly because it is focused on convection analysis. Besides this, the use of past trends in echo size and intensity to forecast future cells have not improved the nowcasting techniques, as shown by Tsonis and Austin (1981) and Wilson et al. (1998). They concluded that the physical processes that may change the rainfall pattern of a storm are not necessary observable in past echo trends. This is also applicable in forecasts of start of convective storms, where the physical processes often occur in the boundary layer (Garstang and Cooper, 1981), and are not visible just by extrapolating the characteristics of past cells.

Considering that this paper is centred on a centroid-tracking based algorithm, the following state of art review focuses on this type of technique. One of the most well-known centroid-type algorithms is TITAN (Thunderstorm Identification, Tracking, Analysis and Nowcasting) (Dixon and Wiener, 1993). This method uses unique and fixed reflectivity and volume thresholds to define convective cells. Then, cells centroids are tracked across consecutive radar scans while applying a combinatorial optimisation technique in addition to a geometric algorithm to handle anomalous movements of thunderstorms such splitting or merging. The Enhanced TITAN algorithm (Han et al., 2009) goes one step further and introduces a dual threshold process while the convective cells are identified. This process is followed by a growth and dilation operation to avoid false mergers when there is a high level of convective activity, with a large number of close cells. Furthermore, the tracking process is changed to an overlapping technique combined with a constraint-based combinatorial optimization method, changing the maximum speed constraint of the storm depending on its area. The method was developed for cases in which cell shapes change quickly and constantly, in order to handle possible violations of the maximum speed constraint.

Another well-known algorithm is the SCIT (Storm Cell Identification and Tracking Algorithm) (Johnson et al., 1998). In this case, 3D cell identification is carried out in stages. 2D storm structures in each volume level are created using seven thresholds and imposing a minimum area of 10 km^2. Then, the cores of these 2D convective structures are isolated from surrounding areas of lower reflectivity, and the centroids are calculated. From this point onwards, 2D convective structures will be considered to be those identified in each volume level (elevation scans), and are the first step of the entire 3D identification process. 3D cells are obtained by associating 2D storm cores in consecutive elevation scans, connecting their centroid by imposing a distance constraint (5 km). The potential for multiple associations is resolved by taking the core with the largest mass (equivalent to the liquid water content estimated through radar reflectivity). Non-associated components are matched by imposing larger distances between the current and previous cells (7.5 km and 10 km). A storm must be defined by at least two 2D cores at consecutive elevations (referred to as segments), and with a vertical gap of no more than 3° (~two elevations). For the tracking module, the SCIT algorithm makes a first guess of the locations of the cells by calculating the motion vector of past scans using linear least squares. Then current cell locations are compared to the first guess, and a path is constructed by connecting the centroids that match the given distance threshold.

This algorithm was adapted for Spain by the Service of Applied Techniques (*Servicio de Técnicas Aplicadas*, STAP) of the National Weather Service of Spain (*Agencia Estatal de Meteorología*, AEMET), who added some constraints in the identification process. Moreover, they made a slight change to the way the first guess is calculated during the tracking process, where the wind fields from numerical models were also added (Carretero et al., 2001; Martín et al., 2007). In its turn, the STAP algorithm was also adapted to Catalonia (NE Spain) by the Meteorological Hazards Analysis Team (*Grup d'Anàlisi de situacions Meteorològiques Adverses*, GAMA) at the University of Barcelona (Rigo and Llasat, 2002a, 2002b, 2004), and after some updates it is now the operative algorithm used by the Meteorological Service of Catalonia (*Servei Meteorològic de Catalunya*, SMC). The 3D identification algorithm run by the SMC is also carried out in two steps: step one involves identifying 2D convective structures on every level with the same reflectivity thresholds as in the SCIT algorithm, and step two involves building the 3D cell for the entire volume, referring to CAPPI levels instead of elevation scans (a total of 10 CAPPIs). In this case, the minimum 2D structure area is 24 km^2, unless the process and constraints imposed are almost the same than in the STAP algorithm. Furthermore, possible multiple associations during the vertical connection are resolved by choosing the closest cell in the vertical connection. Finally, in the tracking module, the connections are carried out using the real measurements for actual and past centroids. In this case, the distance thresholds applied are 2.5 km and 5 km. If no association is found within the given distances, then the search is carried out with a larger distance (over 7.5 km) and with the two prior images (−12 min.).

The algorithms presented above can separate clusters of cells by applying different thresholds of reflectivity but some of them don't have any special procedure to reproduce the real paths of the cells involved in a possible anomalous motion process, especially in multicell systems. Furthermore, in days with high convective activity, there is a lack of continuity in the cells' characteristics. Cell shapes and intensity may vary sharply and continuously, hindering later nowcasting processes. This is a big setback, especially when it comes to nowcast cells that may show anomalous movements during their life cycle, such as the primary thunderstorm splitting in two different ones, or in the merging process, on the other hand. This issue became more visible following the study