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Automatic recognition of squall line – a way to longer validity of some extrapolation rainfall nowcasting?

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1. Organised convection

Most of meteorological phenomena that have significant impact upon society and infrastructure – such as heavy precipitation, thunderstorms, lightning, hail, hurricanes and tornadoes - are related to convection. Therefore their recognition and forecasting play major role in operational aspects of national weather services, especially in the regions where such phenomena constitute one of the major weather features. Notwithstanding convective phenomena typical for mid latitudes are not so spectacular like those appearing in tropical regions, they are still the most devastating and causing majority of material losses.

Squall line, being an important convective system, quite often bringing severe weather phenomena, is worth to be recognised automatically in order to monitor and forecast strong precipitation and related effects. As it normally lives longer than simple non-organised convection the extrapolation nowcasting of accompanied rain should be valid for longer time.

Many attempts were done to work out the method of forecasting different aspects of convection (Agee, Chen, Dowell, 1973). A lot of failures resulted from very short life time of isolated convective cell and difficulties with predicting of triggering processes. Therefore we decided to focus on more stable phenomena, having simultaneously wider range.

Basically, convective phenomena can be associated with three major types of convection (Markowski, 2005b). The first type is ordinary convection. The term covers variety of deep moist convection that is single-celled and a lifetime of which is approximately 45 minutes. This type of convection usually occurs near or shortly after the time of maximum daytime heating and dissipates after sunset. It rather seldom produces hail or wind gusts that could be classified as severe. In case severe weather is produced, its character is short lived and marginal. In contrast to ordinary convection, multicellular convection consists of numerous updrafts. This kind of phenomena is very common in mid latitudes. Such convective system has a considerably longer lifespan up to several hours and produces very strong winds and heavy hail. Its structure is either linear or formed of clusters of updrafts. Finally, super cellular convection develops from isolated systems in specific conditions. Supercells contain organized, storm-scale rotation. They tend to be the most severe kind of convective storm, producing tornadoes and the heaviest hail.

There is a wide range of weather phenomena related to convective systems. Their taxonomy was proposed by Brooks (2005a, 2005b). The phenomena classification can be based either on the kind of weather produced by a convective system – what is especially useful for operational forecasting and warning purposes – or on its nature and degree of organization. Organization can be considered in terms of individual convective elements as well as in terms of relationship between particular convective elements.

Convective motions in the atmospheric boundary layer often have a common and characteristic element (Markowski, 2005a). Convective motions are often organized into hexagonal cellular patterns, which form seems to be physically optimal. Cellular convection can take form of walls of cloud surrounding open, cloudless areas, with descent in these central open areas, as well as of rings of open areas surrounding solid cloud, with apparently upward motion in the centre (where the cloud is) and sinking motion in the rings. Cellular convection is most commonly observed over the oceans. Convective motions in the atmospheric boundary layer also can be organized into lines of counter rotating horizontal vortices. The phenomenon of commonly known "cloud streets" (nearly unbroken cloud bands within the boundary layer) arise directly from these structures.

One of the typical phenomena is the squall line, extensively studied from the beginning of modern meteorology (Williams, 1948) up to these days (e.g. Pinto, 2005). Such structure can be described as an organized line of thunderstorms. It is classified as a multi-cell cluster, meaning a thunderstorm complex comprising manyindividual updrafts. They are also called multi-cell lines. Squalls are sometimes associated with hurricanes or other cyclones, but they can also occur independently. Most commonly, independent squalls occur along front lines, and may contain heavy precipitation, hail, frequent lightning, dangerous straight line winds, and possibly funnel clouds, tornadoes and waterspouts. In spite of very

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short time of impact on a place on ground (squall line passage) because of very narrow shape (Williams, 1948), the squall lines can develop up to several hundreds of kilometres in length and have a life span of several hours, which is considerably longer than its component thunderstorms. Gusty winds and heavy rains associated with the squall lines are more intense and wide-ranging than individual thunderstorms.

Since this research is based on radar data mainly, the identification of squall lines in radar images is of key importance. Squall lines are often related to bow-shaped convective elements, observed by radar, called bow echoes (Fujita, 1978; Przybylinski, 1995). Bow echoes may occur as isolated thunderstorm cells, or comprise elements of extensive squall lines.

Li and Lai (2004) desribe nowcasting system in Hong Kong, where the nowcast is differenciated for individual convective systems (e.g. squall-lines). Also Corfidi (1998) describes a forecast of mesoscale convective systems.

This article presents a comparison of different advection rainfall nowcast both for linearly and randomly organised convection for lead times ranging from 60 to 180 minutes. The analysed domain is 900 x 900 km area observed by POLRAD (Polish radar network). The principal question was: is the advection (extrapolation) rainfall nowcast better and valid longer time for linearly organised convection than in the case of randomly organised one? At the same time we wanted to compare NIMROD (UK MetOffice) forecast with the forecast proposed by us.

3. Convective cells separation and agglomeration

Before recognising the convective systems thay must be first separated from the overall area of observation. This is performned in consecutive steps as follows:

- cleaning the radar composite map from remaining clutter;
- finding cores of convective cells and approximating them with ellipses;
- extending the cores into surroundings and forming extended convective cells;
- agglomerating the extended cells into clusters;
- recognition of clusters: lineraly/randomly organised.

This steps are described in details by Moszkowicz at al. (2006). We can give here only some general idications in this matter. The cores of convective cells are identified as local ‘hills’ of rain intensity (or reflectivity factor), where the rain drops from the central point with maximum value of rain. The process of cores definition is stopped when the local maximum drops below a certain threshold dependant on the first maximum. The cores are then approximated by ellipses, taking into account the direction of the longest axis. The cores of cells are then extended by joining to them adjacent rain pixels. The pixels are joined using the criterion of smaller distance where the Euclidean distance is weighted by the cell radius (bigger cells attract raining pixels stronger then small cells). Process is stopped when the weghted distance becomes smaller than predefined threshold. Similiar procedure is used to agglomerate the extended cells into clusters, only the distance is weighted in slightly different way and the threshold distance is different.

4. Recognition of clusters

Basing on a set of data where an experienced radar observer has classified the rain clusters into ‘linear’ and ‘random’, the cluster parameters have been analysed in order to find a discriminative function capable to recognise between these two types of convective systems. It was found that the following function gives quite good discrimination (Moszkowicz at al. 2006):

$$F = 8.5452\times 10^{-5}\, r_c + 0.0107 R_c + 1.0013\times 10^{-7} P + 2.0102\times 10^{-6} Mxgr - 0.0153 \quad (1)$$

When $F \geq 0 \rightarrow$ linear cluster, otherwise $\rightarrow$ non-linear one.

Here: r_c – average radius of the cluster; R_c – absolute value of maximum correlation coefficient of x,y points of the cluster rain (maximum at 360^0 rotation of the coordinates); P - power of the cluster = integral of rain inside the cluster; M_{xgr} - maximum local rain gradient inside the cluster.

The total error of recognition of the function (1) ranges from about 6 to about 20%, with dominant values close to 12%. As even visual recognition cannot be considered as sure, we may consider the results of recognition as satisfactory.

5. Compared forecasts

We compare Nimrod (UK MetOffice) advection and Nimrod merged forecasts with our forecast thereinafter called “smoothed motion” forecast (SMF). Nimrod system divides the area of observation into “segments”; to each segment a single steering vector of motion is attributed, then the segments are advected as separate systems. Nimrod merged forecast adds (especially for longer lead times) a component of rain originating from NWP model forecast. Nimrod forecast is based on Nimrod ‘analysis’, where the rain data from additional sources (satellite, gauges, NWP model...) are used to construct an ‘optimal’ rain field.

SMF is based on Nimrod radar composite map (before the analysis) corrected additionally in order to reject clutter remained after Nimrod clutter correction. For SMF the area of observation (900 x 900 kilometric pixels) is divided into 14 x 14 subareas of 50 x 50 km. For each subarea a motion vector is searched for using cross-correlation method applied to consecutive maps appearing in 10 minute steps. As many subareas do not contain sufficient number of rain pixels, many vectors are faulty or not defined. Therefore the field of motion is smoothed by rejecting outliers, averaging vectors in moved space and moved time window, and extrapolating the motion field into full domain. Unfortunately the used method has not yet been published, it was only presented at one of RISK AWARE workshops. This smoothed field of motion is applied to rainfall map in order to construct extrapolation forecast; every pixel is moved separately according to the motion vector in appropriate place and time.

6. Set of data and quality scores

The Nimrod data of 5 day of May, 6 days of June, 12 days of July and 1 day of August 2005 are used for forecast comparison, the rains in those days were quite strong and the archive records sufficiently complete. Unfortunately, the archive of data has many gaps – some data is absent, so that for forecasts comparison there were used rougly 100 maps (minimum 46, maximum 190 maps), the number of compared pixels (rain and no rain, linear and random convection) ranged from about 45 000 to about 200 000.

The comparison contains many variants: division between linear and random convection, simultaneous quality scores of Nimrod advection and „smoothed motion" compared with corrected rain and with Nimrod analysis, the same for Nimrod merged and „smoothed motion" etc. The lead time of **60, 90, 120, 150 and 180 minutes** have been analysed.

Continuous scores: RMSE, Bias and categorical scores: POD, FAR, TSS and OR are used to quantify any forecast.

7. Results of comparison

Only the most interesting results are presented below in Table 1 and Table 2. Another comparisons (e.g. against Nimrod analysis or with rain thresholded by 1 mm/h) give results not very different from those presented. One can easily see that the continuous scores are generally better for Nimrod advection forecast than for SMF, while the inverse is true for categorical scores (only rain above 0.2 mm/h are taken into account). When TSS is negative or OR is below 1, the forecast is completely wrong – the inverse forecast (rain $\rightarrow$ no rain and no rain $\rightarrow$ rain) would give better scores. We see in both tables that it is nearly always true for Nimrod forecast. It seems strange that the continuous scores are better for Nimrod forecast. We shall try to prove later that this is an artifact. It is also easily seen that the categorical scores TSS and OR of SMF are nearly doubled for linearly organised convection with respect to those for random convection. It means the advection forecast in case of linearly organised convection is much better than in the case of random one. TSS and OR scores diminish when lead time increses, but there is not any spectacular difference between linearly organised and random convection if the rapidity of this diminishing is considered.

Table 1: Quality scores of SMF and Nimrod advection forecast for **linearly** organised convection – comparison with corrected rain map

Lead time	SMF						Nimrod advection forecast					
	RMSE	Bias	POD	FAR	TSS	OR	RMSE	Bias	POD	FAR	TSS	OR
60	2.716	**0.168**	**0.748**	**0.459**	**0.392**	**5.4**	**2.610**	0.193	0.643	0.681	-0.130	0.5
90	2.815	0.284	**0.708**	**0.525**	**0.281**	**3.3**	**2.330**	**0.128**	0.559	0.691	-0.123	0.6
120	3.178	0.210	**0.682**	**0.508**	**0.319**	**3.8**	**2.778**	**0.181**	0.609	0.705	-0.139	0.5
150	3.725	0.408	**0.675**	**0.617**	**0.205**	**2.3**	**2.771**	**0.117**	0.445	0.752	-0.139	0.6
180	2.793	0.472	**0.651**	**0.696**	**0.226**	**2.5**	**2.193**	**0.352**	0.462	0.827	-0.170	0.6
Better values of two forecasts are bolded												

Table 2: Quality scores of SMF and Nimrod advection forecast for **randomly** organised convection – comparison with corrected rain map

Lead time	SMF						Nimrod advection forecast					
	RMSE	Bias	POD	FAR	TSS	OR	RMSE	Bias	POD	FAR	TSS	OR
60	3.08	1.23	**0.814**	**0.511**	**0.204**	**2.8**	**2.26**	**0.60**	0.473	0.576	0.012	1.0
90	3.23	1.26	**0.794**	**0.626**	**0.165**	**2.3**	**2.19**	**0.47**	0.353	0.696	-0.028	0.9
120	3.19	1.15	**0.780**	**0.671**	**0.154**	**2.1**	**1.92**	**0.40**	0.319	0.739	-0.037	0.8
150	3.69	1.26	**0.760**	**0.719**	**0.119**	**1.8**	**1.66**	**0.27**	0.243	0.778	-0.038	0.8
180	3.83	1.41	**0.771**	**0.748**	**0.105**	**1.7**	**2.00**	**0.29**	0.193	0.843	-0.089	0.6
Better values of two forecasts are bolded												

Now, it is worth to return to the question why Nimrod advection forecast has so small RMSE if this forecast is wrong from the point of view of categorical scores. If someone looks carefully to Nimrod analysis map (used for Nimrod forecast) and 'corrected rain' maps (used for SMF), he/she can note that Nimrod analysis map contains more pixels with relatively weak rains. Comparison of Nimrod analysis and corrected rain maps shows the number of raining pixels is greater in Nimrod analysis map by about 4% in case of linear and by 2% in case of random convection. At the same time average rain is a little bit smaller and standard deviation much smaller in Nimrod analysis than in corrected rain map. It means that Nimrod analysis smoothes the rain map – number of rain pixels increases, value of rain decreases and standard deviation drops quite rapidly. It is obvious that more smooth rain field gives smaller RMSE. For final prove we made a smoothing of SMF field in 9 x 9 pixels moving window for the lead time +150 minutes. RMSE of such smoothed SMF is nearly the same as it was for Nimrod advection forecast for the same case. We feel to have the right to say that small value of RMSE for Nimrod forecast is an artifact resulting from the procedure of Nimrod analysis. Indeed this anaysis uses date of much worse resolution than radar data what leads to smoothing of the rain field.

8. Conclusions

1. Any rain nowcast is not sufficiently good;
2. Both Nimrod forecasts (advection and merged) are bad: OR below 1, TSS negative. It means that the inverse forecast (rain ← → no rain) would give better categorical scores;
3. „Smoothed motion" forecast though not sufficiently good, have OR>1 and TSS positive, what means that the forecast is in relation with reality;
4. RMSE of Nimrod forecasts is better than this of „smoothed motion" forecast, but it is an artifact, it results from smoothing the rain field by Nimrod;
5. „Smoothed motion" forecast is significantly better in the case of linearly organised convection than in the case of random convection, but there is not significant improvement in difference between those situation when the lead time increses;
6. Automatic recognition of linearly organised convection is valuable, because it gives us information, that the advection forecast is better than in general, and is valid for longer lead time.

9. Remark

The analysis has been performed off line, in order to use the procedures on line a strong effort in optimising the software (rapidity) is necessary.

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11. Restrictions

The views here expressed are those of only the authors and the Managing Authority of the RISK AWARE Project (Italian Ministry of Infrastructure and Transport) is not liable for any use that may be made of the information contained in the paper.

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