Long term analysis of convective storm tracks based on C-band radar reflectivity measurements

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1. Introduction

The very short forecasting or nowcasting of convective storms is a highly challenging problem due to the wide variety of spatial scales and processes involved. The state of the art numerical weather prediction models generally fail in predicting convective storms initiation and development with reasonable accuracy. Weather radars are intensively used by forecasters during convective situation. A radar provides instantaneous reflectivity measurements of precipitation at a spatial scale of about 1km. Convective storms, which occur at a spatial scale of a few kilometers, can then be detected by the radar. Moreover, if the time resolution is short enough, the convective storm evolution can be monitored across successive radar images. Based on those snapshots, the motion of a convective cell can be estimated and used to forecast its future position. However, this simple method does not take into account storm growth, decay and direction changes. For this purpose, a better knowledge of storm evolution characteristic is required. The Royal Meteorological Institute of Belgium has several years of archived volume data from a C-band radar. To process those data, the cell tracker TITAN (NCAR) has recently been installed at RMI. The behavior of this tracking system has been investigated through a sensitivity study to some parameters. The storm tracks provided by TITAN have been analysed by a suitable statistic tool. The interest of this analysis to obtain a robust climatology of convective storms is clear (Han, 2009 ; Tucker and Li, 2009). Furthermore it is worth investigating whether the analysis of convective storm characteristics can be used to improve its nowcasting. In this study, storm tracks from six years of volume data are analysed with different statistical methods. The frequency distribution of the storm tracks properties and their space-time variations are showed. Pairs of storm track properties are tested for a possible linear relation. The characteristics of the kinematic of the storms such as the storm initiation location are also analysed using spatial point pattern statistics.

2. Radar observations

Since 2001, RMI operates a C-Band (5GHz) weather radar located in Wideumont (south-east Belgium) at about 600 m above sea level The radar, which has a range of 240 km, covers Belgium and Luxembourg and also part of France, The Netherlands and Germany. It is a single polarisation radar with Doppler capabilities which are particularly useful for the mitigation of non-meteorological echoes. The radar performs a scan at 5 elevations (0.3°, 0.9°, 1.8°, 3.3°, 6.0°) that begins every 5 minutes and lasts about 2 minutes. The antenna of the radar transmits pulses of 0.836µs at a frequency of 600Hz with a speed of 18°/s. The radar volume data have a resolution of 1° in azimuth (an average of 33 successive beams) and 250 meter in range (an average of 2 successive samples along the beam). Every 15 minutes, the radar also performs a 10-elevations scan without Doppler filtering. A third scan, limited to 120 km, is used to retrieve radial velocities. More information regarding the radar characteristics and scanning strategy can be found in Delobbe and Holleman (2006). RMI also receives volume data from a C-Band radar which is located at Zaventem in the center of Belgium. This radar is operated by Belgocontrol, the air safety agency at Brussels National airport. The volume data of the Wideumont and Zaventem radar are archived at RMI since 2002 and 2004, respectively. Only the data from the first scan of the Wideumont radar will be used here. The second scan, whose volume coverage is larger, is performed at a too low time resolution to properly track convective cells.

3. Storm tracking

3.1 The TITAN tracking system.

The cell tracker TITAN (Dixon and Wiener, 1993) has been developed for automatic identification, tracking and forecasting of convective cells based on radar reflectivity measurements. In a first step, the radar volume data are transformed from polar coordinates into Cartesian coordinates using bi-linear interpolation. The storm identification algorithm defines a convective cell as a 3D region with reflectivity values exceeding a given threshold. The volume of the region must be larger than a given threshold to be considered as a valid cell. The storm tracking algorithm matches convective storms between two successive radar scans using combinatorial optimisation. It finds the set of storm paths that minimise a cost function, which is the sum of volume and distance weighted differences for each path. It also uses an overlapping technique to match the storms before the optimisation step. The algorithm can deal with storms that merge or split. Therefore, a storm which interacts with one or other storms (by merging and splitting) is classified as a complex storm, otherwise it is labeled as a simple storm (or simple track) . Interacting complex storms belong to the same complex track.

TITAN is also able to forecast storm evolution based on simple extrapolation using a linear or parabolic trend. TITAN is in constant development by several contributors. It is now a broad system with capabilities to ingest volume data from various radars, to perform several physically based corrections and to visualise Cartesian volume data and storm tracks.

3.2 Sensitivity tests to TITAN algorithm parameters.

The influence of the interpolation from polar to Cartesian grid on the storm tracking has been investigated. The main difficulty arises with the increasing size of the measurement volume when the distance from the radar increases. Furthermore, the vertical resolution is made of 5 beams at different elevations. Hence, there are regions in space with no measurements : the region above the highest beam close to the radar, the region below the lowest beam far from the radar and also the regions between two elevations whose size increases with the distance from the radar. Different regular Cartesian grids of different size (0.25, 0.5, 0.75, 1, 1.5 and 2 km) have been tested on several cases. The default TITAN parameters are 35 dBz for the reflectivity threshold and 15 km³ for the volume threshold. In Figure 1, you can see that the numbers of simple and complex storms tend to increase when the grid resolution increases. This suggests that some tracking problems occur. The storm tracks obtained are almost the same when using a grid size of 0.25 or 0.5 km resolution. We will then use a grid size of 0.5 km for computation efficiency.

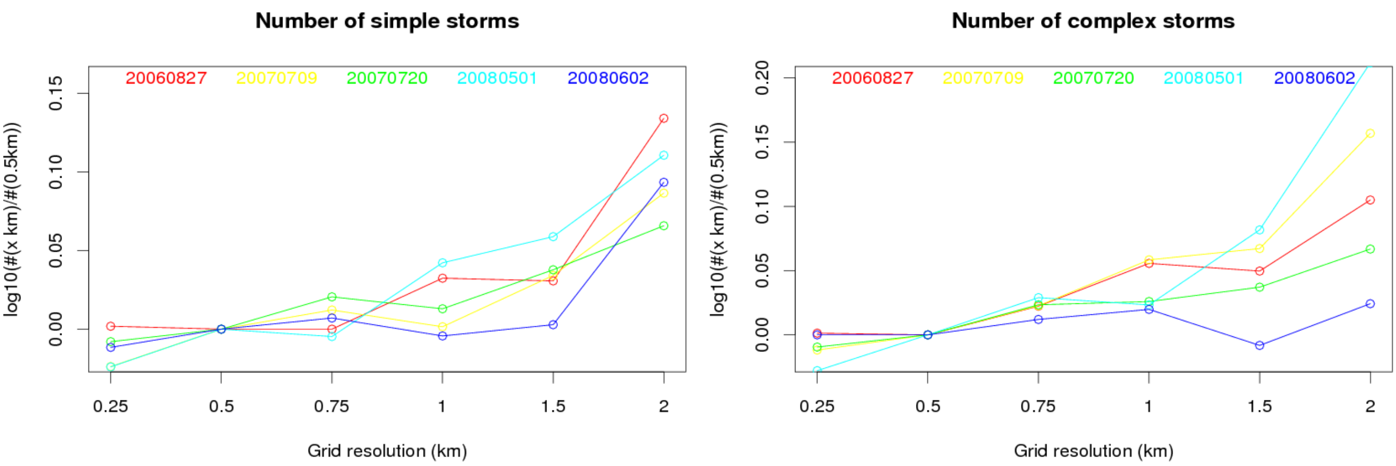

Fig. 1 Number of simple (left) and complex (right) storms as a function of the grid resolution (normalised at 0.5km).

The sensitivity of the storm identification and tracking algorithms to the reflectivity and the volume thresholds has also been analysed. The reflectivity threshold is chosen typically between 30 and 40 dBz. On one hand the effect of a higher threshold is that some detected regions can disappear. On the other hand, different sub-regions can be detected inside a region of lower reflectivity, which increases the number of detections. The effect of the volume threshold is obvious since it discards identified regions with a too low volume.

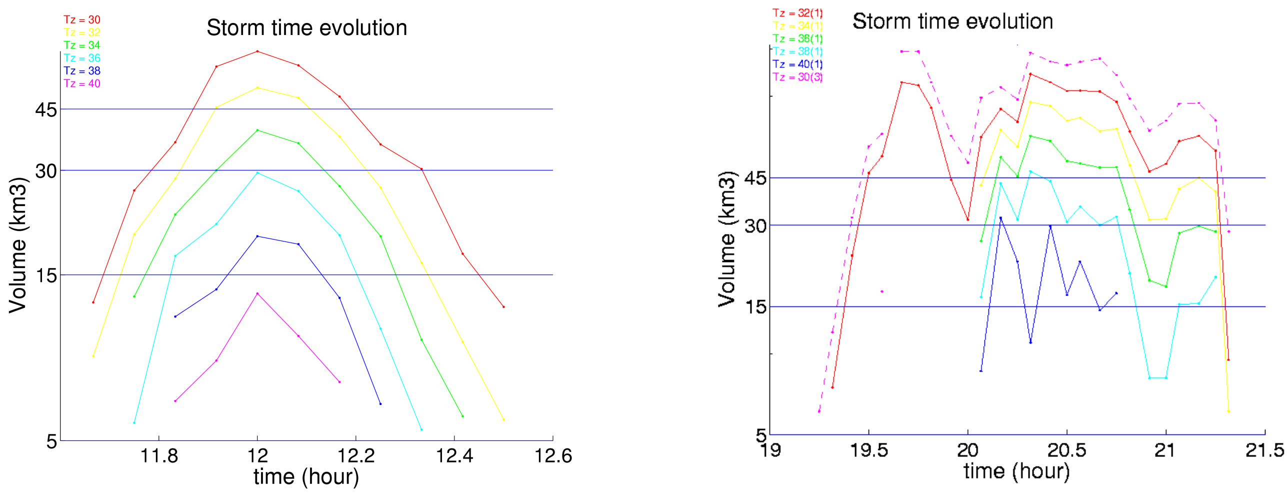

Fig. 2 Examples of storm volume evolution for different reflectivity thresholds.

The easiest way to verify whether the cells identified by TITAN are realistic or not is to perform a verification by eye. This is why we looked individually at several convective events and identified erroneous behaviors of the algorithm. If the volume and/or reflectivity threshold is high, the storm initiation and dissipation phase will not be included into the track. This effect will result in shorter storm tracks (Figure 2, left). If the volume threshold is high and the 3D region exhibits a local volume minimum across time, the storm track might be divided into two parts (Figure 2, right).

The overall effect of decreasing the reflectivity threshold is to increase the number of simple storm track detected (Figure 3, left) while the ratio of the number of simple storms over the number of complex storms decreases (i.e. more storms will be labeled as a complex storms). Furthermore the mean number of storms (lasting at least 15 minutes) per complex track increases (Figure 3, right). This could be explained by the fact that a low reflectivity threshold lead to larger detected regions which will more easily interact with each other.

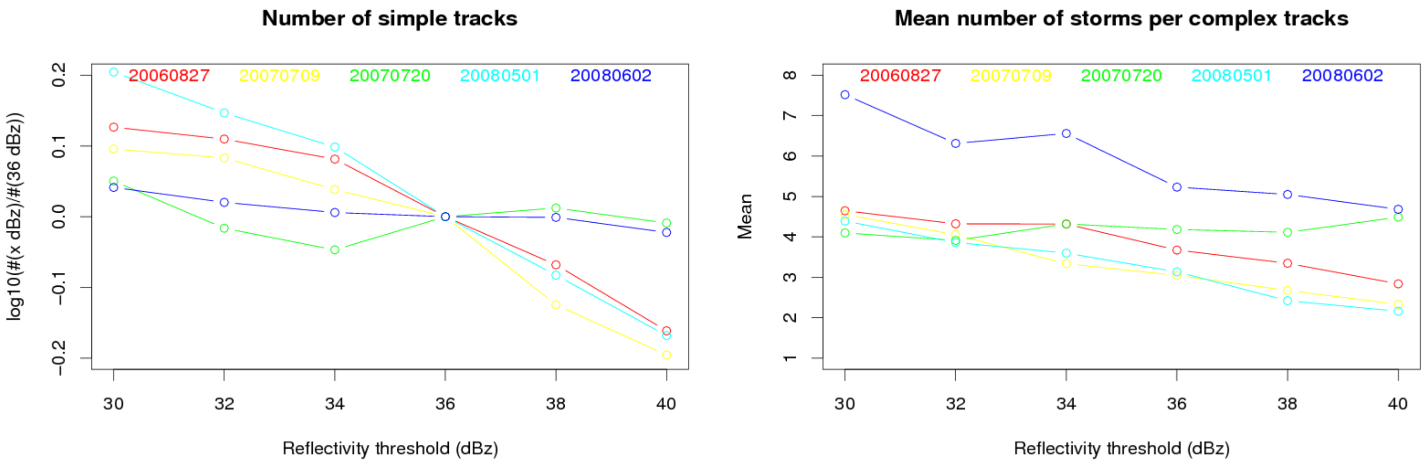

Fig. 3 Number of simple tracks (normalised at 36dBz) and mean number of storms per complex tracks as a function of reflectivity thresholds.

Based on those results, an average reflectivity threshold (36dBz) and a low volume threshold (10km³) have been chosen.

4. Storm track analysis

The TITAN algorithm has been applied to radar volume data from the beginning of 2005 to the end of 2009. The characteristics of the storm tracks generated by TITAN can be classified in two categories :

1) Instantaneous storm properties such as volume, top, position, speed or direction.
2) Aggregated storm track properties such as duration, mean/max of instantaneous properties.

4.1 Storm track selection

To be considered as a valid description of a convective storm, a track must satisfy several criteria regarding its duration, location and characteristic. We must also take into account that the storm track data set is contaminated by different kinds of non-meteorological echoes.

1) A storm track must last at least 15 minutes (3 radar scans). This criterion is automatically used by TITAN when generating storm tracks output.
2) A storm track is discarded if it begins or ends respectively after or before a missing radar file.
3) The complete path of the storm track must lie in a region with a maximum distance of 150 km from the radar and a minimum distance of 40km. This is set to limit the effect of the cone of silence at short range and overshooting at long range.
4) A storm track with a maximum top (i.e. the maximum altitude of the 36dBz echo) below 3.5km is discarded since it is likely not a convective storm.
5) A storm track with a maximum volume below 20 km³ or above 200 km³ is discarded.
6) A mean and minimum speed greater than 5 km/h, a mean major radius superior to 1km and a mean precipitation area bigger than 2 km are further required to eliminate most of the storm tracks made of non-meteorological echoes. The months from October till March when more erroneous tracks could appear are also discarded.

There were a total of 74942 simple tracks and 25852 complex tracks made of 114455 complex storms (with storm duration of at least 15 minutes). For simple tracks : respectively 161, 40496 , 26726 and 12907 tracks do not satisfy the 2nd to 5th conditions. After selection there are 10534 (15%) valid simple tracks and 1167 (5%) valid complex tracks (2115 storms). This significant reduction was expected because of the low volume threshold used in the tracking algorithm. Nevertheless, some valid tracks have been discarded together with erroneous tracks. For example stationary cells will be discarded due to the mean speed constraint. We will show statistical results for the simple tracks and not for the complex tracks which are more difficult to interpret.

4.2 Descriptive statistics

First we focus on convective storms occurrence (Figure 4). The number of storm tracks for each year is relatively similar with slightly more tracks occurring in 2006. When we group the storm tracks by month, we remark that convective storms occur mostly from May to August. The distribution of the storm initiation time during the day is also showed. There is a clear maximum in the afternoon with about 5 times more storms than during the night. This result is due to the diurnal heating of the atmosphere which produces favorable conditions for convection.

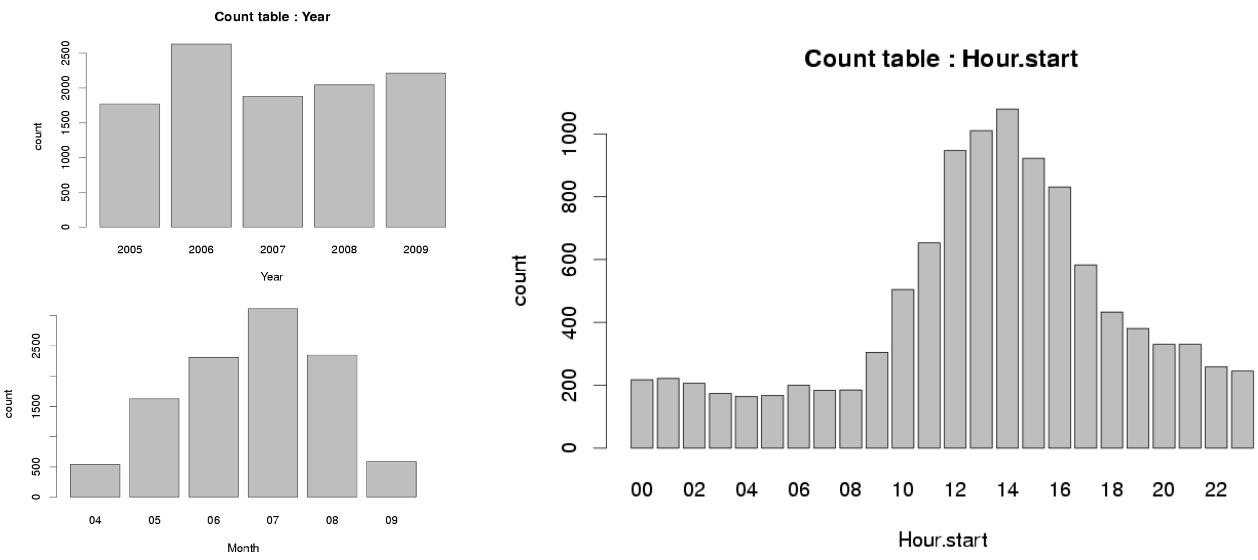

Fig. 4 Convective storm occurrence in function of the year, month and hour of the day.

In a second step, we looked at the empirical distribution of the storm track properties by constructing histograms for continuous variables and bar plots for discrete variables. Figure 5 shows the frequency distribution of the kinematics of the track : the duration exhibits a positive skew with half of the convective storms lasting less than 30 minutes and a few storms lasting more than 90 minutes. The mean speed of the storm tracks is well modeled by a Weibull distribution which is the typical distribution of the wind speed. The distribution of the mean direction of the storm is also consistent with the dominant wind (i.e. SSW) during convective events in Belgium.

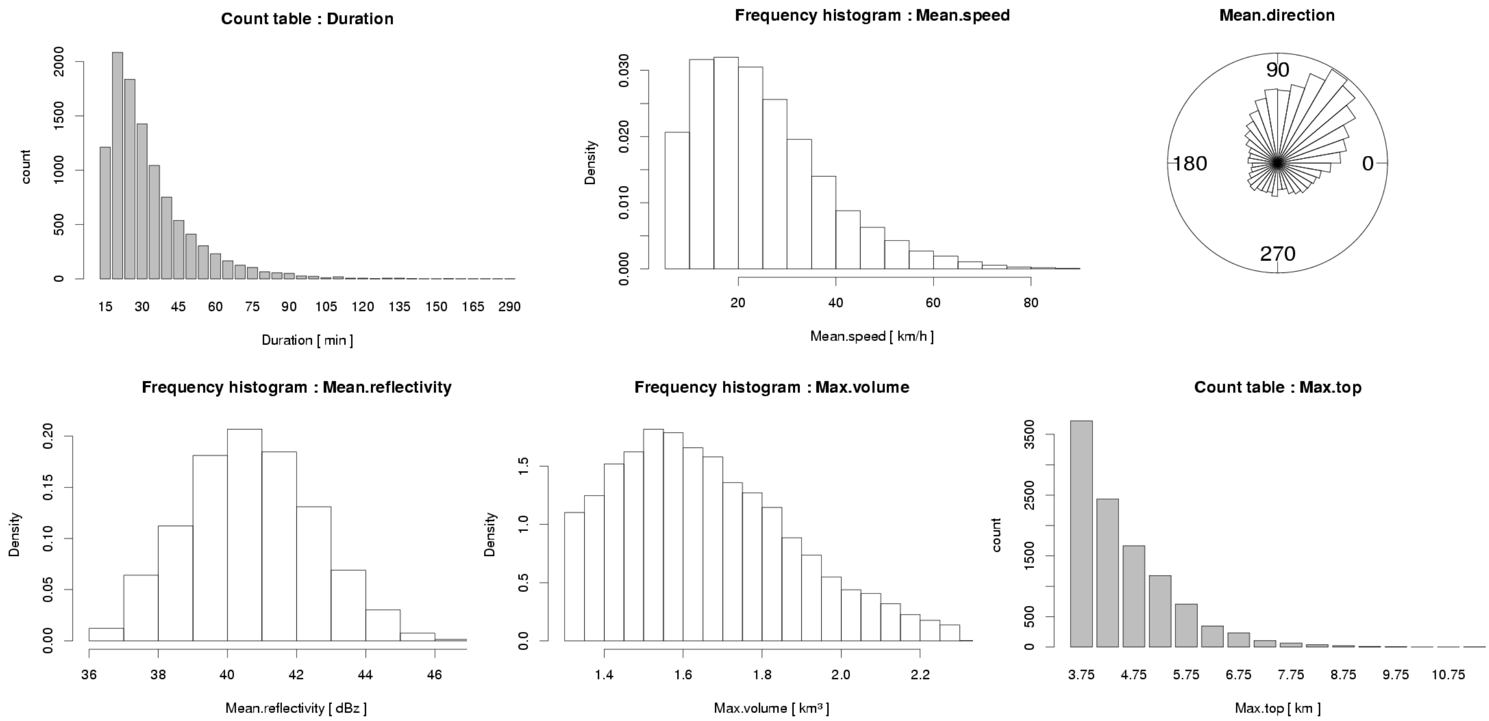

Fig. 5 Frequency distribution of storm track kinematics (duration, mean speed and mean direction) and frequency distribution of aggregated storm track properties (mean reflectivity, mean volume and maximum echotop 36 dBz).

Looking at the aggregated storm tracks properties (Figure 5, bottom) , the maximum volume can be described by a normal distribution after a logarithmic transformation. The maximum height of the storm (echotop 36 dBz) follows an exponential distribution. The mean reflectivity (in dB) follows a normal distribution with a mean of 40.67 dBz.

To have an idea of the seasonal dependence, the distributions of the storm track properties grouped by month have been compared using box-plots. Properties with a significant dependence are reflectivity (Figure 7, left) , volume and top with a maximum in the summer months. The spatial variability of the instantaneous storm properties has also been examined. There is a clear effect of the radar range. When we look at the storm top in function of the range from the radar (Figure 7, middle), we remark line patterns due to the scan strategy. The last graphic shows spatial variations of the expected value (mean) of the mean reflectivity over the domain. This field is obtain by applying a Gaussian filter to the observed values. Further artifact related to range can be seen : the mean reflectivity decreases with the distance (Figure 7, right).

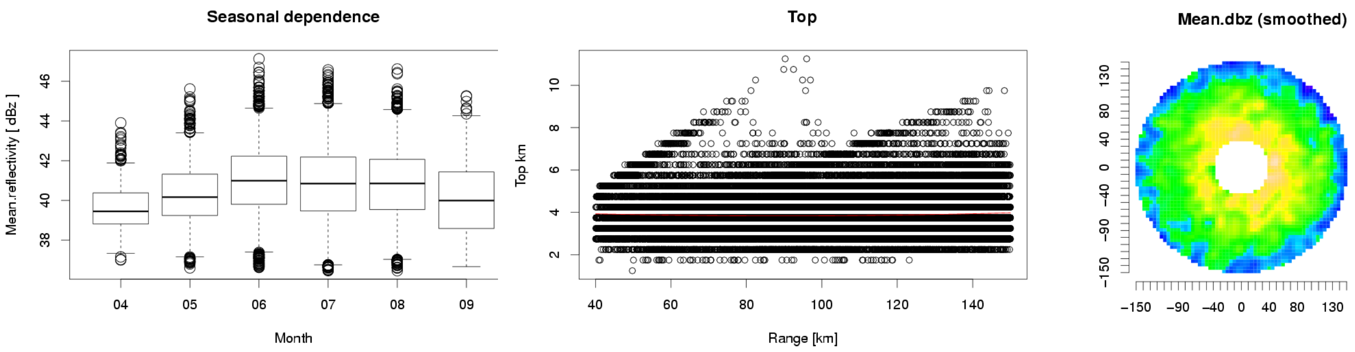

Fig. 7 Storm tracks mean reflectivity grouped by month, echo-top as a function of the distance from the radar and smoothed mean reflectivity over the selection domain

4.3 Regression statistics

A regression analysis between the storm track properties has been performed. A linear regression model between a dependent variable Y and an independent variable X is fitted by a least square estimator. Prior to the regression, some of the variables (volume, precipitation area) are transformed by the common logarithm. The estimated Pearson coefficient R is a measure of the linear dependence between the two variables. The square of R, i.e. the coefficient of determination, is the proportion of the variance in *Y* explained by a linear function of *X*. A relation for all the possible storm track properties pairs have been tested. The results for a few pairs will be shown.

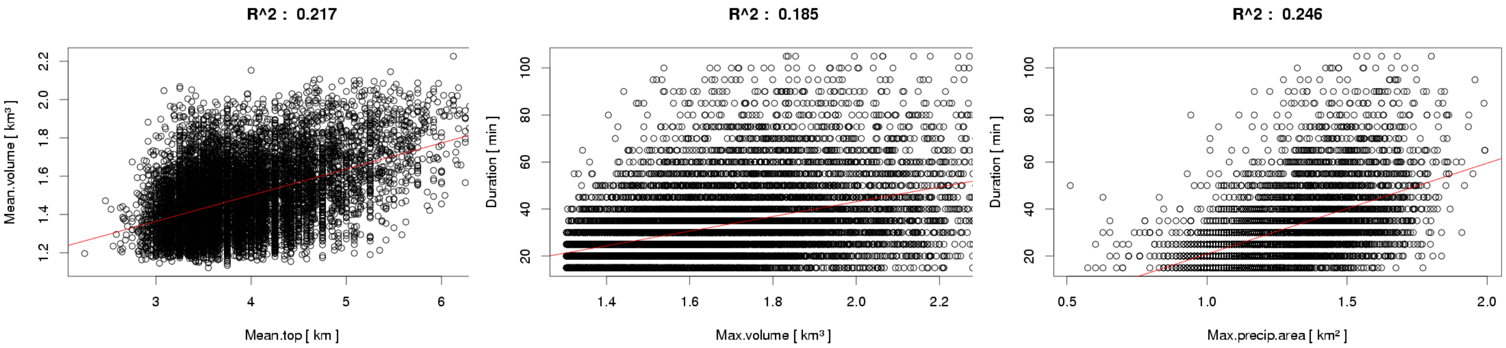

Fig. 8 Simple linear regression : Mean volume versus mean top, Duration versus Maximum volume and Maximum precipitation area.

Some geometric relations are expected : for example a positive correlation between mean top and mean volume (Figure 8, left). Of particular interest is the relation between aggregated storm track properties and the storm track duration. It appears that there is a positive correlation between the duration and the maximum volume or maximum precipitation area (Figure 8, middle, right). However the small values of R^2 show that there is a significant part of the variance which is not explained by those linear relations.

4.4 Spatial statistics

The kinematics of the storm tracks have been analysed using the successive positions of the storm centroid, which is the center of the volume. The storm centroid locations can be considered as a point process in space-time (Baddeley and Turner, 2005). If the time dependance is omitted, it becomes a spatial point process. The observed locations of storms, for a given period of time, form a point pattern which is a realisation of this process. On figure 9, you can see the spatial density of the storm initiation estimated by Gaussian smoothing. Due to the delimited region of observations and the selection of the storm tracks, there are clear border effects. Indeed, the density is higher in the south west of the domain because the majority of the storms that initiate there evolves toward the domain. Furthermore, the density is lower at the North East border of the domain because most of the storms leave the domain and are not selected. The same characteristics appear if we look at the storm dissipation location but with an opposite effect. If we look at the images, there is no evidence for preferred regions of convection initiation or dissipation. To get more insight, the point pattern can be tested for complete spatial randomness by an appropriate statistic. This is equivalent to test if the point pattern is a realisation of a Poisson point process. On the middle of figure 9 you can see the frequency distribution of the theoretical Poisson process and the empirical realisation for the x coordinate. The 2 curves are relatively close together with the slight deviation being explained by the border effects described above. This further suggests that the point process associated with the storm initiation is spatially random.

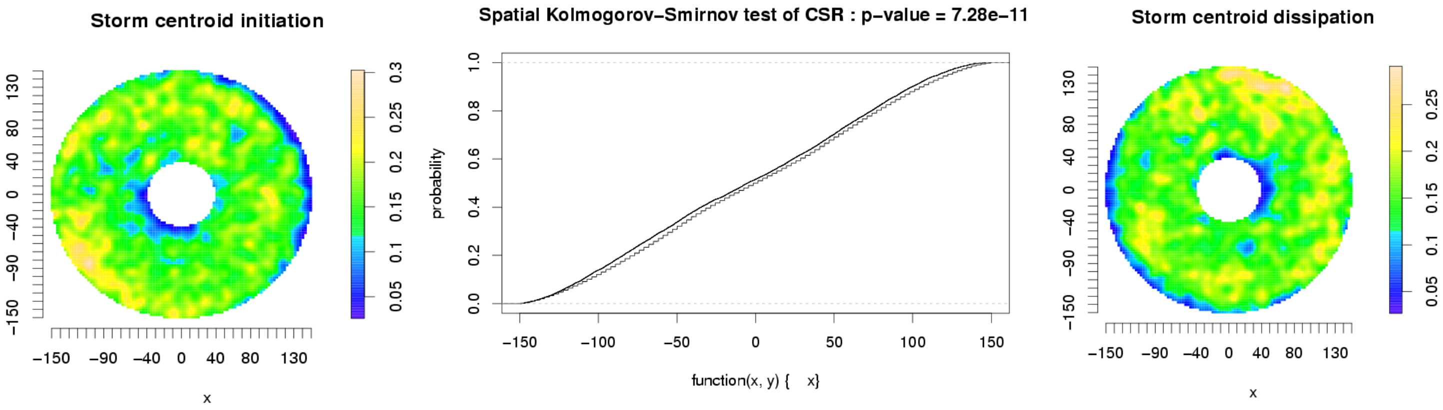

Fig. 9 Spatial density of the storm initiation and dissipation, empirical cumulative distribution of the x coordinate compared with the theoretical cumulative distribution of a Poisson process (test for complete spatial randomness).

5. Conclusion

A 5-year analysis of convective storm characteristics based on reflectivity measurements from the Wideumont radar has been performed. The cell tracker TITAN has been used to identify and track convective cells across successive radar images. The sensitivity of the identification and tracking algorithm to the value of some parameters has been investigated on several convective episodes. Some bad behaviors of the algorithm have been highlighted which led to the choice of appropriate parameters to avoid them. The storm tracks generated by TITAN have been selected against several criteria to ensure the good quality and representativeness of the data set. Statistical methods have then been used to analyse about 10000 valid storm tracks. It appears that convective storms occur mainly from May to September and mostly in the afternoon. The storms are mostly short lived with a duration frequency positively skewed and a median equal to 30 min. Storm motion are also consistent with the wind speed statistics observed during convective events. The maximum echotop 36dBz is positively skew. Storm tracks maximum volume and mean reflectivity follow a log-normal distribution. Storms occurring from June to Augustus tend to have a larger volume and a higher reflectivity. Radar range effect can be seen on the spatial variations of the expected value of instantaneous storm properties over the domain. The possible correlations between pairs of variables have been investigated. A positive linear correlation have been found between storm duration and maximum volume or precipitation area. Nevertheless there is large part of the variance in the storm duration which is not explain by this simple relation. The point processes associated with the convective storm initiation and dissipation have been analysed. A statistical test suggests that these processes are spatially random.

Further developments can be considered to improve this analysis. The limitations of the the radar reflectivity measurements have been highlighted. Besides the 5-min time resolution, the biggest source of uncertainty is the scanning strategy with limited volume coverage. Using the additional second scan should be considered. Ground clutter should be more carefully removed before using TITAN to avoid the need of filtering tracks with the risk of deleting valid tracks. The statistical analysis of the storm tracks should be improved. Of particular interest is the analysis of the temporal evolution of the instantaneous storm properties. Several models of storm evolution can be tested against the data. The use of a second radar in the vicinity would also be useful to validate the results obtained here, especially for the spatial statistics. Radar artifacts will be more easily identified. The use of convective storm variables derived from other observation systems should also provide additional information. One can think about lightning information, cloud characteristics observations by satellite, water vapor derived from GPS measurements or different variables derived from NWP models.

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