

Organization and evolution of mesoscale convective systems using radar data: objective description. The “dominating thunderstorm” conception and its application to MCS climatology.

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1. Introduction

Mesoscale convective systems (MCS) typically develop in meso- α domain ~ 300 km of extension during $\sim 7-8$ hours changing their shape, size, precipitation rate, storm type, associated severe weather phenomena etc. A lot of comprehensive studies, commonly called as “classification” or “MCS climatology”, are devoted to generalization of radar precipitation patterns describing MCS organization through their life cycle. The importance of MCS climatology studies is unquestionable, looking on scientific impact of the only two comparative classifications: the initial formation of severe squall lines of [10] and the mature precipitation systems forms of [13]. Since these seminal works, many efforts were done to create diagnostic and prognostic practice connecting MCS category and their severe weather capacity. Various techniques were proposed to classify spatial structure of MCS and to attribute them a probability of hazardous phenomena (wind gusts, tornadoes, hail, heavy precipitation). We don't concentrate here on details of these approaches, dealing with image recognition or clustering problem, but point out to another critical problem limited practical utility of any MCS climatology. The problem is that the rigorous definition of spatio-temporal MCS stages is not exist. Really, when we pretend to use the MCS climatology as severe weather forecasting guidance during observation or to evaluate numerical modeling results, we need to determine the representative instance(es) of MCS life cycle when morphology of all observed and/or modeled systems can to be compare adequately.

The goals of the present study are: (1) to review shortly the historical routes of problem and how the conception of “dominating thunderstorms” resolves the question of representative instance; (2) the development of practical method leading to objective description of MCS organization; and (3) construction of MCS climatology permitted the use of derived climatological properties as evaluating tool in severe weather forecasting and numerical simulation. In order to illustrate the main steps of developed methods (2) and construction of preliminary MCS climatology (3), we use radar observation in Central Russian region, where a diversity of mesoscale organization was observed.

1. Objective description of MCS using radar data

1.1 Routs of problem

In spite of the fact that today nobody consider the mesoscale convective systems as indefinite entity with intermediate time – space scales situated between cyclones and individual clouds / convective cells, several questions regarded to

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recognition of MCSs are still remaine. A lot of questions can be performed as the branches of one synthetic tree formulated as: “What does “mesoscale organization” means?” The “routs” of this tree connect us with earliest radar observations when i) the cellular structure of individual thunderstorm was discovered [9] and ii) it became evident that synoptic scale cloud systems are the combination of at least 3 hierarchically interacted scales of vertical motions, associated on radar PPI with cells, small and large mesoscale precipitation area [8]. It was evidenced also that all of mesoscale precipitating systems exhibit well-defined life-cycle associated with their elements appearance and decaying. Obviously, if anyone resolves to respond about “organization” of pre-selected mesoscale system he has to describe the evolution of system during entire life cycle, including spatial and temporal interaction between sub-systems, and how this system reacts to external forcing of up-scale system or another concurrent system. And is it not so! It’s also important to find some criteria that supports the decision to qualify the organization our system both as a “unique” and as “a similar” to organization of the other one.

Understanding the complexity of *organization* description, let’s put more simple question: “Whether exist any plausible way to distinguish the scales of processes that govern MCS evolution from external forcing or internal interactions?” Generally, the MCS acronym is used to describe a diversity of thunderstorm ensemble forms which has, as is supposing, an interdependent evolution at least in some period of their life. For example, consider the well-known definition of MCS as “a cloud system that occurs in connection with an ensemble of thunderstorms and produces a contiguous precipitation area ~ 100 km or more in horizontal scale in at least one direction” [11]. In this definition the “extent of contiguous precipitation area” is the explicit feature that permit not only to demonstrate the size of ensemble at least 3-4 times larger than storms ~25-30 km embedded within, but to qualify the organization of MCS ensemble as a process when several thunderstorms occurred very closely both in space and in time.

Evidently, *size criteria* is one of a “plausible way” to delineate MCS from storm-scale interactions, but not to limit the upper MCS scale or MCS organization. For this propose we need to combine this size criteria with several other *natural thresholds* which can be applied for all type of convective systems, and demonstrate some useful system properties. For example, radar reflectivity, echo top height are the natural *severity* criteria that separate almost of convective from stratiform precipitation (~40 dBZ) and severe MCS (~55dBZ) from moderate convection.

An experience of application of size, severity thresholds and explicit MCS cinematic to construct regional MCS climatology will be described in next section. Purposely, we provide shortest description, as it is possible, of MCS referred as squall lines.

1.2 An example of regional climatology based on radar observation

Conventionally, the moment when convective system meet the *selected size criteria* can be adopted as representative reference instance in MCS life cycle.

When reference instance is introduced in life cycle of MCS, as we look in definition of mesoscale convective complex [15], we can clarify transition between stages and, consequently, can produce comparative classification and climatology.

Thus on the basis of size criteria, life cycle of severe squall lines in Rio Grande do Sul state (extreme Southern of Brazil) can be divided to the following three distinct stages [2,3,4]. During the first *formative* stage, growing and merging groups of initially isolated convective cells and small thunderstorms tend to form “continuous convective line”, the “solid line” with extension of radar reflectivity zone $Z > 40$ dBZ more than 50 km; in a second, *mature* stage this “solid line” is continually sustained / grown due to appearance of new cells in along line direction (i.e. parallel propagation). Finally convective activity in “solid line” is ceased, and MCS enter in a third, *decaying* stage characterized by reasonably slow disappearance of pos-convective stratiform precipitation. Although, organization of selected southern squall line is not very different from boreal lines, some methodological remarks are useful. The remarks are associated with possible steps of classification procedure: (i) precipitation patterns preceded to line formation; (ii) precipitation patterns defined mature line morphology; (iii) contribution of internal storm-scale interaction and external forcing to line organization.

(i) Frequently observed, that the initial distribution of thunderstorms preceding to mature linear stage is characterized as linear or more complex [Bluestain and Jain, 1985, Blanchard, 1990, Jirac et all, 2003]. Introducing “solid line”, as measure, we observe that preference mode of initial formation is “buck-building” segued by «broken areal» with predominance of linear storms.

(ii) Four types of mature MCS morphology were observed in respect to passive translation (i.e. ordinary cell advection): leading and trailing convective line with narrow band of pos-convective stratiform rains along of line axis and convective lines accompanied by trailing or leading stratiform precipitation. It is observed that all line types demonstrate visible asymmetry between convective and stratiform regions just after forming and more pronounced trough latest mature stage.

(iii) All types of MCS organization are the combined result of up-scale forced velocity of passive translation and thunderstorm-scale propagation. As far as, multicells or supercells, living in extreme cases 1,5-2 hours, solely can't create long lived solid line, at least one thunderstorm must to arise hourly at line edge headland to maintain “solid line” structure. In the other words, the continuous parallel propagation about of 30 km per 1 hour (~ 10 m/s) or more is expected in mature line. The values of line normal and parallel propagation is the crucial aspect of width and length of stratiform region, and in combination these values determinate MCS type and MCS asymmetry [2,3]. Thus, the trailing or leading stratiform region will be observed in mature squall line only if the mean value of line normal propagation is exceed the mean stratiform cloud dissipation by 3 m/s.

Although, the squall line classification procedure can be modified, but steps described in present section, probably, are most common: select of MCS by severity and hierarchy (size) criteria, compare structures of all MCS in one unique instance (e.g. when object meet any criteria) by more or less objective way (e.g. as

we determine leading or trailing convection in respect to translation) and describe the influence of external and internal component to MCS evolution.

2. Application of “dominating thunderstorm” conception to MCS climatology

As we demonstrate above, the determination of reference instance as a first time of solid line appearance, is a major key to objective and practical climatology of squall lines. It is clear that for more ample MCS climatology we need another reference. In next section we demonstrate how the concept of “dominating thunderstorms” resolves the problem of representative instance.

2.1. *Representative instance is associated with dominating storms.* As depicts observation of MCS life cycle [1,5,6] both squall lines and MCS with more complex morphology, demonstrate so-called MCS auto-organization. It means the quasi-periodically striking of intense dominating thunderstorms occurred with ~1 hour one after other, and 2-3 large meso- β ensembles, compounded by 2-4 dominant and subdominant thunderstorms, that define entire convective activity of order 8-10 hours (see Figure1).

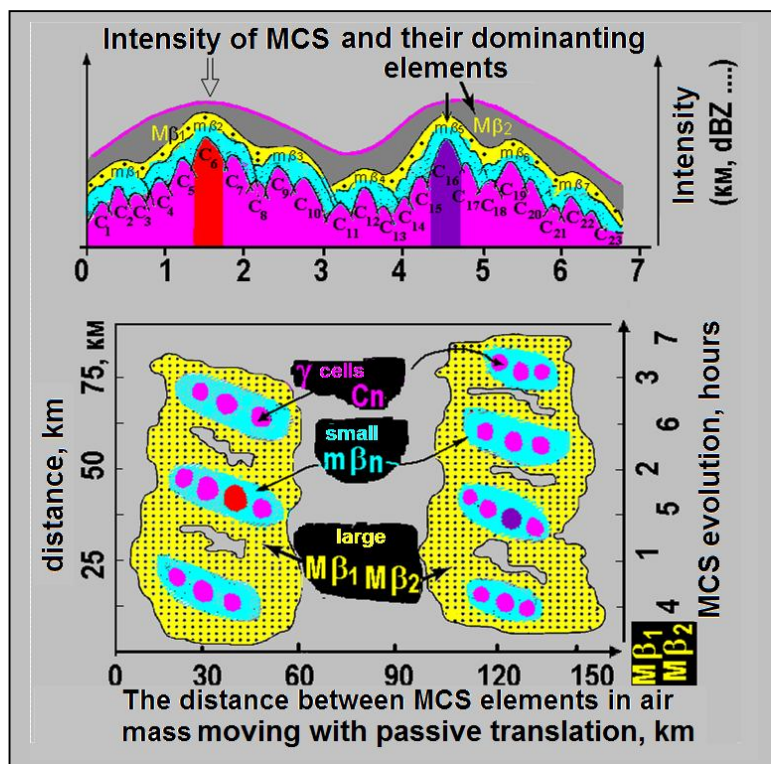


Figure 1. Life-cycle of MCS described in terms of their dominating elements. Some intense cells (pink) combine dominating multi-supercell thunderstorms (blue) – the storms with cells of major intensity (red and purple) in respect to other subdominant thunderstorms. Groups of dominating severe thunderstorms compose large meso- β ensembles dominating (yellow). The oscillating convective activity is associated with quasi-periodic occurrence of dominating elements. Occurrence of cells, storms and ensembles lead to ~0, 25, 1-hour and 3-hour oscillation of MCS intensity [adapted from 6].

Commonly, severe dominating thunderstorms are linear or bowed shape and, as we demonstrate with moving reference composite analysis techniques, its appeared along the some invisible axis translated by mean wind (i.e. cell’s advection vector). Someone can speculate that MCS with this ulterior axis can be considered as squall line cousins with less profound external forcing / more evident self-organization.

Evidently, using temporal sequence of dominating thunderstorms radar parameters (e.g. reflectivity maxima or radar echo tops) we can determine some interval around of the moment when dominating thunderstorm of maximal intensity is observed. E.g. this interval is depicted by red colour on fig.1. That

unique period of system's life, so-called maximal intensity stage, can be found during life cycle of any mesoscale system independently its origin, scale and severity. Thus, only a quality of radar data sample deputed to analysis may restrict the objective classification possibility. For example, if the resolution of radar data not permite to distinguish two cells with closest reflectivity we can observe "second" maximal stage (purple on fig.1)

As an example of developed methodology, in next section, it is constructed a MCS climatology for Central Russian region. Various possible applications of MCS climatology in forecasting are described also.

2.2 The objective classification and it's using as object oriented forecasting tool

Design of semi-automatic classification procedure for radar derived MCS climatology includes five main phases:

1. Expert estimation of sample representativeness
2. Identifying life cycle maxima of individual systems
3. Description of individual MCS morphology and combination the unique patterns to categories
4. Obtaning MCS properties and construction of their climatological cumulative distribution function (CDF) quantiles
5. Membership determination of observed and modeled MCS

In sections a)-d) we present comments to these phases.

a) *Expert estimation of sample representativeness.* Looking to the sequence of

radar images with 10 min time step and resolution ~2 km, anyone who pretended to classify MCS or to compare observation and numerical modeling results has to answer some basic questions about quality of dataset which will be used to objective description of MCS properties. First, a climatological dataset has to describe MCS associated with all possible seasonal weather

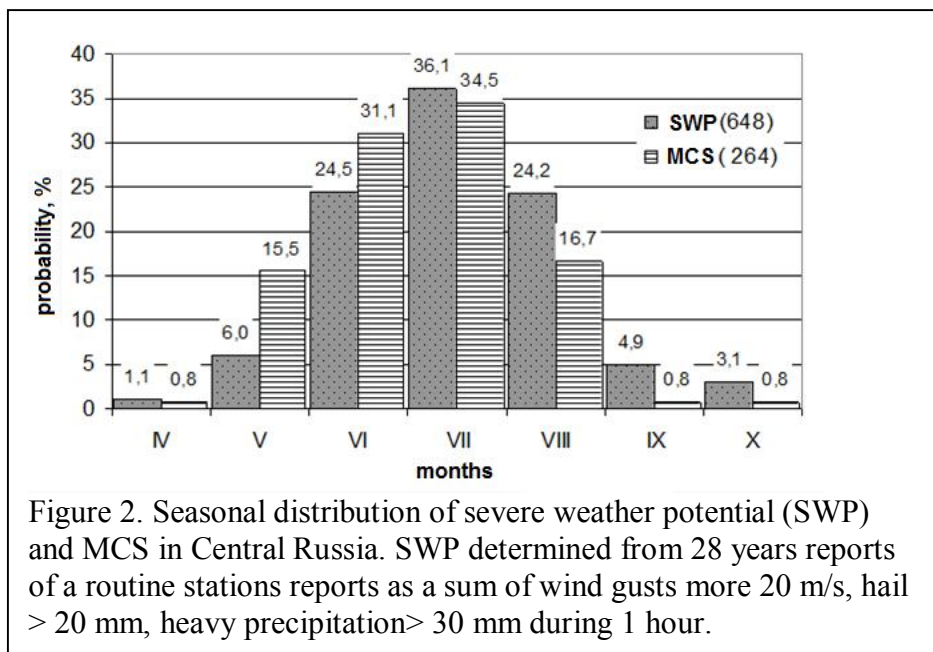


Figure 2. Seasonal distribution of severe weather potential (SWP) and MCS in Central Russia. SWP determined from 28 years reports of a routine stations reports as a sum of wind gusts more 20 m/s, hail > 20 mm, heavy precipitation > 30 mm during 1 hour.

types. Relative frequency of MCS types, e.g. squall lines vs. non-squall clusters, severe storms events vs. moderate ones represents inter-annual variability (e.g. in association with ENSO like phenomena). So, to create MCS climatology it's need a sample at least five-year continuous period. Some tests to prove the consistence of this sample to severe event frequency may be proposed. The easiest is to compare a seasonal MCS frequency with as long as possible stations records of hail, wind gusts, heavy precipitation events, referred as SWP (severe weather

phenomena) in Figure 2. The distribution of 264 MCS observations selected to classification [7] is slightly differ from severe weather distribution. But separate counting hazardous events reveals that our sample is more close reflects wind gusts seasonal frequency and possibly underestimated heavy precipitation events during last summer.

b) Identifying life cycle maxima of individual systems. Temporal variations of

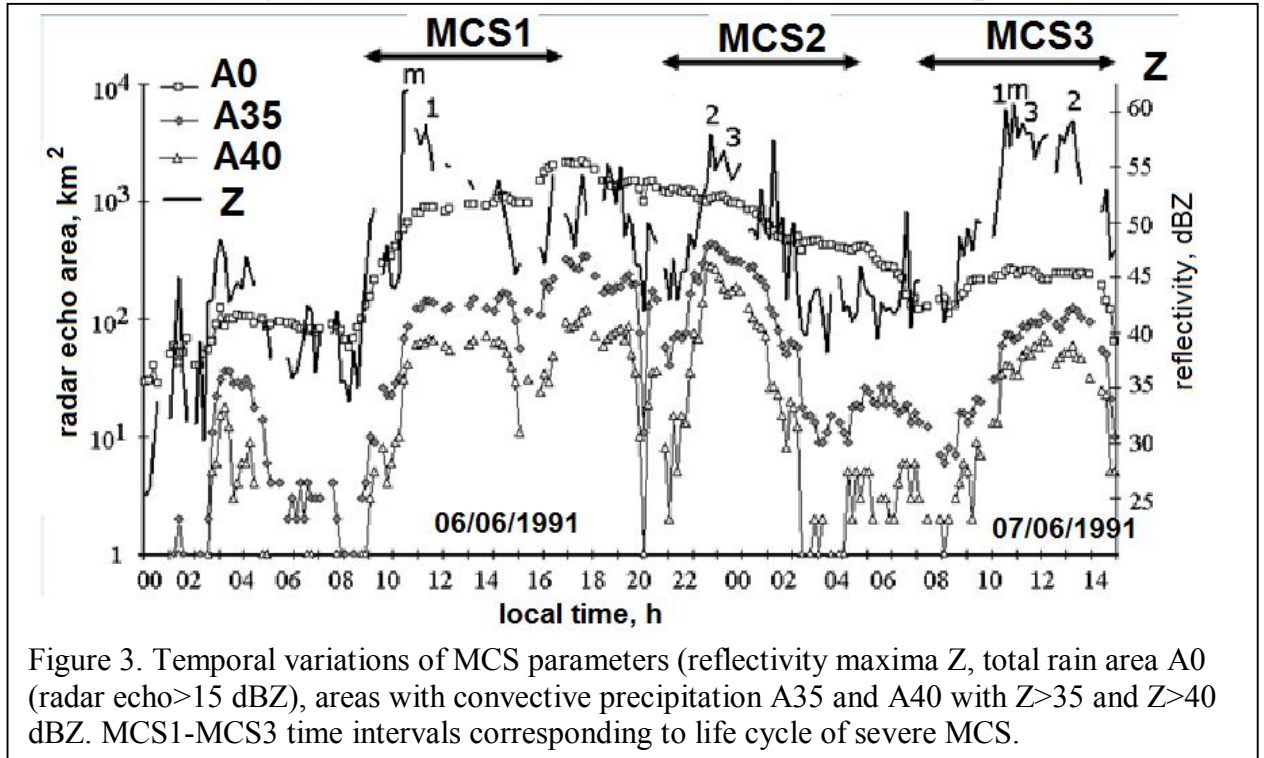
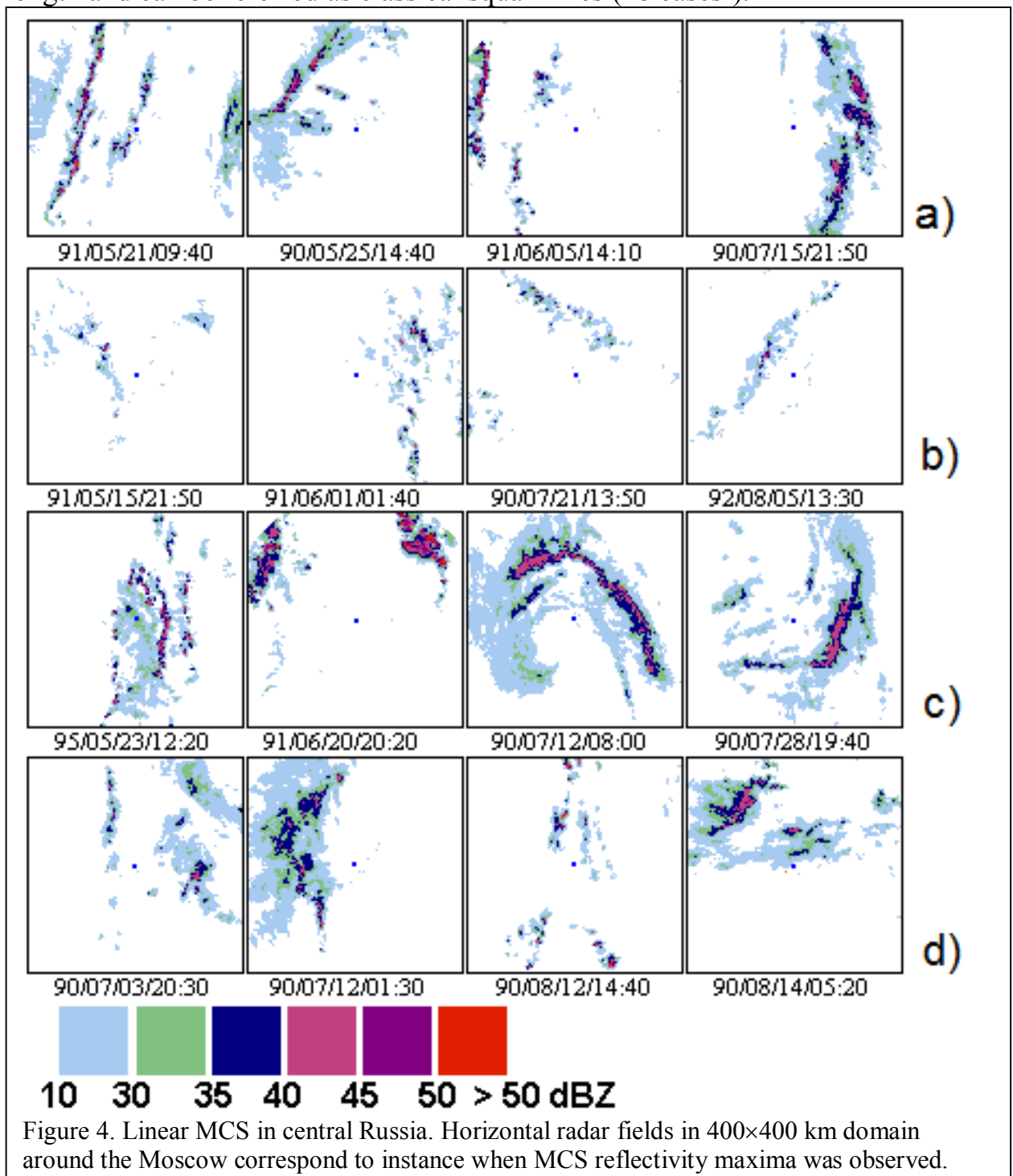


Figure 3. Temporal variations of MCS parameters (reflectivity maxima Z, total rain area A0 (radar echo > 15 dBZ), areas with convective precipitation A35 and A40 with Z > 35 and Z > 40 dBZ. MCS1-MCS3 time intervals corresponding to life cycle of severe MCS.

MCS properties can be derived automatically from digital radar data using some simple software as it is demonstrated on figure 3. We can obtain reflectivity maxima in entire radar CAPPI or convective areas, echo top maxima and other parameters. The reference instance when MCS achieves Z maxima is easy obtained when the only one MCS is developed on the radar range, but sometimes we can observe the passage of 2-3 or more individual MCS during one day. For example, in the case on figure 3 during 24 hours we observed 3 severe MCS referred as MCS1, MCS2 and MCS3. What of MCS will be entered as «a case to study» to our sample? To preserve the selection from subjectivity just one system containing daily Z maxima (m, on Figure 3) is selected. All MCS properties will be described exactly for this life-cycle instance.

c) Description of individual MCS morphology and combination the unique patterns to categories. Various automatic techniques can be used to describe spatial organization of MCS, but for preliminary separation of about 300 images we use the notion of «gradual 2D/3D transition» from simplest linear patterns when the major pattern of MCS appeared as 2D structure (figure 4a) to more sharply and complex 3D cases (figure 4d). Linear systems in figure 4a appeared as

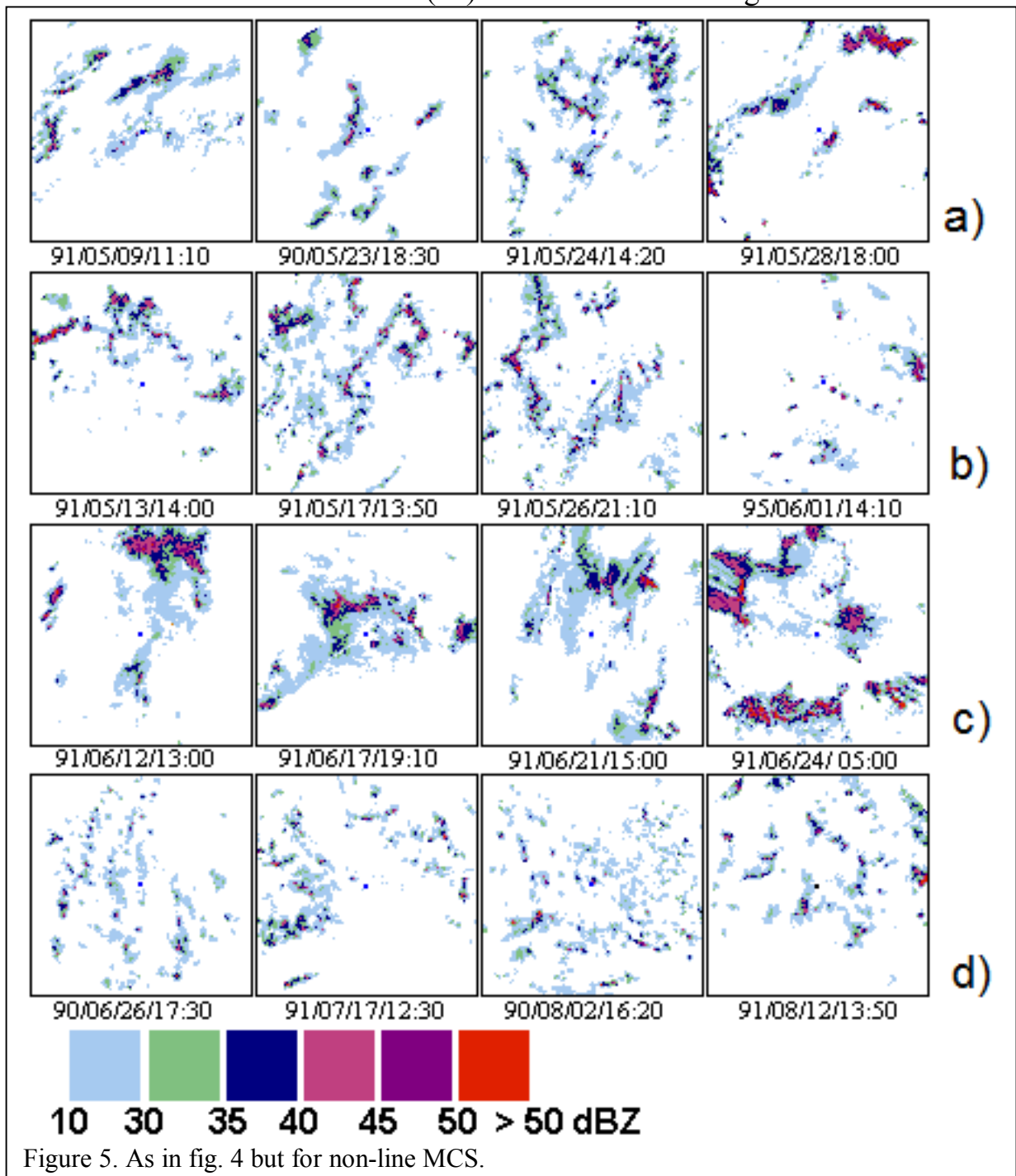
interrupted lines with solid segments of reflectivity of 40 dBZ of about 100 km length and can be referred as classical squall lines (18 cases²).



Linear MCSs on figure 4 b exhibite a mixture of linear and noses-like storms and can be referred as broken lines or segmented lines (40 cases). Linear MCSs on figure 4c are examples referred as “bowed” lines. Probably, the selection of curved lines in individual class organization is not strongly argued, because of smoothed arcs sometimes can be found in «classic lines» also (see last image on fig 4 a). But if we look on total sequence of images on figure 4 we can recognize

² The number of cases MCS demonstrated in this section is the fraction of sample of 216 MCS with fully digital CAPPI of one radar used for climate description. The data of another 48 MCS cases are more recent cases collected from network of 7 radar and using as testing sample for evaluation of numerical modeling.

that family of bowed lines forms around some imaging, but well defined «vortex center». As we look to “occluded lines” on figure 4 d we can see that this type of MCS is the combination of two or more lines with concave and convex arc, i.e. different opposite centers. Thus, occluded and bowed lines can be separated from classic and broken linear MCS as (34) lines with “central organization».



The principal aspect of 124 non-line MCSs, referred as complex of local storms, is the arrangement of ordinary cells into small bow segments ~30 km (figure 5). Frequently, this storms form “open meso- β -scale cells” structures, but most of these MCSs have “propagation axis” connecting major local storms, also. Indeed, moving from figure 5a, where severe and moderate thunderstorms aligned in one or 2-3 parallel bands, to figure 5 d, we continually observe that intense echoes have

less degree of along band concentration, however, the sense of some “external linear forcing” controlling the precipitation das not disappear. Thus, the concept of «gradual 2D/3D transition” can be applied to non-line MCS also.

d) *Deriving MCS properties and construction of their climatological cumulative distribution function (CDF) quantiles.* Climate characterization useful to following forecasting proposes can be obtained from distributions of MCS properties derived on the instance T_m of MCS, values of reflectivity maxima Z_m , areas of precipitation with $Z > 40$, A35, and their ratios. Evidently, the reflectivity and areal extents characterize hail, heavy precipitation, and cloud-to-ground lightning potential of individual MCS, referred as *explicit severity parameters* (ESP). Various forms may be used to perform statics of ESP, but our recommendation is to construct Cumulative Distribution Functions (CDF) and tabulate of ESP quantiles, as it do on Table 1 where in rows 1 to 7 CDF deciles of ESP are presented. Obviously, the ESP category must be supplemented by extremes of vertical parameters commonly used in severe weather diagnostics and nowcasting practice: maximas of convective echo tops, vertically integrated liquid (VIL) etc.

Table 1. Climatological characteristics of MCS in central Russia

№	Characteristics, MCS	Deciles, %										
		min	10%	20%	30%	40%	50%	60%	70%	80%	90%	max
1	Z_m , dBZ	32,25	44,00	46,50	48,00	50,00	51,00	52,50	54,25	56,00	59,00	62,50
2	T_m , hours, Local Time	0:10	3:50	8:00	10:10	12:50	14:00	15:10	16:50	18:30	20:30	23:30
3	Area A40, км ²	0	32	64	128	208	272	416	672	960	1424	8160
4	Area A35, км ²	0	112	272	448	688	864	1408	2032	2736	3968	16880
5	Area A0, км ²	246	2384	4464	6640	9952	12208	14994	17072	21840	30064	73520
6	A35/A40	1,00	1,76	2,01	2,25	2,51	2,83	3,32	4,02	5,31	8,33	40,03
7	A0/A35	1,90	4,18	5,87	7,4	8,45	10,8	13,64	18,81	25,96	39,53	746
8	Line segment, км	31,0	61,1	93,6	105,6	120,3	140,9	157,6	190,3	218,8	254,6	440
9	Segment orientation, degree	96,5	127	137	153	169	186	200	217	233	243	268
10	Translation $V_t = (V_x^2 + V_y^2)^{1/2}$, M/c	1,30	3,81	5,56	6,87	8,11	9,16	10,54	12,02	13,47	16,41	27,51
11	Azimuth, from) °	9	135	180	207	219	236	252	270	303	327	360

The set of these ESP are easy obtain from radar volume and from numerical model results, however it performs only crude image of real MCS severity. In order to complete instant MCS picture, we need to use various distinct properties associated with dynamics of dominating storm and whole MCS organization. Of course, that assortment of lucid dynamics and organization properties which can be extracted automatically from one CAPPI, even from Doppler radar volume, is limited by few examples e.g. thunderstorm overhang, Doppler radar mesocyclone features, or vertical wind shear maxima. Moreover, many of explicit severe weather indicators as bow storm and multi, super-cell structures are very hard to quantify adequately. Another way to complete forecast oriented MCS climatology is to create any suitable numerical estimation to qualify MCS organization and reconstruct severe weather potential. These estimations are referred as *implicit severity parameters*

(ISP). Based on radar data the diversity ISP can be proposed, but we concentrate only on two basic properties just discussed in previous sections.

The simplest one is the maximal extent of continuous precipitation of convective or intermediate intensity, conventionally measured as interrupted line segment of > 35 dBZ (row 8) with selected width of 12 km (3 radar pixels). As it was discussed previously, this segment can be considered both as selected size criteria for MCS definition, or as a measure of MCS linearity. As can be observed in our sample about 80% of MCS formally meet to MCS criteria, but all of MCS have at least one thunderstorm of 30 km extension.

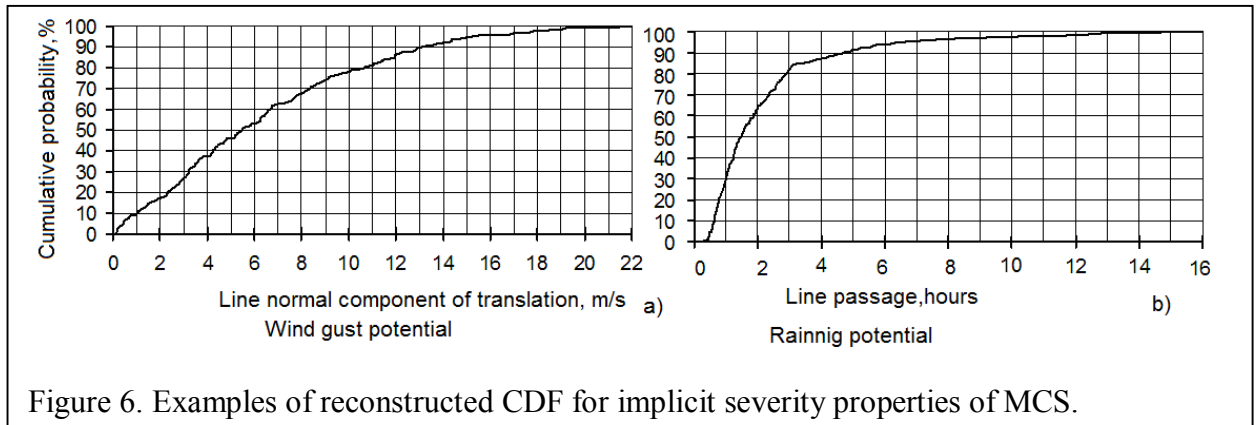


Figure 6. Examples of reconstructed CDF for implicit severity properties of MCS.

Another basic ISP is the passive translation velocity performed as advection of convective element with some mean wind for entire MCS domain. Translation can be estimated easily if the time resolution of data is small enough to identify radar cells on consecutive CAPPI: mean velocity of radar cells is closer to translation. If temporal resolution are in order of 30 min or more, translation can be estimated by tracking of preselected meso- β fragments persisting during some time period: some of radar echo meso- β scale elements have unique shape that has not changed significantly in the time period between two images. Both translation estimation algorithms are in good agreement.

Obviously, the translation velocity value is an implicit criteria of severity of synoptic scale disturbances that forcing the MCS development. As can be seen from row 10 of table 1 about a half of MCS are translated with velocities less than 10 m/s. Consequently, the same number of linear and complex MCS structures in our sample may be explained by external synoptic scale forcing.

From two basic ISP we can derive another two ISP. Conventionally, linear segment can be adopted as segment of squall line. Using line orientation (row 8) and translation (9, 10) we can easily estimate principal components of translation in respect to line axis and reconstruct some ISP evidently associated with possibility of severe weather. For example, we calculate line normal velocity that is gross measure of wind gusts: as wind gust value correlate with line velocity and in gross manner can be estimated as line normal translation plus 5 m/s. Thus, from reconstructed CDF (figure 6 a) about 10% of MCS can produce gust more than 18 m/s. Calculating the temporal interval as mean width (e.g. 30 km) line segment pass one point on the ground it can be obtained a suitable measure for duration of convective precipitation or raining potential. Without discussion from CDFs on

figure 6b it can be concluded that at least 20% of MCS possibly produce heavy rain 30 mm/h or more.

Although, more sophisticated methods have been proposed to estimate MCS properties, e.g. how calculate MCS and storm-scale propagation or quantify MCS asymmetry, however the discussion of these methods is slightly beyond of the scope of present paper.

e) Membership determination of observed and modeled MCS is the technologic procedure using a natural frequencies of MCS properties to evaluate the uniqueness of individual MCS and to estimate a quality of numerical prediction in terms of probability distances. The procedure schematically demonstrated on figure 7 is some kind of object oriented method, when we extract observed and modeling object properties and compare their relative probability in climate sample, in other words, MCS membership. If CDFs perform as a set of property intervals, containing ten percents of MCS population of climate sample, any value of observed MCS property get into interval limited by boundaries of one corresponding decile³. These deciles hereafter called as maternal decile (MD). Let's determine the uniqueness of MD. Evidently, that physical distances (e.g. measured in dBZ, length, square units and etc.) between down and upper boundary of deciles will be seen relatively shorter or longer corresponding to climatologically common or rare cases. Thus, uniqueness of MD can be measured as "a rarity degree" by ranking of physical distances between down and upper boundary of all deciles. Conventionally, MCS can be considered as "unique" if at least one of their maternal deciles is appeared as "rare". For example, correspondingly row 2 of Table 1, MCS which local time of maxima observed between 03:50 and 08:00 is very rare early morning system, but MCS with maximal stage between 12:50 and 14:00 or between 14:00 and 15:10 are very common diurnal cases. It is clear that "rarity" is not full equivalent of "severity", e.g. reflectivity maxima Z_m of MCS with value less than 44 dBZ is rare weak MCS cases!

The introduction of "maternal decile rarity" first of all is useful for "pedagogical" application for demonstrate what MCS events are really rare in some geographical regions. In the second it is helpful to evaluate the real quality of any mesoscale model output, and particularly with using radar data. Although numerical modeling and radar meteorology philosophy is not a matter of present text, we need remark some similarity and dissimilarity of radar and model evolution in connection of «rarity». The model and weather radar are scientific instruments and their perfection are quit similar to upgrading of any analogous to digital human being apparatus e.g. a simple digital TV set. As the transmission of codified TV image occurred on narrow diapason of electromagnetic waves frequencies limited by environmental condition, the model and radar were invented to receive a digitalized weather signal and transform it into a new information. The common purposes of radar/model development are to ingest weather signals compound by more and more variables and work well in all environmental conditions. Principal

³ We use deciles only for demonstration

difference between radar and model concerned to MCS “rarity» is exactly connected with *all environmental conditions*. Since the objects of radar observation are precipitation and severe weather systems resulting from relatively rare combination of meteorological conditions, the MCS types observed by radar are relatively less frequent objects to day-by-day numerical prediction and, consequently, has statistically least importance to formal prediction performance. Following described above logic, the extreme MCS cases with rarest combination of maternal deciles have minor significance to the quality of mesoscale model! As the prediction of extreme cases have major significance to community, it is necessary to use a object oriented methodology for estimation of model quality. Generally these methods are based on construction of some distance describing differences between predicted and observed MCS. But the application of any object oriented technology without referential climatology leads to erroneous conclusions. Indeed, any appropriate distance in physical space that was used as error measure between observations and prediction, even it is normalized, has different statistical significance if we compare observation and prediction of common and rare events. As we point out above, physical length (e.g. measured in dBZ or meters) of CDFs quantiles contained rare events is longer than common ones. There are two possible ways to use climatological CDFs as a “rarity” reference: 1) to create not uniform measure of prediction success in physical space or 2) to use uniform measure in frequency space, as in Table 1 or directly from CDFs curve (figure 6).

We’ll provide shortest discussion about of second alternative applications. From figure 6 it is easy to determinate the difference in percents between maternal quantile i.e. observation of some MCS property and property extracted from predicted reflectivity field. Using the continuous CDFs or deciles it can be created criterias of prediction success. For example, if membership of observation and prediction on continuous CDFs differ not more $\pm 5\%$ or $\pm 15\%$, we can refer our prediction of defined property as “excellent” or “regular”. Analogically if predictions get out into maternal deciles or into two nearest “familiar” we can considerate this cases as “good” and “regular”. Containing score for all empirical properties, and by any appropriated way calculating the summary it can be objectively estimated how model descript whole rare and common MCS. After we collect some adequate statistics of common and rare MCS events (e.g. separated by severity) we can that produce conclusion about real model utility to predict these events.

The technology described above appeared a robust, but can be applied directly only in case when time of radar MCS maxima and time of model MCS maxima are coincident. When it is no case, we need the dynamical time adjusting, in the other words, to determinate the instance when model dominating thunderstorm occurs and extract all MCS properties for this model time.

3. Cases study and perspective

In order to explore MCS climatology on basis of radar data and model output we select radar sample of 48 severe MCS occurred in the Moscow region

during 2009-2012, including 20 MCS with severe weather report from routine meteorological stations: 30 mm of precipitation during 1 hour, or 50 mm/3 hour, or gust wind more than 18 m/s. The severity of 11 MCS was clearly appeared in local news or particular videos. This sample is the compound diversity of linear MCS and complexes of severe local storms with along axis propagation, having some predominance of linear form with long, slightly bowed segment of 40 dBZ. Most of severe weather phenomena with wind gusts and F-5 tornado were associated with quasi-stationary fronts on June 03 2009, when along warm-side of the front several linear-to-bowed line passed over the Moscow (figure 7).

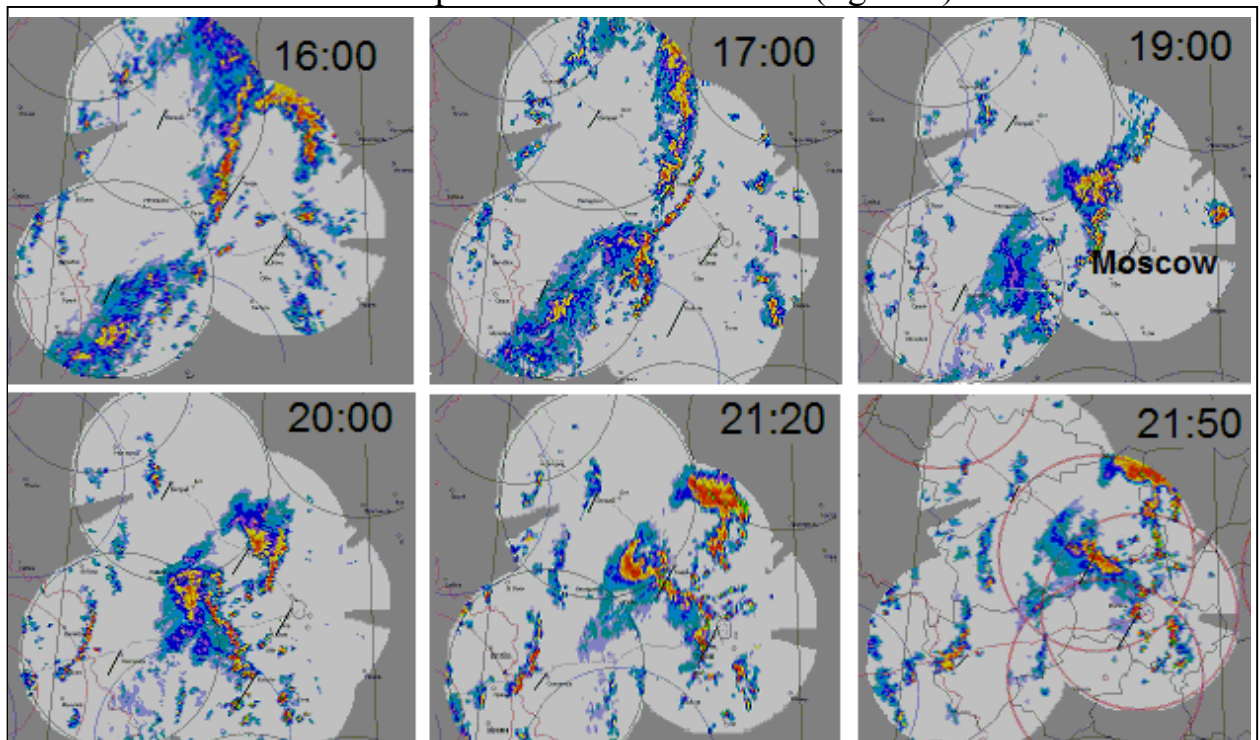


Figure 7. Most severe wind gusts are associated with serial derechoes on June 03, 2009. Just one hour of latest image 21:50 lcl F5 tornado destroy on part of Krasnozavodsk city, ~100 km at NE of Moscow. Translation of MCS ~20 m/s is approximately coincident with black lines direction in the circles center produced by standart cross-correlating technics of Melnichuk.

To simulate MCS evolution WRF-ARW model was applied in cloud resolving mode.

A 24-h simulation (0000 UTC 03 June – 0000 UTC 04 June 2009) was conducted with the initial and boundary conditions from the NCEP FNL Analyses on a $0.5^\circ \times 0.5^\circ$ grid. The grid spacing of two nested domains is 6 km (190×125), 2 km (241×217) (see fig. 8). The vertical grid contains 35 sigma levels from the surface to 50 hPa. We use new Thompson microphysics scheme with ice, snow and graupel processes suitable for high-resolution simulations; the RRTM longwave radiation scheme; Eta similarity surface layer parametrization; Noah Land Surface Model; the Mellor-Yamada-Janjic PBL scheme; direct simulation of convection (e.g. cu_physics=0)

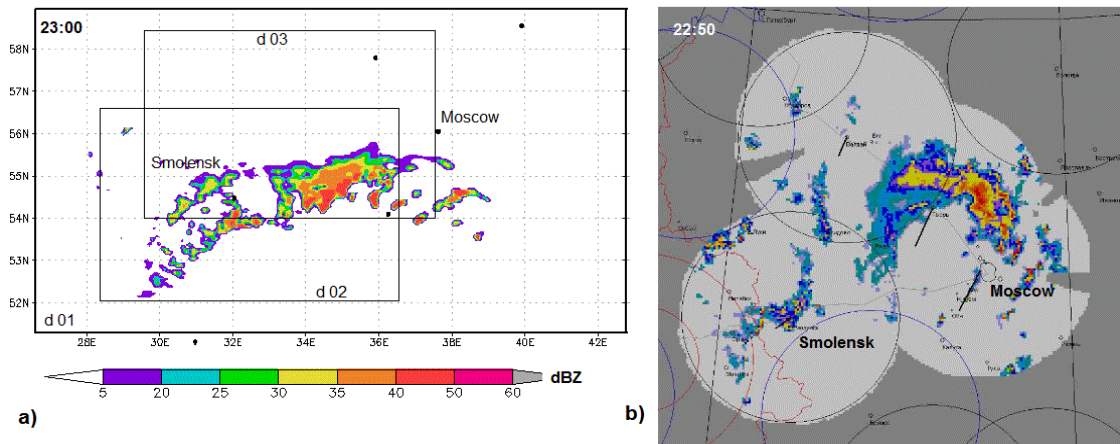


Figure 8. Comparison of MCS simulated (a) and observed by radar (b) at the time when tornado was observed on 03 June 2009. Configuration of 2 nested domains (d01 and d02, d03) for WRF – ARW simulation over Moscow region. The distribution of radar reflectivity on 5 sigma level (~ 650 m above the ground). The red color on precipitation scale or radar image correspond to 10-20 mm/h .

1) *Identifying life cycle maxima of individual systems.* As can be seen from figure 9 area occupied by echo ≥ 35 dBZ run up it's maximum at 21:30 local time (17:30 UTC) in whole simulation domain d01 that includes Moscow region. Note that analyzed areas covered by radars and simulation domain are different, at the same time this instant has a good accordance with observed by radar.

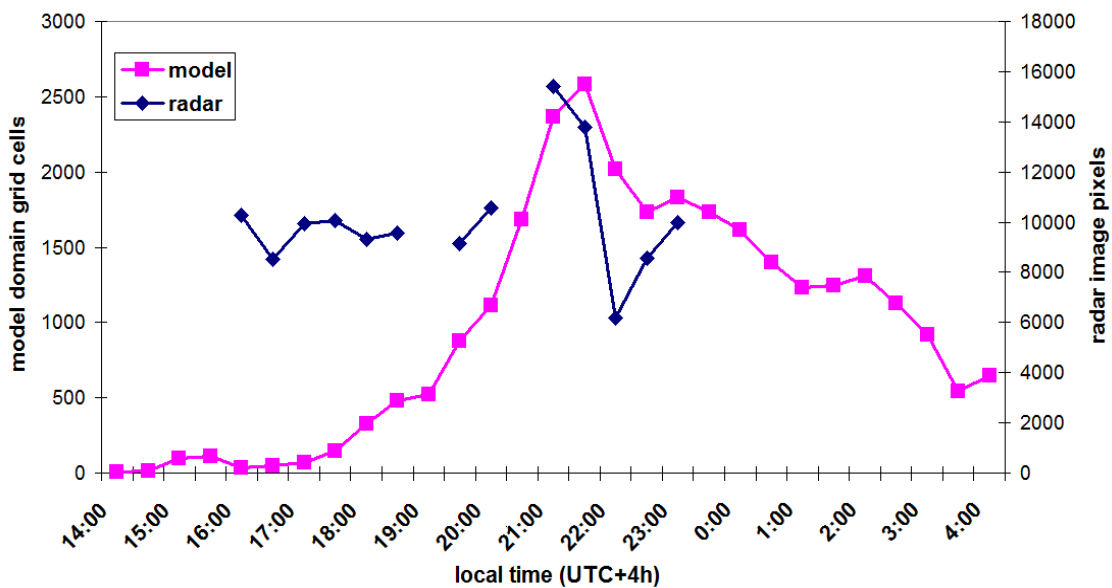


Figure 9. Temporal serie of grid cells number in simulation domain d01 and pixels on radar images occupied by radar echo ≥ 35 dBZ 3–4 June 2009

2) *Description of individual MCS morphology and combination the unique patterns to categories.* Based on the radar image of MCS just after 21:30 when maximum occurred one of MCS can be classified as linear (see fig. 10 b MCS 1 over Smolensk) with ~150 km of extension and orientation quasefrom S to N. Another MCS 2 on radar image near Moscow that will produce tornado at 22:50 (see fig. 8b) consists of severe thunderstorms and is oriented from NW to SE. This MCS 2 can be classified as linear and “bowed”. Figure 10 a shows precipitation

patterns at the same time of convective maxima. As can be seen the simulation result overestimates precipitation area and model produces more intensive precipitation system. It's difficult to recognize their position of MCS 1 and MCS 2. The location of precipitation area on the picture doesn't coincide with observed by radar and is situated much southward.

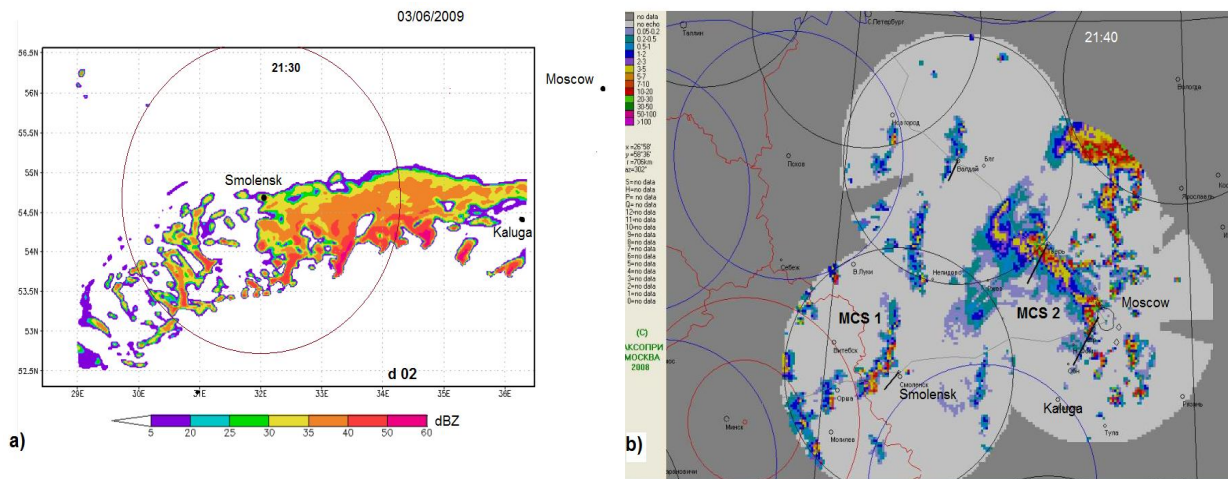


Figure 10. Spatial distribution of MCS simulated with WRF (a) and observed by radar (b) at the instant of convective area maximum. The result on (a) shows MCS in domain 2 with grid spacing 2×2 km and direct modelling of convection. The color scale on (b) shows precipitation rate, red 10-20 mm/h, green 20-30 mm/h.

3) *Deriving MCS properties.* At the same time some principal properties of MCS observed and simulated are similar. In accordance to Table 1 for instant 21:30. $Z_m = 55$ dBZ both for MCS 2 and for simulated system; system translation observed by radar is 20 m/s, from 230° and simulated is 23 m/s azimuth from 240° . This characteristics both observed and simulated system meet the same deciles in CDF. As can be viewed on the fig. 10 a the simulated system presents periodical structures: storms with orientation perpendicular to axis of whole line system and separated by lower precipitation zones. The similar configuration of MCS 2 is observed by radar: linear systems are oriented perpendicularly to their translation.

Resuming this case of study we can note that for radar data and model output the separated MCS have to be compared, not as in the presented complicated severe weather process. Of course, many questions to technology arise, e.g. about spatial distances between modeled and observed dominating storms but their ground relative position is the consequence at least of time maxima, translation and propagation errors.

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