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Enhanced object-based tracking algorithm for convective rain storms and cells

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ABSTRACT

This paper proposes a new object-based storm tracking algorithm, based upon TITAN (Thunderstorm Identification, Tracking, Analysis and Nowcasting). TITAN is a widely-used convective storm tracking algorithm but has limitations in handling small-scale yet high-intensity storm entities due to its single-threshold identification approach. It also has difficulties to effectively track fast-moving storms because of the employed matching approach that largely relies on the overlapping areas between successive storm entities. To address these deficiencies, a number of modifications are proposed and tested in this paper. These include a two-stage multi-threshold storm identification, a new formulation for characterizing storm's physical features, and an enhanced matching technique in synergy with an optical-flow storm field tracker, as well as, according to these modifications, a more complex merging and splitting scheme. High-resolution (5-min and 529-m) radar reflectivity data for 18 storm events over Belgium are used to calibrate and evaluate the algorithm. The performance of the proposed algorithm is compared with that of the original TITAN. The results suggest that the proposed algorithm can better isolate and match convective rainfall entities, as well as to provide more reliable and detailed motion estimates. Furthermore, the improvement is found to be more significant for higher rainfall intensities. The new algorithm has the potential to serve as a basis for further applications, such as storm nowcasting and long-term stochastic spatial and temporal rainfall generation.

1. Introduction

Extreme convective rain storms may cause pluvial flooding and potentially severe socio-economic consequences. For this reason, convective events have been a fundamental object of study in the hydrological and meteorological field. Convective weather systems imply highly dynamic spatial and temporal processes which understanding remains a challenging issue.

The development of high resolution radar products in recent years (Einfalt et al., 2004; Seo et al., 2015; Thorndahl et al., 2016) has significantly advanced the observations of these phenomena. Due to its ability to better capture the spatial and temporal variability of the rainfall fields, high resolution weather radars allow for a more detailed analysis of the forming and movement of convective storms (Emmanuel et al., 2012; Liguori et al., 2012; Sebastianelli et al., 2013; Vulpiani et al., 2015).

Proper study of the spatial organization patterns and the temporal evolution of convective precipitation fields demands accurate tracking algorithms. There are two main types of methods that have been extensively developed to approach the storm tracking issue when using radar data; these are field and object based methods (Reyniers, 2008). The general idea of the former (also known as field trackers), is to compute a field of displacements/movement vectors over a continuous spatial grid by comparing two successive reflectivity/rainfall rate radar images. The images are often divided into grid blocks with an identical size. Then, the advection vectors of the blocks are obtained by using a certain measure of similarity between these two images. These methods have proven to provide a good 'global' motion estimation for the entire radar image field. For example, TREC (Tracking Radar Echoes by Correlation) method employs 'spatial' correlation coefficients to identify the movement of each of the pre-defined grid blocks (Rinehart and Garvey, 1978; Tuttle and Foote, 1990); VET (Variational Echo Tracking) and optical flow based methods derive the storm movement for each pixel location by determining the field of displacements that minimize the overall 'variation/difference' between two successive radar images (Bowler et al., 2004; Germann and Zawadzki, 2002; Laroche and Zawadzki, 1994; Laroche and Zawadzki, 1995; Pierce et al., 2012; Pierce et al., 2004).

In contrast to the field trackers, the object based tracking methods (or cell trackers) derive motion by first detecting storm objects (or

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entities) following a particular identification process, and then, associating similar entities on two successive images based upon specific matching techniques. The final motion estimate is thus obtained by computing the associated object centroid displacements. The fact that storm entities can be identified and tracked provides this types of methods a great potentiality to deal with the smaller high intensity rainfall details shown in high resolution radar images (Lakshmanan et al., 2003). One of the well-known object based tracking algorithms in the literature is the TITAN (Thunderstorm Identification, Tracking, Analysis and Nowcasting) algorithm (Dixon and Wiener, 1993). TITAN was specifically built to identify, track and further forecast convective storms and has been routinely used during the last two decades (García-Ortega et al., 2009; Gascón et al., 2015; Goudenhoofdt and Delobbe, 2013; Han et al., 2009; Potts, 1993; Thorndahl et al., 2014; Yang et al., 2014). Despite its good performance in general, the settings of the original TITAN has been found unable to fully exploit the advantages that high resolution radar data sets can provide, as further explained in Section 3.1. For that reason, a new enhanced adapted version of the original TITAN algorithm able to better handle high resolution data is implemented in this work.

This paper is organized as follows. The data used for testing the new algorithm are described in Section 2. An overview of the TITAN algorithm, the deficiencies identified in its original structure and the treatments included to tackle them are introduced in Section 3, as well as the methodology applied to evaluate the new algorithm performance. Results are shown and discussed in Section 4. Lastly, in Section 5, main conclusions are presented, and future expectations of this work are proposed.

2. Data

High-resolution weather radar data provided by the Royal Meteorological Institute of Belgium (RMI) are used to develop and to evaluate the proposed storm tracking algorithm. Also known as the Belgian radar composite (Reyniers, 2008), the RMI radar product, is a composite of the Wideumont and Zaventem radar observations. Both the Wideumont and Zaventem radars, which location is depicted in Fig. 1, are single-polarization C-band Doppler radars that utilize 5 and 1 PPI elevation scanning strategies, respectively, to provide horizontal reflectivity data up to a range of 240 km. After applying a number of quality-control (QC) procedures, a pseudo-CAPPI composite reflectivity product at a height of 1500 m is produced at 5-min temporal and 529-m spatial resolution. For a detailed description of QC procedures that have been applied to the Belgian composite, readers are referred to Delobbe and Holleman (2006) and Foresti et al. (2016).

Radar reflectivity (dBZ) data from a total of 18 convective storm events over the entire Belgium area between 2012 and 2014 were employed in this paper. These events were selected based upon the convective storm classification methodology developed by Goudenhoofdt and Delobbe (2013). The selection process was focused on choosing storm events containing clear 'convective systems', namely with well-defined clustering structures with high reflectivity storm cores (Goudenhoofdt and Delobbe, 2013). Among these selected events, six of them (hereafter called, 'calibration events') were randomly chosen to tune the key parameters of the proposed tracking algorithm, and the rest of 12 events (hereafter, 'evaluation events') were used for evaluation. The list of events is summarized in Table 1.

3. Methodology

3.1. Original TITAN scheme

In the implementation of the original TITAN algorithm, convective storm entities are identified by defining contiguous regions that exceed a single reflectivity threshold value (i.e. 35 dBZ). Afterwards, TITAN employs a combinatorial method to match these identified entities between two successive time steps, followed by an additional scheme able to handle splitting and merging processes.

The combinatorial method is formulated as an optimization problem, of which the aim is to minimize a cost (objective) function that indicates the similarity of storm entities. This cost function includes a couple of geometrical and physical features of storm entities: the velocity vectors (distance between entity centroids) and the difference in volume of the storm entities under consideration. In addition, some restrictions are imposed to narrow down and to ensure the feasibility of the solution domain. Constraints on the velocity parameter, and overlapping techniques (i.e. it is assumed that, if two storm entities overlap between two successive time steps, it is very likely that they are same entities at different time steps) are used for such a purpose.

Finally, the Hungarian numerical method is employed to solve this optimization (minimization) problem. Movement vectors representing the displacements of the centroids between each pair of 'matched' entities are eventually obtained. Afterwards, merging and splitting situations are handled using a 'short-term' forecast scheme. A merging situation occurs when the centroids of two or more storm entities at current time step are expected to be located within the same storm entity at the next time step. In contrast, a splitting situation takes place when a storm entity at the current time step is expected to overlap with the centroids of two or more storm entities at the next time step.

In spite of a generally good performance in tracking convective storm entities, a number of deficiencies can be identified in TITAN.

First, the single thresholding setting can effectively identify large convective systems, but appears to be insufficient to well isolate small-sized yet high-intensity storm details that can be observed in high resolution radar data images. In turn, single-thresholding approaches often lead to false merging problems in the identification process (Han et al., 2009; Handwerker, 2002), i.e. when two or more smaller independent storm entities are wrongly identified as a larger unique one.

Second, overlapping techniques may show difficulties in matching storm entities in fast moving storm cases since it is likely that no overlapping at all may occur (Dixon and Seed, 2014). Similarly, this lack of overlapping may also be largely magnified if high-intensity storm details are captured because smaller sizes are expected.

Third, the current criteria used to quantify the similarity of storm entities at successive time steps (merely dependent on the volume differences of storm entities) may not be able to cope with the highly dynamic behavior of small-sized storm entities and therefore it may not be able to provide satisfactory results when matching them.

Finally, motion estimates obtained from object centroid displacement may lack accuracy due to, first, object mismatching outcomes resulting from the use of overlapping techniques and the oversimplified criteria of similarity and second, the random centroid displacement problem (Han et al., 2009). This problem occurs in cases where a storm entity changes drastically its size or shape at two successive images due to the threshold application and it specially affects to larger size and false merged storm entities. As a consequence of these motion estimates inaccuracies, the algorithm may also show difficulties when handling merging and splitting situations, since possible unreliable motion estimates may be employed in the 'short-term' forecast scheme used to identify splits and mergers.

In order to overcome these known deficiencies, this study applies three main modifications to the original TITAN structure. Techniques that benefit from the advantages of having a high resolution data set, are incorporated. As shown in Table 2, first, a multi-threshold identification method is implemented to substitute the original single-threshold identification approach. Second, a more sophisticated matching scheme that avoids overlapping techniques by integrating a field tracker to optimize the combinatorial method, is constructed. It also makes use of a more comprehensive cost function and includes a new approach to deal with merging/splitting situations. Third, a more elaborated methodology to obtain motion estimates is developed.

These proposed changes aim at 1) creating an enhanced