DIAGNOSTIC AND FORECASTING TECHNIQUES BASED ON RADAR DERIVED TRANSLATION AND PROPAGATION OF CONVECTIVE SYSTEMS

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1. INTRODUCTION

A basic assumption used for definition of mesoscale convective system's (MCS) movement is based on translation and evolution of MCS's element through it's lifetime. Translation is a scale independent process when every convective cell and storm moves with the same horizontal "mean" wind velocity. Whereas, MCS evolution is a combination of multi-scale propagation and dissipation processes having contrary to conservative translation significant temporal and spatial variations.

Based on translation velocity, storm movement, propagation and life-cycle methods a number of diagnostic products, forecasting rules of thumb and conceptual schemas have been developed for different types of MCS organization [Abdoulaev et al. 1999; 2001; 2002; 2009; 2012; Corfidi et al. 1999; 2003]. Some rules of thumb are statistically validated for both extratropical and tropical mesoscale systems, and can be applied as probabilistic severe weather warning and nowcasting tool.

On figure 1 we demonstrate some principal results extracted from various, mainly climatological, studies of severe MCS having more complex then squall lines organization of local storms (see, figure 1 a). A great point in storm-scale study is an adequate storms selection. It should be considered an equally all types of severe MCS occurred in the same geographic area. For example, figure 1 b, c, d illustrates data analysis of two the most intense storms (dominating) observed during one MCS case. The combined method using translation / propagation idea consists of several phases: 1) composite storm structure (fig. 1b); 2) decomposition of storm motion vector to translation and propagation (fig 1 c); 3) storm trajectory analysis (1d); 4) conceptual model (1 e); 5) determination of MCS α-scale propagation and estimation of case complexity (1 g).

Composite structure. The composite RHI of these multi-super cell thunderstorms at the instance when these storms were the most severe is presented on figure 1b. The composite RHI provides information about averaged expected properties of severe thunderstorm, e.g. ~6 km extent of overhang in relation to ~20 km surface precipitation.

Vector decomposition. Figure 1c demonstrates three steps sequence of vector decomposing method to analyze the storm kinematics. First step (i) for all dominating individual thunderstorms the translation component (blue set) is subtracted from mean storm motion, then mean storm propagation (red) is estimated. Using data obtained in step (i), the composite diagram (ii) is constructed. Here all dominating thunderstorm are divided on 3 subsamples: "left" and "right" movers and others. As is expected in southern semi-sphere left-movers is more frequent ~60%, but right moving dominating storms ~30% also has the considerable quantity. The mean value of propagation is ~20-25 km/h. On the ultimate step (iii) that is recommended to calculate the regression in order to estimate the probable storm velocity from translation rate or sounding data.

Analysis of dominating thunderstorms trajectories. As *pointed* out above the selection of MCS type and equal representation of these system case in thunderstorm sample are very important to obtain useful results. Thus, the complex organized MCS separation from squall lines, generally lead to exclusion of major part (but not all) of cases with translation more than ~15 mc^{-1}. It is clear that small quantity of translation velocity is the consequence of weak synoptic scale forcing. Evidently, in these conditions circulation induced by some regional geographical features can play more pronounced role in MCS evolution. One of the simple techniques that reveal influence of these features is the overlay of dominating storms trajectory on regional landscape map (figure 1 d). As we can see, the major number of dominating trajectories in the eastern part of Rio Grande do Sul state (Brazil) are initiated on the tops of valley slopes around of 3 main river valleys and has the confluence over river mouth areas, abruptly terminating while the storm passes land/lake or land/ocean limits.

Conceptual model. On figure 1e one of the possible conception is presented. It was developed for explain the trajectories confluence of dominating thunderstorm in localities with some plausible conditions to generation of local planetary boundary circulations. All of these circulations, such as urban heat island, valley-hill

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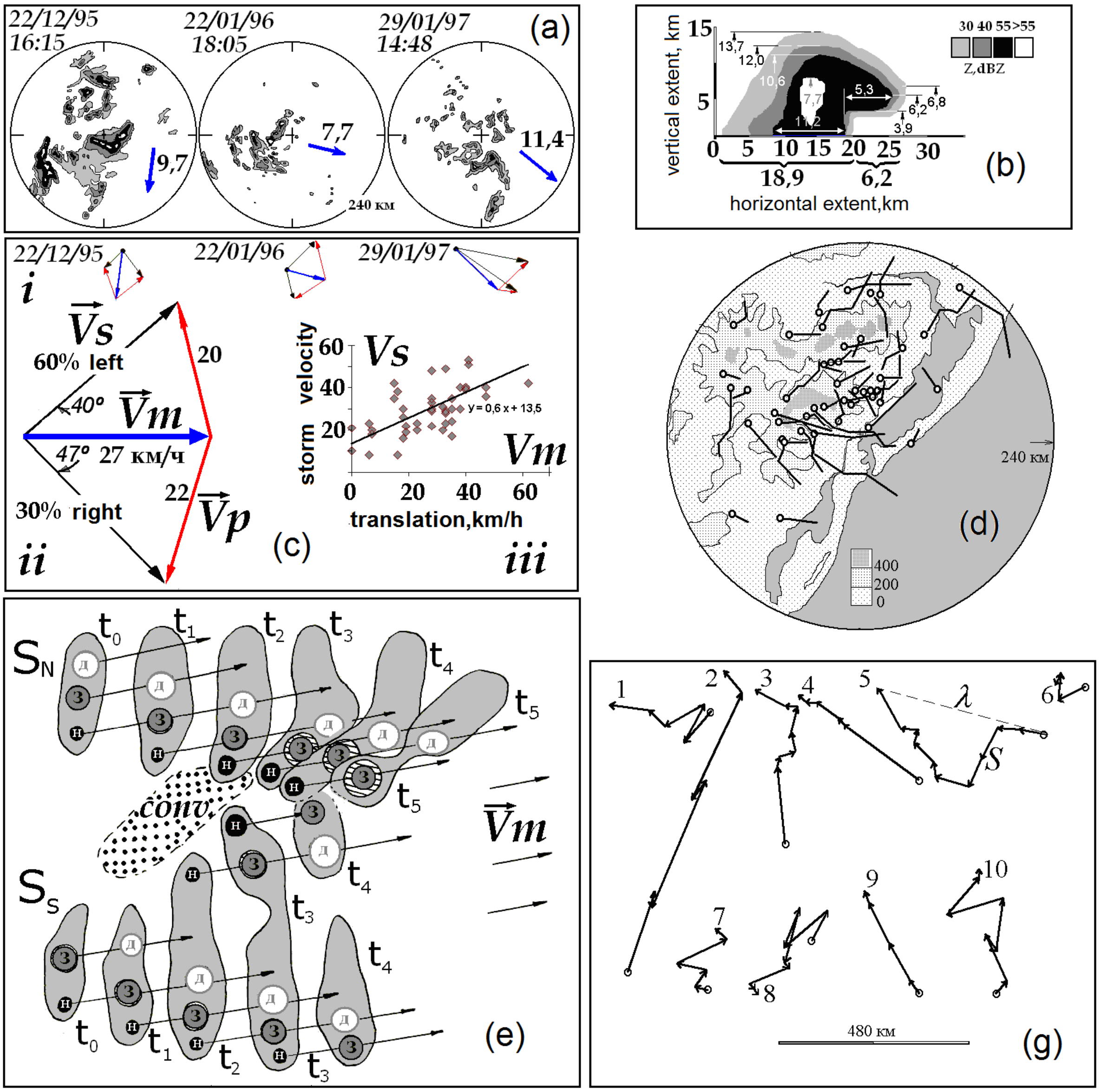

Figure 1 The study of mesoscale systems with complex organization of severe local storms. a) Stage of maximal intensity, Southern Brazil, blue set corresponds to translation velocity V_m . b) Averaged structure of dominating thunderstorms. c) Vectorial method: i) decomposition of individual dominating storms pair veliocity V_S to translation V_m and propagation V_p; ii) mean velocity and probability (%) of left-right moving thunderstorms in Southern hemisphere; iii) storm velocity vs/ translation; d) Trajectory method: trajectory of dominating storms accumulated on landscape map. e) Conceptual model of Cb ensembles evolution in the vicinity of stationary convergence zones explain the causes of domination and life cycle of thunderstorms in Northern hemisphere. Letters H, 3 and Д mark the new, mature and dissipated Cb, correspondingly; g) Dominating ensembles method: trajectories of intensity of meso-α-clusters in moving reference. Initial point of trajectory corresponds to the first 1-hour maxima marked by circle, the second and successive ones depict by sets. Numbers 1-10 correspond to cases of study. Case 5 demonstrates the difference of trajectory S and distance λ between initial and final point of trajectory. Adapted from [Abdoulaev et al. 2001; 2009]

sides circulation, breeze fronts etc., can presented as a surface wind convergence zone (*conv*) provided more suitable environment to initiation of new convection. As thunderstorm ensemble S_N translating and propagating as right-mover, outflank convergence zone on the north, it can activate new development enhanced by local circulations then contemporary groups of Cb tend to appear closer and closer to this zone. Visually, northern more intense part of right-moving storm accelerates, retards and finally as backward propagated storm tends to persist leeward of convergence zone. In another situation, when initially right-moving storm outflanks convergence zone on his southern side, the convergence zone convection is activated on the left flank in respect to previous clouds, and new dominant left-moving storm develops, sometimes leading to visual effects of storms bifurcation. It is evident that both northern right- and southern left-moving storms have confluent trajectories. In spite of it's simplicity the presented conceptual model explains also other phenomena. First of all why the observed probability of most intense right-moving (left) storms is ~2/3 of total to the north (south) of equator, and why 1/3 of storms deviate from "hemispheric rule", or why the probability of severe weather phenomena is enhanced leeside of metropolitan area.

Dominating ensembles method: intensity of meso-α-clusters in moving reference. Recognizing that MCS propagation has multi-scale nature, the questions about visualization of propagation characterized entire MCS life. Indeed, conceptual model on figure 1 (c) accumulate the history of MCS elements and can be applied equally to local storms ~25 km, their meso- β ensembles~100km and entire MCS~300 km, referred as *meso-α-clusters*. However, α-clusters convection lasts at least 7 -8 hours, and accumulating history of MCS in earth surface reference, is very difficult to analyze e.g. because storms overlapping as it is occurred on leeside of convergence zone (figure 1 c).

There were many reasons, to present the history of MCS propagation in reference moving with translation, referred as *life-cycle display*. Some of these *reasons* will be discussed in section 3. But one of principal reasons is shown on figure 1d where in moving reference points of successively dominating thunderstorms are matched during entire life of MCS characterized visually as "chaotic" (see figure 1a). The main "unexpected result" of this procedure is that many of severe chaotic MCS have well-defined axis of development of intense ensembles! In the other words some MCS can be classified as implicitly linear. More over, implicit linearity or MCS complexity can be measured easily in terms of propagation, e.g. as relation between length of individual propagation trajectory S and absolute value of mean MCS propagation λ. An introduction of "complexity measure" idea can serve as the first step to discussion about the similarity and difference in MCS evolution with various levels of complexity including explicitly linear squall lines.

Thus, short results and methods described above demonstrate how translation and propagation of convective systems derived from radar images can be used in interpretation of observed MCS evolution and MCS climatology.

The next sections content is more close to operational practice, where multi-scale propagation of MCS must be predicted. We discuss the possibility to use translation and life-cycle methods in automated nowcasting algorithms to identify real-time severe weather potential of observed MCS.

2. TRANSLATION ESTIMATION ALGORITHMS

From the practical view point translation velocity can be considered as steady advection of radar reflectivity field. Suggested algorithms designed to estimate this velocity are classified in *structure* and *object* techniques. [see Han et. al. 2009, Lakshamanan, 2010]. The calculating of spatial cross-correlation matrix between sequential gridded precipitation frames is the example of methods capturing mesoscale precipitation *structure*. The examples of *object* based techniques are cells identification and tracking algorithms. Translation velocity is obtained by averaging of individual convective cell's velocities. As radar echoes of ordinary cells are small short-living objects, these algorithms work well when we have a data at least with spatio-temporal resolution ~2 km $\times$ 2 km and ~10 minutes. Evidently, it is not possible if radar operates in volume scan mode.

There were also developed several techniques which combine both object and structure approaches. Some of combined techniques apply a kind of thresholds (precipitation intensity, space cluster scales, keeping the shape convective patterns) providing selection or filtering of slowly and rapidly evolving precipitating elements (field fragments, frames). The example of application of nowcasting techniques using fully automatic object algorithms and interactive structural procedure, referred as "*identifying and tracking meso-β-scale conservative fragments*, is demonstrated on figure 2.

For interactive steps of procedure (figure 2b) we apply moving window large enough to contouring of several thunderstorms in area of interest on two sequential images, e.g. square frame 80 km $\times$80 km is used. As center of window position approximates to the preselected storm's group, e.g. in the vicinity of group containing dominating thunderstorm where storms apparently conserve their relative positions on the first and second images (i), any one can overlay two frames extracted from earliest and latest images trying to find the "best" possible coincidence of corresponding conservative structural fragments (ii). The translation is calculated automatically by comparing windows position in "best" composite images (iii).

Conventionally, translation vector can be applied in severe weather nowcasting, as we demonstrate on figure 2c, where the latest image (1300 LST) is translated one hour ahead to new position corresponding to 1400 LST. As we look on real image (fig. 2d) the position of intensifying dominating storms is predicted relatively good. This "satisfactory" result is the consequence of

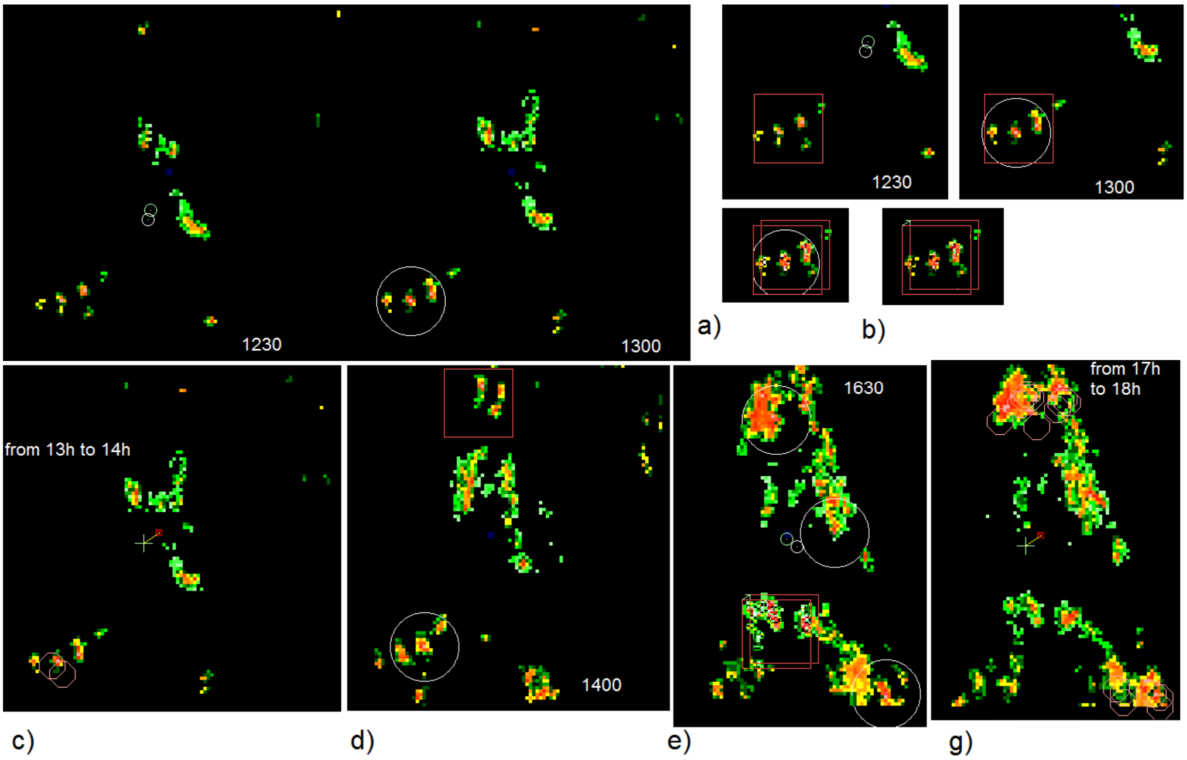

Figure 2. Example of combination automatic and semi-automatic algorithms to severe weather nowcasting. a) MCS motion of 23 km/h azimuth 195º derived automatically from two initial CAPPI, and marked by 2 small circles on first images. Large circle with radius of 40 km is placed in the point of possible severe weather Z>50dBZ: b) translation interactively derived by 3 steps: 1) move square onto target thunderstorm area, and after choosing; 2) overlay thunderstorm area from second image to area on first image, and automatically derive translation of 22 km from 236º; c) prediction is made by automatic translation of radar echo from image of 1300 to 1- hour (1400), two red octahedrons are the areas of severe weather warning, d) real time image on 1400 demonstrate relatively good forecasting of old convection areas and appearance of new ensemble on the north (depicted by square); e)-g) as in a) and c) for 1630-1700 time interval (see text). Pixel's with convective precipitation Z>40 dBZ colored by sequence from dark yellow , orange and red.

scale separation: although individual dominating small meso-β thunderstorm life-cycle lasts not more then 1,5 hours, the large meso-β thunderstorm ensembles frequently dominate ~3-4 hours. From figure 2d it is evident also that during 1 hour after prediction, a new ensemble developed on 150-200 km just north to radar. This ensemble and thunderstorms entering to radar observation area from the south are intensifying and dominate during at least 3 hours after 1500 LST (fig. 2 e, g).

Although, interactive translation procedure appeared to be some subjective, but operational experience demonstrates that translation estimation by adjusting of conservative fragments works well in many of MCS cases where automated motion algorithms, by any reasons, are failed. For example in the instant shown on figure 2e, g, as is expected storms are continuously translated from SW to NE, but MCS motion determined formally have direction from SE to NW, mainly because of entrance of relatively large precipitation area from southern border and several echoes on western border.

The utility of interactive translation velocity procedure can be recognized from next facts. To evaluate performance of real-time automatic algorithms utilizing on 22 radar mainly on European part of Russia (18), Ukraine (2) and Belorussia (2) we arbitrary selected radar patterns corresponding to 132 MCS during May-August of 2013. The result of 2660 radar images analysis complemented by severe weather diagnose and precipitated area motion, is that vector of motion was not available during more than half-life-time development of 78 MCS, i.e. in 60%.

3. LIFE-CYCLE MAPS: COMPOSITE IMAGES TO PROPAGATION/DISSIPATION DIAGNOSIS

A range of MCS propagation forms and scales is available. Storm scale propagation appears as discrete multi- or continuous super-cell thunderstorm. A horizontal expansion of thunderstorm ensembles combines ongoing storm propagation and new objects development.

As already pointed out after spurious fluctuations removing, *object* techniques can produce various cinematic characteristics of individual cluster motions such as the cluster center of mass velocity, severe convection core velocity, absolute maxima velocity etc. In this case magnitude and direction of ongoing cluster propagation are estimated from vectorial difference between translation and one of representative cluster velocities. Unfortunately, the propagation vector obtained by this way will describe only the mean evolution of preselected scale elements.

The principal method to capture all of propagation and dissipation scales and forms simultaneously is to create *MCS life-cycle matrix* (LCM) that represents some kind of translating reference where "precipitation histories of all pixels embedded in translating air mass" are recorded by any way. One of robust, widely adopted in practice, LCM based method is *2D life-cycle maps* overlaying of time-labeled radar frames i.e. more recent storms layer covers the previous one, as do it in "Napoleon" pastry cake [Starostin et al. 1983, Starostin et al. 1996, Abdoulaev et al. 2001, Abdoulaev et al. 1999, Abdullaev et al. 2009]. With some programming adjustment LCM*s* can be transformed into *pseudo 3D life-cycle display* where new propagation regions, ongoing and dissipation convection or convective / stratiform transformation are conventionally outlined.

One of the possible application of *life-cycle* display in forecasting of convective precipitation is demonstrated on figure 3.

a) Display construction. The figure 3 is the screenshot of serial composite frames based on the information extracted from pairs of real-time digital radar images separated by equal time intervals, e.g. 1 hour. Of course 1 h intervals, we use only for demonstration, depending of practical needs 15-30 min sequence is more convenient. All frames are produced by overlaying at least 3 horizontal informative layers. First layer is obtained by translation of initial radar real-time image and constructed by similar manner as in extrapolation procedure (see figure 2c and 2g) and contain information in conventional cores in dBZ. The second layer, colored by dark red contains precipitation pixels extracted from most recent paired image. The third layer, colored in grey scale, is the result of post-processing of first and second informative layer: If precipitation pixels localized on second top layer cover the precipitation pixels in first bottom layer, bottom pixels "arise" to the top layer.

b) Diagnostic interpretation of resulting colored frames is very simple. The dark-red matches moving areas precipitating on the moment of analysis and consist of mainly convective precipitation developing during last hour. The grey areas also mark contemporaneous precipitation, but contrary to predominantly younger convection in dark-read areas, it depicts the offsetting of precipitation life-cycle. And finally, the colored areas of the bottom layer are the moving areas where precipitation observed in the instance of first images (e.g. in 1100 LST) during 1 hour translation is totally terminated. Black areas on composite frames are the areas where precipitations not observed during 1 hour intervals.

From the view point of forecaster's education, areas on life-cycle display can be considered as a gross measure of success of extrapolation procedure. Dark-red (colored) areas correspond to *surface* points were precipitation is underestimated (overestimated) by extrapolation and gray areas are the points with reasonable prediction skill. Looking to the frames sequence, students can observe some interesting process and phenomena regarding MCS life-cycle just after onset of convection (frame 1). First process is rapid expansion (frames 2 and 3) of MCS elements along two confluent south-to-north axis. The distinctive visual feature of this MCS stage: area of new "underestimated" thunderstorms is considerably larger then "overestimated" dissipation one and total area of well-predicted precipitation is relatively small. Second process characterized by propagation / dissipation equilibrium maintained in the vicinity of MCS maxima stage that commonly observed after 3 hours of initial expansion [see more Abdullaev et al. 2012, Lenskaya et al. 2013]. Indeed, on frame 4 we observe that in the instance, when the MCS severity achieves maxima, one hour developing and dissipation areas are approximately the same. During mature MCS (frame 5) these areas are apparently compensated one other and soon after (frame 6) the predominance of dissipation is evident. It is clear also that area of extrapolation success is continually growth from frame 1 to 6!

c) Prognostic issue. Thus, life-cycle display, based on accumulation of precipitation in translating reference, outlines all scales propagation and dissipation areas. However it must be admitted, that 1 hour ahead translating precipitations may not have simulated fairly those occurring really. Prognostic quality may be considerably higher, recognizing that all areas on composite images as figure 3 are the remnants of previous intensification of convective updrafts (dark-red) and convective/stratiform precipitation downdrafts (grey) and "clear sky" downdraft (colored). Consequently, new convection can not develops in moving regions on life-cycle display that previously matched by these areas. This nature of convection is clear revealed by comparing of consequent frames, e.g. frames 5 and 6 on figure 3. As dark-red and grey areas on frame 5 appeared as colored one hour translated areas on frame 6, we can observe that one of region occupied by relatively intense storms abruptly disappear (marked by set on frame 6) and severe weather forecast is failed. The forecast failure may be prevented, with more close-up inspection of position of this area on the frame 5. As we see on instance of frame 5 this thunderstorm area really was relatively young, but it positioned just to the north of moving areas were was precipitation recently terminated. Consequently, an expectance of new right flank thunderstorm and associated severe weather (depicted automatically by octagons of ~30 km)

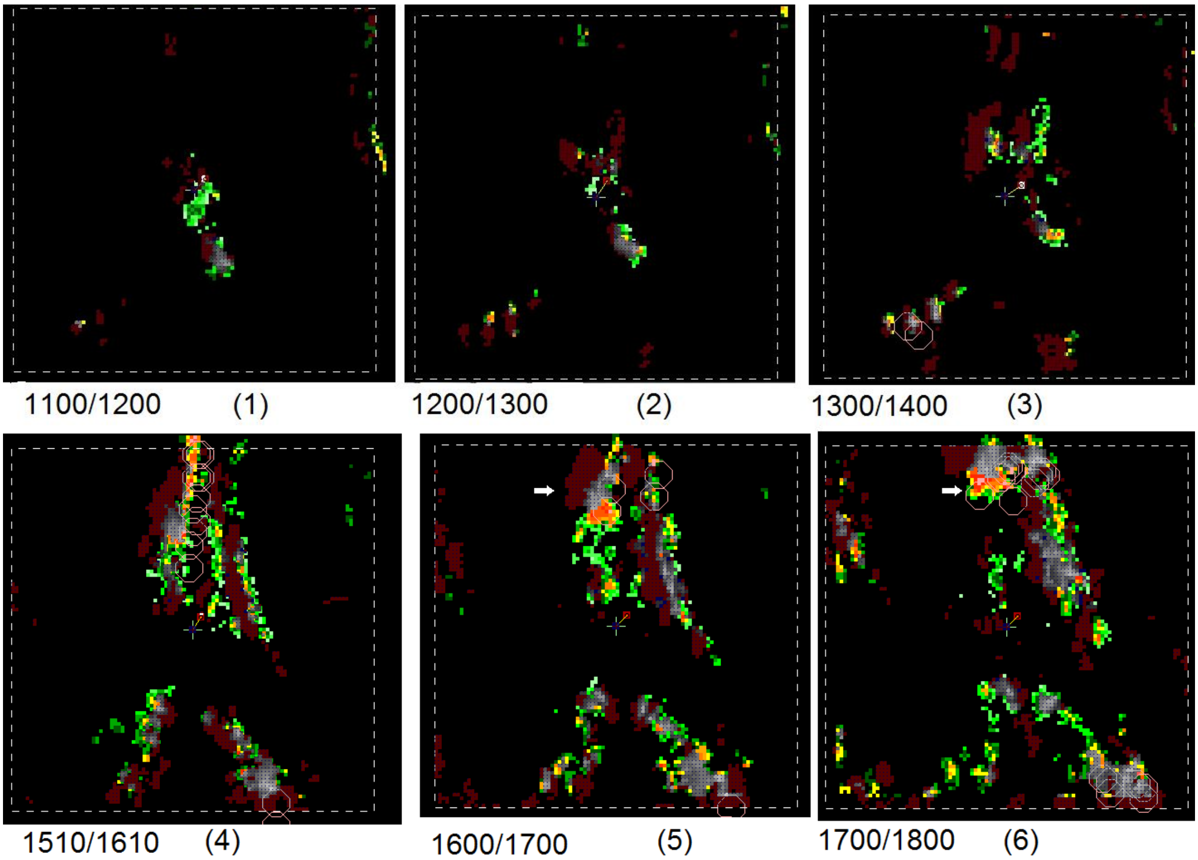

Figure 3. Life-cycle display adapted to evaluation of translation based short-range forecasting techniques, real-time diagnostic, and as educational and prognostic tool. See text to explanation about of significance of colored, dark-red and gray painted areas.

was erroneous. Obviously, these forecasting errors may be excluded, when nowcasting procedure is complemented by automatic analysis of entire life-cycle frames containing all accumulated precipitation.

4. CONCLUDING REMARKS

Easily implemented extrapolation based on routinely derived translation and related MCS life-cycle display based on accumulation of precipitation in translating reference must be considered as complimentary source of information to contemporary forecasting technologies: a) in some conditions, when automatic tracking procedures are failed, the “propagation free” motion obtained by semi-automatic conservative meso-β fragments techniques can be applied in extrapolation forecasts; b) as poor extrapolation forecasts associated, mainly, with growth and decay of storms in the forecast period, life-cycle composite images provide valuable information about of developing, dissipating areas and areas prohibited to new development.

There were many application of life-cycle displays and *Mean Wind Relative* (MWR) reference analysis which is based on translation component subtracted from Doppler radial velocity can be found in the references [Abdoulaev et al. 1999; 2000; 2002]. In order to detect the convective and mesoscale circulation one can be applied our unique *Mean Wind Relative* (MWR) reference analysis which is based on translation component subtracted from Doppler radial velocity. Guidance for key mesoscale inflow/outflow patterns is presented in [Abdoulaev et al. 2002].

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