CLUSTER ANALYSIS OF THUNDERSTORMS DEVELOPMENT IN RELATION TO SYNOPTIC PATTERNS

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1. INTRODUCTION

Development of new operative technical means of lightning detection and location is aimed to the improvement of the quality of information provided to different customers on hazardous convective weather on different space-temporal scales. It is known [1] that use of lightning electromagnetic radiation in very high and ultra-high frequency bands associated practically with all types of intra-cloud (IC) and cloud-to-ground (CG) lightning discharge processes (total lightning) could provide a reliable information to a rapidly developing and becoming hazardous storms and is a good base for creation and modification of devices and systems for storm onset early detection, reliable warnings of lightning ground stroke hazard, damaging thunderstorm winds, strong rain falls, hail, tornadoes and so on. High technical possibilities of VHF systems lead to the necessity of changing traditional approaches in analysis of lightning phenomena, elaboration of methods and algorithms of registered data grouping in clusters corresponding to such physical objects as single storm cells, storm clouds, meso-scale storm complexes, creation of new methods of storm activity real-time tracking, depicting and storage, their adaptation for different fields of applications (hazardous storm areas identification for aviation, to early identification of high precipitation potential cells for hydrology; to provide flash flood nowcasting and so on). The decision of these problems can be realized by using of different methods and algorithms of objects classification considered as a special case of statistical analysis theory. Preliminary results of some of these methods' application to the analysis of real storm situations have been reported in [2]. Here we will give the results of analysis of space-temporal distributions of storm activity (build with use of special procedures of thunderstorms clusterization) in relation to different kinds of synoptic conditions.

2. SPACE-TEMPORAL CLUSTERIZATION OF THUNDERSTORMS

Storm spatial distributions can be presented, accumulated, stored and depicted in various forms. Alongside with traditional ways of storm-activity presentation as either sets of points determining the positions of individual lightning flashes or the density of the number of flashes calculated per some given area, in [2] it has been suggested a method of lightning location data storage and imaging based on the exploitation of some clusterization procedure using the features of several well-known algorithms discussed in [3]. The first discharge of each lightning flash is the object under study and is characterized by two Cartesian coordinates (characterizing its position on the horizontal plane) and by occurrence time. The cluster is considered as a circle of radius r. Its value can vary around its initial value r_0 in some range (from r_{min} to r_{max}) during the clustering process. In the first stage of clusterization procedure the initial data set is formed with objects (lightning flash locations) accumulated during a certain specified initial time interval T_b. With value of it equal to 5 min, which was assumed in the further estimations, the number of objects in the initial set was, on average, several tens of lightning flashes. The number of clusters was a priori unknown. The modified algorithm FOREL [3] was used for the initial division and for estimation of the source number of clusters.

At the next stage of the clustering procedure, which is similar to the ISODATA (Iterative Self-Organizing Data-Analysis Technique) one [3], a new subset of objects was formed by adding to the source data set the location data recorded during additional time interval δT. At the same time a certain part of the data recorded during the similar interval at the initial stage of their accumulation is excluded. Two additional procedures: cluster combination and separation, — are included in the clustering algorithm. The first procedure combines two clusters if the distance between their centers is less than the threshold of inter–cluster discrepancy Θ (the minimum admissible distance between cluster centers). The separation procedure divides the cluster into two ones if the current value of the cluster radius exceeds r_{max}. The formed cluster is depicted if the number of objects in a cluster accumulated during its full lifetime was greater than some minimum admissible value n_{min}.

So all the procedures mentioned above involve several constant parameters and parameters controlled during the clustering process. The constant parameters used in subsequent estimations are: $r_0 = r_{min}$ = 10 km, r_{max} = 30 km, T_b = 5 min, δT = 2 min, n_{min} = 8. Cluster's radius r belongs to the controlled parameters and is corrected according to the estimation of the current spread of experimental points inside cluster.

By studying the current clustering stage (number of clusters is assumed to be known according to the data obtained at the preceding stages) one can estimate the current state of storm activity (locations of individual clusters, intra–cluster scattering, and current average values of the parameters of electromagnetic radiation of lightning flashes and its imaging on monitor screen). The estimated parameters of lightning flashes include the duration *D*, extension *E*, ratio *R* of the number of intra-cloud flashes to the number of flashes with CG discharges, and multiplicity *M* (the number of the CG discharges in a flash).

Figure 1 illustrates the current image of storm activity registered during 5-minutes time interval after 16h 45min (local time) on 10-06-96 given as set of points characterizing positions of single lightning flashes (their first pulses) and clusters calculated for above mentioned parameters and marked as circles of calculated radii. For the subsequent imaging of clusters on the display's screen is used position of centers of formed circumferences. As example the image of clusters centers tracks (CCTs) given in Figure 2 characterize space-temporal distribution of storm activity on 10-06-96 in diurnal cycle of its development (the increment of circles radii given in this picture is 50km) .

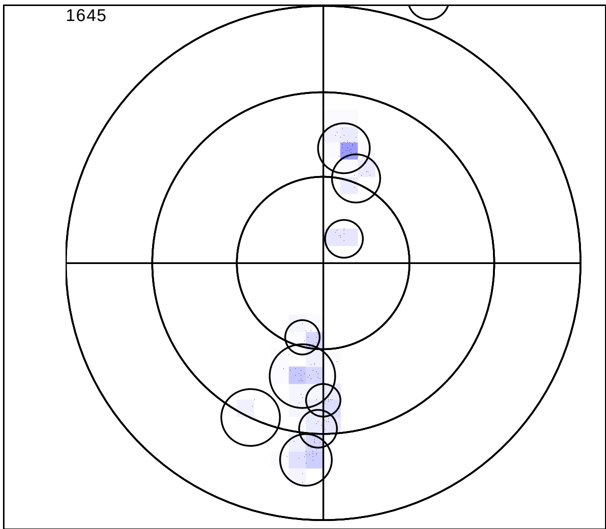

Figure1. The current space distribution of storm activity registered during 5-minute time interval after 16:45 LT on 10-06-95. Points show positions of single lightning flashes; circles characterize position of separate clusters.

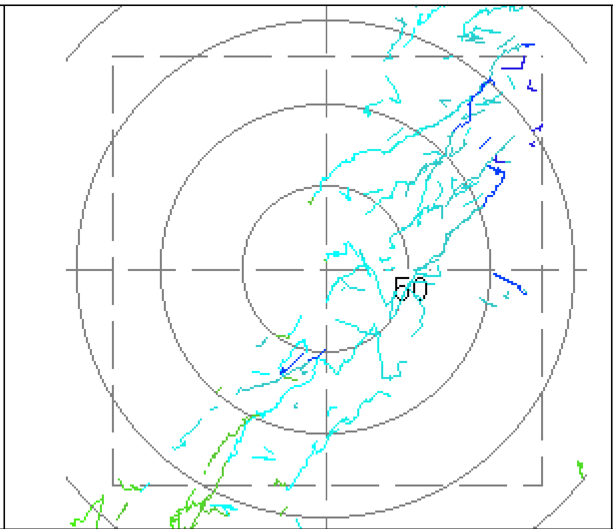

Figure 2. Space-temporal distribution of storm activity on 10-06-96 registered in diurnal cycle of its development and depicted by the cluster centers tracks.

The spatial distribution of the storm activity after the completion of the clusterization procedure can be depicted in two forms: as lightning flash density per some square unit or as a set of Cluster Center Tracks (CCTs), which enable to characterize the storm activity at the thunderstorm cell scale all along of its lifecycle. The last form of storm activity presentation is preferable by the reasons of its higher space-temporal resolution, the possibility to identify the electromagnetic radiation of lightning flashes with separated clusters and to control temporal variations of its parameters with the purpose of the determination of current state of the cloud's complex and of the short-term forecasting of its future development. One can change the scale of this representation by varying the initial cluster radius.

3. REGISTRATION DATA AND DATA ANALYSIS

Testing of the described clusterization algorithm and its application to analysis of storms images based on the CCTs presentations in relation to synoptic conditions has been made on the data sets obtained by SAFIR location system during the continuous observation of storm activity in France in July and August 1995 and several storm days registered in 1996 (they are interesting because of the possibility of comparison of the clusterization results with storm radar images). During specified observation period in 1995 more than 130,000 lightning flashes have been detected and located. Figure 3 illustrates the distribution of storm active days fixed during this observation period. 29 days with different types of storm activity and above 130 thousand lightning flashes were recorded. One can select eight storm active groups (including from one to five adjacent storm days). It follows from the results of the experimental data processing that the peak intensity of recorded lightning flashes may exceed 100 pulses per minute in case of the most active storms. In most cases (22 storm days) the average diurnal values of this peak intensity exceeded one pulse per minute; these values ranged from one to ten pulses per minute for 8 storm days and exceeded 10 pulses per minute for the other 14 storm days.

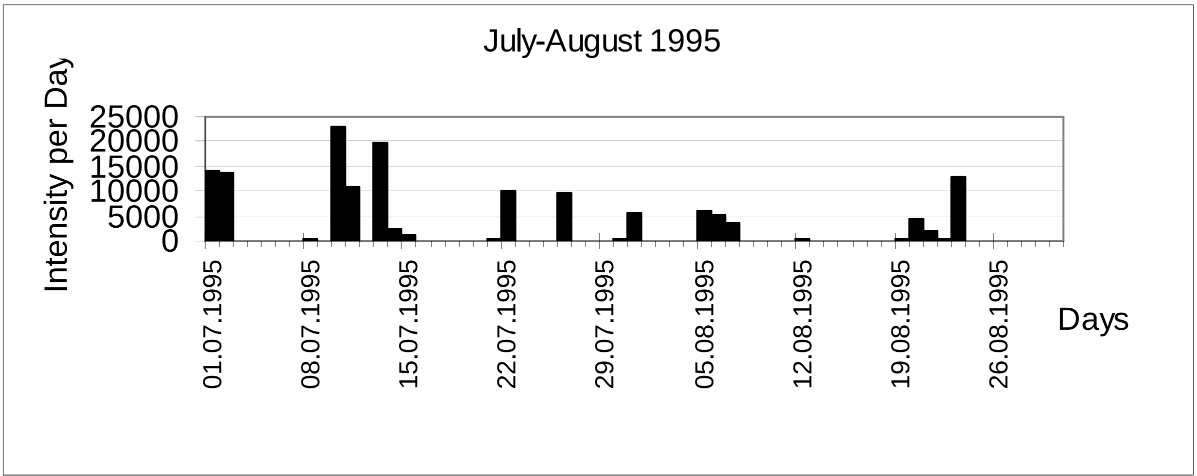

Figure 3. Distribution of storm active days during July-August 1995.

The processed data on the storm activity that were obtained during the aforementioned two-month period of continuous observation show that the choice of parameter r_0 in the limits 10-15 km and n_{min} in the range of 8-16 flashes ensured the reference of given clusters either to single isolated storm cells or to the sequence of cells successively developing and replacing each other in the process of storm evolution.

Types of clusters, their space distribution characterizing a general image of storm activity, features of their temporal evolution are determined by many factors such as synoptic conditions, relief and so on. Among them synoptic conditions are of a vital importance.

As it follows from the analysis of space-temporal behavior of CCTs one can distinguish three different types of thunderstorms:

1) *Multi-cells storms* with several long (sometimes up to one hundred and more kilometers) and long-living (up to one-two hours) *regulate clusters* formed by successively developing cells. Usually one can observe several simultaneously developing clusters practically parallel moving with great velocity (up to 50 km/h and more) in one direction. Their CCTs are separated by distances of 20-30 km and usually form space images of storm activity as rather elongated (200-300 km) strips. Groups of such a kind clusters can arise simultaneously or successively in different places of this strip (at the distances 50-70 km between groups) and move in one direction. In most cases the direction of CCTs propagation practically coincides with the direction of leading air jet movement but deviates from the direction of storm activity spreading to angles up to 90^0. Most clusters of this storm type are formed by several successively developing convective cells. One can draw attention to some interesting feature of cluster's development: as a rule a new cell arose on the right flank of the cloud (relatively the

direction of its propagation) at the distance 3-5 km from the existing cell. During 10-15 min they can be jointly electrically active, after that the old cell is disappeared, and the next new cell arose on a right side of the preceding one. On this phase of cluster development the value of its radius estimated from RMS of scattering points can be significantly increased (up to 20-25 km).

2) *Multi-cells storms with irregular clusters*. In many details they are similar to the preceding type but CCTs are shorter, direction of their propagation can significantly differ from each other, their forms can significantly differ from the straight line (over hills one can observe half-circular tracks). Locations of arising clusters are unpredictable and their movement is not so regulate as for storms of the first type. This type of storms is more typical for fronts of occlusion.

3) *Single-cells storms* consisting of several convective cloud complexes without pronounced direction of propagation and characterizing by isolated non-interacted slow moving short clusters accidentally arising in space and time. They arise independently from other clusters (cells) and are characterized by very fast (several minutes) growth of lightning flash rate. The places of birth of these clusters are practically unpredictable, and can be spread over a large area preliminary over hills and hill slopes. As a rule the direction of general storm activity development is unpredictable too.

The typical samples of daily CCTs images of the *first* and the *third* types of storms registered accordingly on 10-06-96 and 31-07-95 are given in Figure 4. The upper images in this figure illustrates the CCTs images formed during daily evolution of storm activity, the lower curves – the daily variations of lightning flash parameters averaging on 4-minutes time intervals: their intensity (number of lightning flashes both of IC and CG types per minute), duration and extension.

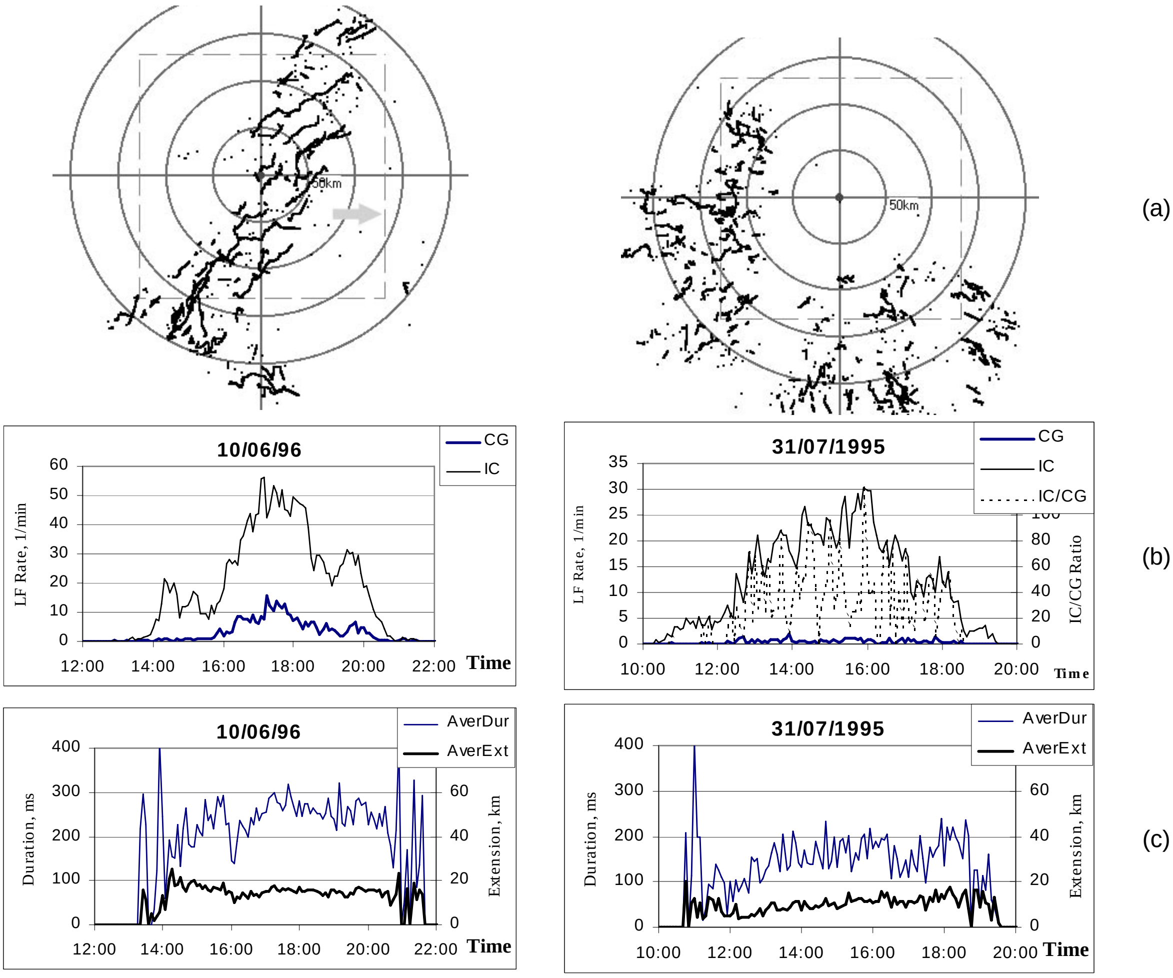

Figure 4. Typical samples of storm activity of the *first* type (on l0-06-96, left column) and the *third* type (on 31-07-95, right column): space images of CCTs formed during storm day – (a), temporal variations of lightning flash (LF) rate (both IC and CG types) – (b), LF duration and extension – (c).

The more detailed description of the dynamic features of considered storm of frontal type is illustrated in Figure 5.

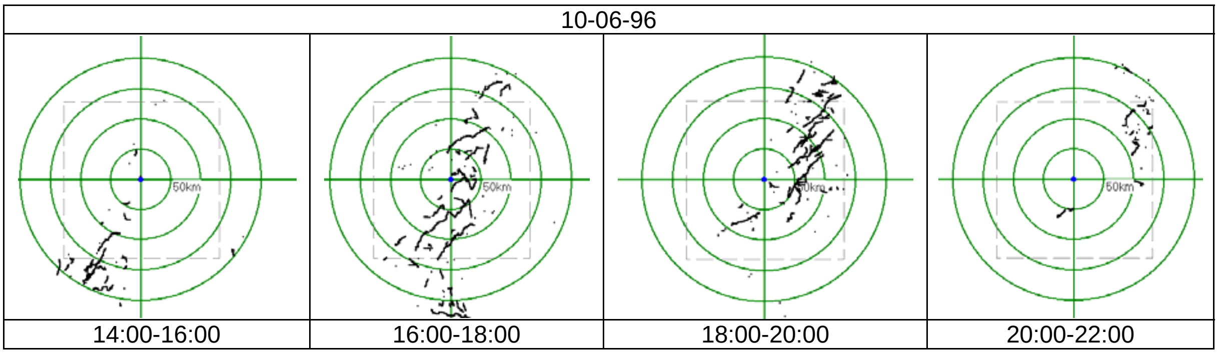

Figure 5. Dynamic pictures of CCTs images of frontal storm on 10-06-96 formed during adjacent two hours intervals in process of its continuous daily registration.

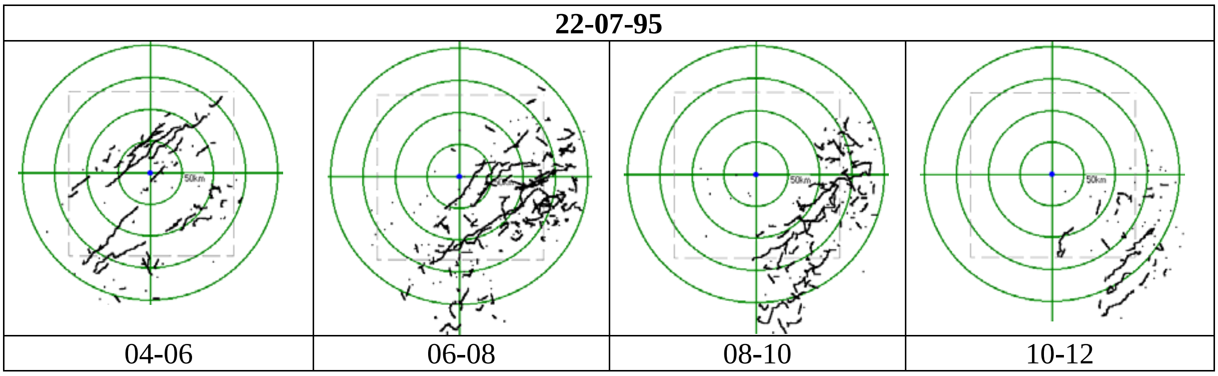

Figure 6. Dynamic pictures of CCTs images of frontal storm on 22-07-95 formed during adjacent two hours intervals in process of its continuous registration.

Character of the weather on 10-06-95 was determined by a south periphery of the cold front of the high cyclone fast crossing the observed area in the east direction. As it follows from the dynamic CCTs pictures of storm activity of this day and radar reflectivity images (renewed with 5-minutes time increment) its development began at 13:30 LT on the south–west edge of the region (at the distance about 250 km from the central observation site) as two single convective clouds. Later (after 17:00 LT) several storm complexes arose along the narrow (about 50 km) but rather long (up to 250 km) strip oriented in north–north–east direction (coinciding with the direction of the leading air jet).

The direction of the general storm activity development is exactly east, velocity of its front spreading is about 35 km/h. Clusters depicted by their CCTs propagate with greater velocity (up to 50 km/h) in the north–east direction (about 40-45^{o} on the left of the direction of storm activity motion). On the beginning stage of storm complex development one can observe several small clouds with fast growing short-living (20-25 minutes) single cells. As it is seen from the curves of lightning flashes rate given in Figure 4, in this stage (during about one an hour) the IC lightning flashes significantly predominated over CG ones (IC/CG ratio was more than 10). The duration of lightning flashes has been twice increased in average to the end of this two-hours time interval (up to 300 milliseconds) but this increasing was non-monotone. Later along with single cell clouds vaster multi-cell cloud complexes have been developed. Process of their evolution was determined by the arising of two-three electrically active cloud cells and was characterized by some pronounced feature: as a rule a new cell has arose on the right flank of the cloud (relatively the direction of its propagation) at the distance of 3-5 km from the existing cell. During 10-15 minutes they were jointly electrically active, after that the old cell disappeared. In the mature stage of the cloud system development the number of simultaneously living cells in one multi-cell cloud system can attain 3. In this time period the cluster's radius (estimated from the root-mean square value of the scattering of lightning flash locations against the cluster's center) increased from the initial value of 10 km up to 20-25 km. IC/CG ratio on this stage has decreased to 4-5 (against of 10 and more on the beginning stage). The increasing of the radius was accompanied by the increasing of the lightning flash rate and precipitation intensity. Another kind of frontal storm forming is illustrated in Figure 6.

Examined area on 22-07-95 was situated in a long “tail” of a deep depression elongated in north-west direction and forced out by a high anticyclone fast moving from the west. Very intensive storm activity began at night in central part of region. Clusters arise practically simultaneously in different places of a vast long strip and move with the great velocity (up to 55 km/h) in the north-west direction (practically across the direction of storm activity spreading). Most of them are formed as very long (up to 200km) tracks intermittent with more short and twisted ones over the mountain south-west part of region. To the early morning the worm unstable air masses were forced out by a cold ones and storm activity was fully stopped to the midday.

The right column of preceding Figure 4 illustrates space-temporal characteristics of the storm activity on 31-07-95 typical for the convective storms of the *third type*. The weather of this day was determined by the small–gradient low–pressure fields. Progression in the south direction of altocumulus clouds appeared in the morning over Brittany and Norman hills has led after midday to the formation of unstable air masses and numerous sporadically arising spots of storm activity in the western and south parts (over northern slopes of Massive Central) of examined area. Not accompanying by precipitation storm activity has achieved its maximum to 16^h LT and after that began sharply decrease. Two minor maximums on the decaying slope of the lightning flash rate were caused by arising of several new storm-active spots in west and south–east parts of the region. Storm activity during all daily cycle of its development was characterized by the formation of short-living clusters, and significant predomination of IC lightning flashes over CG ones. IC/CG ratio was no less than 10 during all storm day and in some time intervals exceeded 100. Average lightning flash duration and extension were approximate twice less than for above-discussed storm type on 10-06-96. Directions of both general storm activity spreading and of separate clusters' propagation were practically unpredictable.

In real synoptic conditions the space-temporal CCTs pictures of storm activity usually are more complicated and can change their character not only from day to day but in the daily cycle of storm's development.

The patterns of daily space storms distributions based on CCTs representations, which reflect some other fine features of meteorological condition variations are given in Figures 7-8 for two groups of storm active periods.

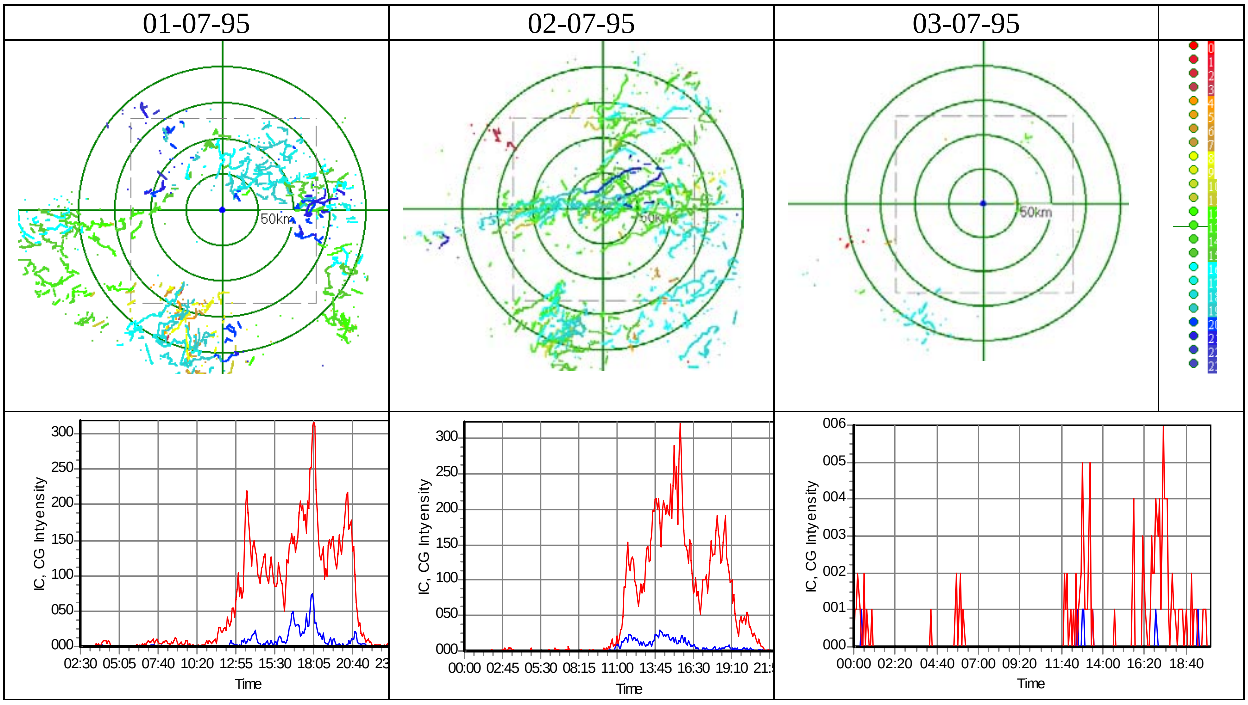

Figure 7. Space-temporal characteristics of storm activity on 01,02,03-07-95.

The first sequence of considering three-days storm activity on July 1995 has been started on 01-07-95. As it is follows from the synoptic charts the weather of these days was determined by an eroding cold front slowly moving from England to the north part of the examined area and by a high-altitude filling depression situated over Spain and moving to the south part of region in the north-east direction. Examined area was in a zone of weak-gradient field of relatively low pressure. Very weak storm activity with short living clusters characterized by low lightning flash rate (no more than 1 min^{-1}) one could observe in the night time and in the early morning (from 3^h to 9^h LT) as a local small spot in the south part of area. The sky over the most territory of France was small–cloudy in this period of time. There were observed only unstable altocumulus over the south part of Brittany. From 10^h the next phase of storm activity in this part of area as two narrow strips formed by short-leaving clusters LT began to develop. The slow spreading of the convective phenomena was westerly while the moving of single CCTs was in general almost opposite. To 14^h LT these strips have merged in one rather vast zone over the western part of Norman hills, storm activity attained its local daily maximum (with lightning flash rate about 40 min^{-1}). The direction of single clusters movement in this zone changed to the north and north–west. The above-mentioned features of storm clusters' behavior can be roughly explained by the features of the leading air jet fixing on the 700 hPa surface charts. This jet, north-directing in the costal western part of region, sharply turns from the seashore to the east direction.

As the solar heating increased (after midday) the unstable masses of wet air were spreading over the whole south part of the region. The storm activity in this period arose as several single local storm spots formed mainly over hills both in western and eastern parts of the region. It was characterized by the great value of IC/CG ratio (more than 10). Later (after 16^h LT) a storm activity has spread into the south-south-west part of area and to 18^h LT a vast zone of storm activity has arose in this part. CCTs became longer and regulate (oriented in north-east direction). The fraction of CG discharges significantly increased too in this time period (IC/CG ratio became less than 5 for most storm clusters). The lightning flash rate attained its absolute maximum (up to 85 min^{-1}). The next maximum of storm activity (45 min^{-1}) about 20^h30^m was caused by the formation of new separate storm spots in west and north–west parts of the region merged in one rather wide (70-100km) band oriented in south-east direction. It was characterized again by a rather short irregular clusters with small fraction of CG discharges. During the most time of development the storm was of the third convective type (with unpredictably arising clusters). Meteorological conditions of the next day 02-07-95 were in general identical to the preceding one. Examined region was in a zone of weak-gradient field of low pressure. But the geo–potential lines on 700 hPa chart have become more compressed and distinctly oriented in north–east direction. The velocity of the air jet was several times greater than in preceding day. A very weak dispersed storm activity was observed in early morning in the eastern part of area. After 11^h LT the mixture of wet warm air with cold air masses spreading from south–west formed along line of deep occlusion in the central part of area has let the arising of strong convection and intensive storm activity. Its development was accompanied by rather strong precipitation (the daily quality of precipitation fixing at single meteorological stations situated in this zone has attained 6-43 mm). The space CCT picture of the area with the most intensive storm activity is seen in Figure 7 as a long (more than 300 km) and a rather wide (about 50-100 km) band oriented west–easterly. It was formed by several successive waves of rather long CCTs arising practically simultaneously in different spots of its southern periphery and moving parallel to each other in the north–east direction with great velocity attaining the value of 55 km/h. The number of such a type clusters simultaneously existing in different time intervals achieved 5-7. There were formed also several other storm active spots with short-living clusters, which arose in different parts of area in far south and north of considered zone. As it is seen from Figure 7 the slope of the daily total lightning flash rate variations on 02-07-95 in main details repeats the features of one registered during preceding day. One can observe also another general feature of lightning flash parameters' variations – the fraction of CG lightning flashes was significantly decreased in last three-hour stage of storm system evolution (for both considered days the value of IC/CG ratio was more than 50).

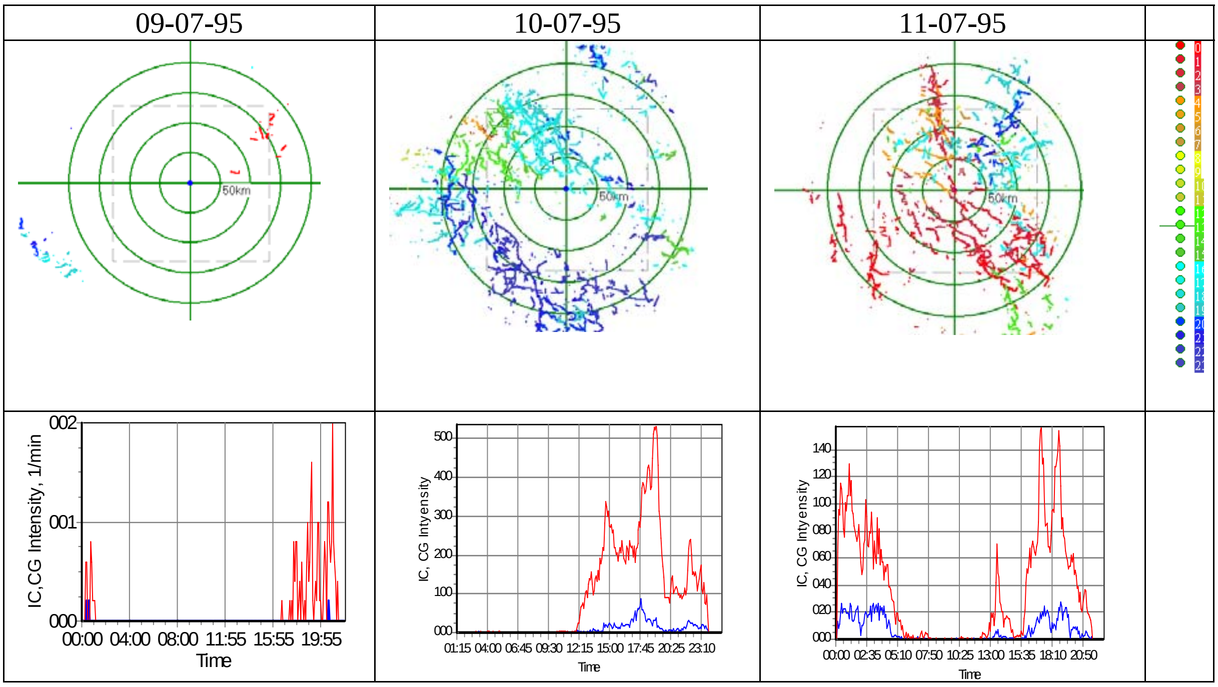

Figure 8. Space-temporal characteristics of storm activity on 09,10,11-07-95.

The next rather long thunderstorm period began on 09-07-95 and lasted up to 15-07-95 with daily break of storm activity on 12-07-95. In general the storm activity in these days was determined by the south–east periphery of the high-altitude slow-moving depression (cyclone) with coordinates of its center 55°N, 25°W. But during first three-day (9-11 of July) stage of this week's storm active period the influence of this cyclone was negligible, and the weather was determined by local centers of low pressure and short cold fronts spreading mainly in the north-east direction. A weak storm activity has been started at 17^h LT on 09-07-95 as a small local spot formed by short CCTs (and existed during three-hour time interval) in the south–west part of area. The weather of the next two days (see Figure 8) was determined by a weak-gradient field of the low pressure situated over the central part of France and in general was identical to one on 02-03 of July. Storm activity on 10-07-95 has resembled after 11^h LT in the west part of area over the northern slopes of Norman hills. Convective clouds of Cb, Cb_{inc} types slowly moved in north–east direction and were accompanied by a rather strong lightning activity with predomination of IC lightning flashes. It was influenced by the local orographical features of the country. To 18^h LT the space structure of a storm activity was formed by short CCTs concentrated in several rather narrow strips. After this time its space image has been formed by rather long CCTs arising practically simultaneously in different spots merged to 24^h LT in three bands separated by the moderate distances about 150 km and elongated in south-east direction. After midnight the character of storm activity development significantly changed. As it is seen from the space picture of storm activity on 11-07-95 (given in Figure 8 for 00-03 hour time interval) its more distinctive feature is a rather long (up to 150 km) narrow strip formed by short CCTs elongated in the north direction (perhaps along the line of a local occlusion). The lower semicircle of examined area was filled by rather long CCTs, which formed several strips oriented in north–west direction. Storm activity was of the *second type* and has been continuously lasted during night–time up to the 8^h LT of the next day morning (11-07-95). The new stage of storm activity in this day has resembled after 12^h30^m LT and has been lasted up to 21^h LT. It was mainly of the *third type* and not so intensive as one during preceding day.

After the daily break on 12-07-95 when the stormless weather in the region was determined by the weak-gradient pressure field the new cycle of storm activity has been started on 13-07-95 after 11^h30^m LT. It was caused by the local cold front fast moving in the east direction. In process of its passing through the area two narrow bands elongated in the south-north direction were formed by the CCTs simultaneously arising in different parts of these bands and propagating in the north-north-east direction. After 17^h LT an essential transition into a new phase of storm activity development started. It was caused by the inflow of air masses of the warm segment on the south-west periphery of the deep filling cyclone with center 52°N, 17°W accompanied by a sharp increasing of lightning flash rate (up to 50 min^{-1}). The space picture of storm activity was formed by very long CCTs successively arose along a wide band crossed the operational range of SAFIR system in the north–east direction. At the beginning of two-hour stage of this storm phase development the fraction of CG lightning flashes was very small (the average value of IC/CG ratio was greater than 50). After 19^h30^m LT the number of CG lightning flashes was sharply increased. The IC/CG ratio decreased to 3-4 (the lowest values for the examined area during all two-month observation period in 1995) practically for all long CCTs. Meanwhile, the front hypothetically propagated easterly, whereas the right flank of space image of storm activity was sharply limited by practically motionless line. The same zone was filled by storm clusters in the next day on 14-07-95. But this filling began at 12^h00^m LT on its left flank and then spread south–easterly with average velocity of about 20 km/h. The direction of CCTs propagation was north–easterly (as usually practically orthogonal to the direction of storm activity spreading).

The above-mentioned features of space-temporal storms distributions cannot be explained on the base of very rough synoptic information used in ordinary practice. In turn it is seen that such a kind storms images formed by CCTs could be used as a sensitive tool for the analysis of meteorological conditions in micro-synoptic scale.

4. CONCLUSION

The storm situations discussed in this research give some reasons to believe that the analysis of CCTs space-temporal distributions can give reliable information about the place and time of occurrence of convective events attributable to the organization of convective clouds into some convective complexes and systems. It provides weighty contribution to understanding of some fine details of such a type cloud system evolution in micro–synoptic scale and can be used as a good operative supplementation to routine meteorological observations. Clusterization makes it possible to relate the electromagnetic radiation of storms with separated clusters. In turn it provides a possibility (using correlation of its parameters with precipitation and stage of development of macro- and microstructure of clouds) to make the current state diagnosis of storm system, its hazardous level estimation and short-term forecasting of future development.

5. ACKNOWLEDGMENTS

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6. REFERENCES

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