Proceedings of ERAD (2004): 206–211 © Copernicus GmbH 2004

ERAD 2004

Nowcasting thunderstorms in the Alpine region using a radar based adaptive thresholding scheme

A. M. Hering[1], **C. Morel**[2], **G. Galli**[1], **S. Sénési**[2], **P. Ambrosetti**[1], **and M. Boscacci**[1]

[1]MeteoSwiss, ML/RASA, 6605 Locarno-Monti, Switzerland
[2]Météo-France, DPREVI/PI, 31057 Toulouse, France

Abstract. In this paper we present a new automated, radar based tool for thunderstorms nowcasting called TRT (Thunderstorms Radar Tracking). The goal of this real-time tool is the automated detection, tracking and characterization of intense convective precipitation systems. TRT uses the reflectivity data of the composite image of the Swiss radar network.

The algorithm is based on an adaptive thresholding scheme, which allows the detection of convective cells at individual thresholds, depending on their development phase. In this way, thunderstorms can be tracked very early during their growing phase (cells as small as a few 2×2 km pixels) as well as in the mature stage, and trajectories are created from a sequence of radar images. The tracking is based on the method of the geographical overlapping of cells. Splits and merges are also taken into account. TRT forecasts storm movement by extrapolating the motion of individual cells up to 1 h, using the weighted cell displacement velocity. TRT is used as a nowcasting tool in a pre-operational mode at MeteoSwiss since May 2003.

1 Introduction

The possible devastating consequences of convective events such as e.g. heavy thunderstorms with strong precipitation and hail are well known (e.g. flash floods). Such convective storms are still difficult to predict by operational numerical models because of the relative coarse resolution, the lack of observations of the initial state at the mesoscale, and the limited predictability of small mesoscale phenomena. Therefore, for very short-range forecast in the time range from 0 to a few hours ahead (nowcast) the national weather services tend to develop and use automatic non-numerical methods, which analyze the features of present weather and predict the development of already initiated phenomena, heavily based on observations. The main tools in this context are remote sensing observations like radar, satellite and lightning, as well as mesonet data. Operational nowcasting systems for precipitation are mainly based on the extrapolation of radar echoes.

Wilson et al. (1998) give a comprehensive status report of nowcasting thunderstorms. They discuss radar tracking as well as advanced nowcasting systems (expert systems) like e.g. the Auto-Nowcaster (Mueller et al., 2003). Based on conceptual models these expert systems try also to predict thunderstorms initiation combining the output of several sensors with a numerical model. During the Sydney 2000 Olympic games, sophisticated state-of-the-art nowcast systems were tested in an operational environment as part of the World Weather Research Programme Forecast Demonstration Project (e.g. Keenan et al., 2003; Weather and Forecasting, special issue, 2004). However little information is available concerning the performance of such expert systems in mountainous regions with complex orography, like e.g. the densely populated Alpine region in central Europe. Warner et al. (2000) state that in mountains the forecasts accuracy of complex nowcasting systems can greatly be limited by the poor quality of some of the required input data. They used the Auto-Nowcaster expert system to forecast a flash flood event in the mountains of Colorado. The complex terrain imposed serious limitations on the use of most of the components of the expert system. The only component of the Auto-Nowcaster that could be employed was the TITAN algorithm (Dixon and Wiener, 1993), a cell tracker that extrapolates radar images. According to Roberts and Rutledge (2003) it is difficult to detect boundary layer convergence lines in complex terrain with the Auto-Nowcaster and thus to predict the initiation of convection, because the radar beam is blocked at low altitudes. The only operational European expert system NIMROD/GANDOLF (Golding, 1998, 2000; Pierce et al., 2000) is mainly applied to areas with rather simple orography.

Correspondence to: A.M. Hering
(alessandro.hering@meteoswiss.ch)

Some radar based tracking tools are employed as well in mountainous regions in central Europe. Mecklenburg et al. (2000) discuss the application of the COTREC algorithm derived from the pattern recognition technique TREC, to the Swiss Alpine region. Steinacker et al. (2000) applied their automatic tracking method, based on lightning and radar data, to the Alpine region of Austria and southern Germany. The CONRAD system is an operational nowcasting tool of the German Meteorological Service (Lang, 2001). It is a radar cell tracking program that interprets convective cell activity, analyses cell stage and produces warning items. TRACE3D (Handwerker, 2002) is a tracking algorithm that identifies convective cells only by their reflectivity values (larger than a variable threshold), considering also splitting and merging. Extrapolation is performed using an individual velocity for each cell. The algorithm was applied to different case studies in southern Germany.

This contribution presents TRT (Thunderstorms Radar Tracking), a new automated, radar based tool for thunderstorms nowcasting, currently developed by MeteoSwiss and Météo-France. TRT is a real-time object-oriented nowcasting tool for the identification, tracking and monitoring of intense convective precipitation systems. It uses the reflectivity data of the Swiss radar network and provides real-time information to the forecasters for convection warning.

TRT is based on the adaptation to Alpine radar images and further development of the severe thunderstorms detection and tracking methods developed for the RDTproduct (Rapid Developing Thunderstorms). RDT is a tool for the detection of convective systems, from isolated cells up to mesoscale convective complexes, in the infrared images of the 10.8 μm channel of geostationary satellites like MSG (Morel et al., 2000, 2002). The RDT-product is developed by Météo-France, within the framework of SAF (Satellite Application Facility) Nowcasting of EUMETSAT.

The core of the RDT satellites algorithm could be maintained in the TRT radar algorithm. Nevertheless, substantial modifications were necessary for the data input modules and a suitable post-processing for data output was added. The large differences in the characterisation of a convective cloud by satellite data (mainly brightness temperature on a linear scale) and the corresponding radar cells (mainly reflectivity on a logarithmic scale), as well as different data formats, time and spatial resolutions and georeferencing, must be accounted for in the new data input. The RDT output mainly describes morphological (e.g. area) and radiative features of the detected cloud systems, as well as trajectories characteristics. This requires a major post-processing of the output, in order to account for the differences when ingesting radar data into the system and to calculate radar features not relevant for the satellite tool. A comprehensive study of the RDT algorithm parameters, such as the different reflectivity thresholds (see Sect. 3.1), was also necessary for their adaptation to radar data.

TRT first detects cells and then tracks them in consecutive images. In Sect. 2 an overview of the radar data source used as input is given. Section 3 will briefly present the TRT detection and tracking algorithms. Finally a case study showing an application of TRT is discussed (Sect. 4), and the preliminary results and impressions from the use of TRT in the operational service are given in Sect. 5.

2 Input data

The input radar data used by the TRT algorithm are reflectivity values of the Swiss composite image. The radar network consists of 3 volumetric C-band Doppler radars (Gematronik) located at 1680, 930 and 1630 m a.s.l., with a sensitivity of 0.2 mm/h at 230 km. A 20-elevation volume scan between $-0.3°$ and $40°$ is performed every 5 minutes. The Cartesian composite images are available with a spatial resolution of 2 km on 16 reflectivity classes between $<$13 and $>$55 dBZ. At present the vertical maximum projection from 12 constant height horizontal surfaces (CAPPI) between 1 and 12 km, is used for TRT.

A qualitatively good radar network with effective clutter elimination algorithms is a prerequisite for a successful detection and tracking of convective cells in complex orography. The main problems concerning the data quality of the Swiss radar network in the Alpine area are caused by shielding effects and ground clutter. Thus a sophisticated 7-step clutter elimination algorithm is applied at the MeteoSwiss radar sites, as well as an extensive quality control program. The reflectivity values have already passed these clutter and quality check algorithms before the ingestion into the TRT-tool. An overview of the MeteoSwiss solution to avoid and eliminate ground clutter can be found in Germann and Joss (2003).

3 The TRT algorithm

3.1 Cell detection

The detection algorithm aims at identifying convective cells in a precipitation system. Each cell detected by the TRT is described as a meteorological object with its computed particular attributes like e.g. geographical location, area, motion vector, velocity, average and maximum reflectivity, and growth rate. The TRT detection method is based on a reflectivity thresholding of radar images that allows the detection of convective cells at individual thresholds, depending on the stage of their life cycle, thus an adaptive reflectivity thresholding (Crane, 1979). For each cell it permits the selection of the lowest reflectivity threshold that allows to distinguish it from nearby cells, if it shows a large enough reflectivity range (see Fig. 1). The challenge of convection warning is the early observation of thunderstorms formation and the isolation of multicells agglomerations. A low fixed threshold would lead to the clustering in a unique object of large areas including cells with very different reflectivity values, whereas a high threshold would detect only reflectivity cores in mature cells. With algorithms using a fixed threshold (e.g. TITAN, Dixon and Wiener, 1993) this is a difficult

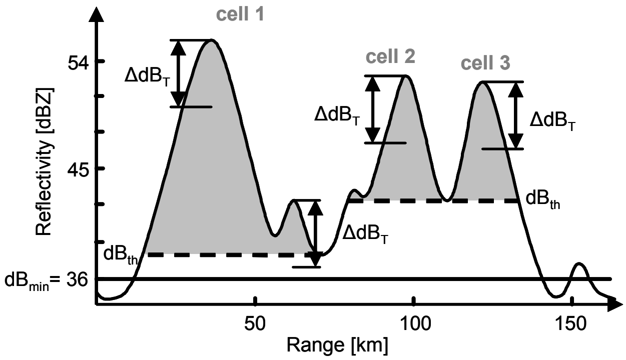

Fig. 1. Vertical reflectivity cross-section of an idealized precipitation system with a schematic illustration of the TRT detection algorithm. Reflectivity thresholds: dB_{th} (detection), dB_{min} (minimum value), and $\Delta\mathrm{dB}_T$ (vertical extension).

task. To this purpose the adaptive method used in TRT, derived from the RDT-product (Morel et al., 2000, 2002), is based on three different reflectivity thresholds: dB_{th}, dB_{min}, and $\Delta\mathrm{dB}_T$ (see below).

A cell is defined as a connected zone of radar pixels (8-connectivity) larger than a given area (area threshold at present $\geq$4 pixels i.e. 16 km^2) and whose reflectivity exceeds an adaptive detection threshold (dB_{th}). This threshold must reach at least a minimum value dB_{min} (at present 36 dBZ, bold line in Fig. 1). In order to detect only cells with a sufficient vertical extension (dynamic range in reflectivity), as represented in Fig. 1, the difference between the maximum reflectivity value and the value at the base of a cell must be larger than a vertical extension threshold $\Delta\mathrm{dB}_T$ (at present 6 dB). The lowest possible detection threshold (dB_{th}) satisfying these conditions is then chosen (dashed lines in Fig. 1).

These different threshold values are derived from our experience with the testing of several threshold combinations. In this sense 36 dBZ is not an exact definition of a convective cell, but an empirical threshold on one hand suitable for an early detection of potentially dangerous convective cells and on the other hand it prevents the detection of a too large amount of weak cells in the region of interest. The area threshold ($\geq$4 pixels) is the smallest value that allows to eliminate most of the few remaining "clutter-cells" in the radar images, and at the same time to limit the number of detected very small cells to a reasonable number for the forecasters. With the actual thresholds configuration cells are therefore considered convective and thus detected if they reach an area of 16 km^2 (4 pixels) at 36 dBZ (or higher) and at least one pixel attain a reflectivity of 42 dBZ (=$\mathrm{dB}_{min} + \Delta\mathrm{dB}_T$). In this case the detection threshold would be dB_{th} = 36 dBZ.

The application of these rules leads to the detection of three cells in Fig.1: cell 1 and cell 2 both include a less intense cell, less tall than the vertical extension threshold $\Delta\mathrm{dB}_T$ and which is thus incorporated in the more intense cells. The cell located at a range of 150 km does not have a sufficient vertical extension and is rejected.

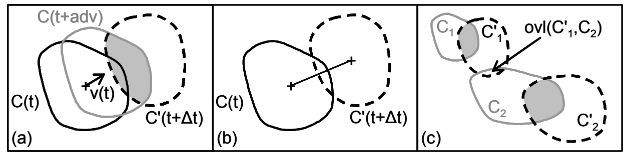

Fig. 2. Principle of the TRT tracking algorithm showing a simple overlapping (a) leading to a unique link (b) between cells at time t and t+Δt. Complex case (c) with a rejected overlapping. Centres of gravity are represented by "+". Adapted from Morel and Sénési (2002).

Cells are thus each detected at a specific threshold, depending on their development phase. This allows the detection of thunderstorms at an early stage of their life cycles (at present cells as small as 16 km^2) at the lowest possible reflectivity threshold (dB_{min}), as well as in the mature phase at a higher threshold. The TRT detection method is somehow similar to the SCIT algorithm (Johnson et al., 1998), which uses several fixed thresholds at 5 dB intervals, and also to the principle of the TRACE3D algorithm (Handwerker, 2002), which define cells from a contiguous region at 10 dB beneath the region maximum, but TRT detects cells at the lowest possible reflectivity threshold using 3 dB intervals. This should lead to the definition of slightly larger cells, easier to track.

3.2 Cell tracking

The goal of the tracking is to link objects in consecutive radar images at time t and t+Δt if they represent the same phenomena. Detected cells are tracked in successive images by the TRT tracking algorithm based on the method of the geographical overlapping of cells, taking into account their displacement velocity. Trajectories indicating time histories of cells displacement can thus be created from a sequence of radar images. A detailed description of the TRT tracking algorithm, derived from the RDT, can be found in Morel et al. (2000, 2002), and Morel and Sénési (2002). It is summarised afterwards.

The idea of the tracking algorithm is to search for an overlapping between a cell C detected in the image at time t and a cell C' detected at time t+Δt (Fig. 2a). To this purpose, the cell C(t) is first advected (grey cell in Fig. 2a) according to its estimated displacement velocity to the position C(t+adv). If the overlapping (grey area in Fig. 2a) between the advected cell and C'(t+Δt) is sufficient, a link is created between these cells (Fig. 2b). Complex cases with several cells are handled analogously linking cells with enough overlapping. Figure 2c shows such a case with a secondary link between the advected cell C_2 and C'_1(t+Δt). Since this overlapping ovl(C'_1,C_2) is less than a fixed percentage of cells area (not shown) it is rejected.

Splits and merges of cells are taken into account as well. In this case several links are created between detected cells, and trajectories are continued in the larger cell, whereas the smaller ones die (are born), ending (beginning new) trajectories. For an improved tracking of very small cells, if no

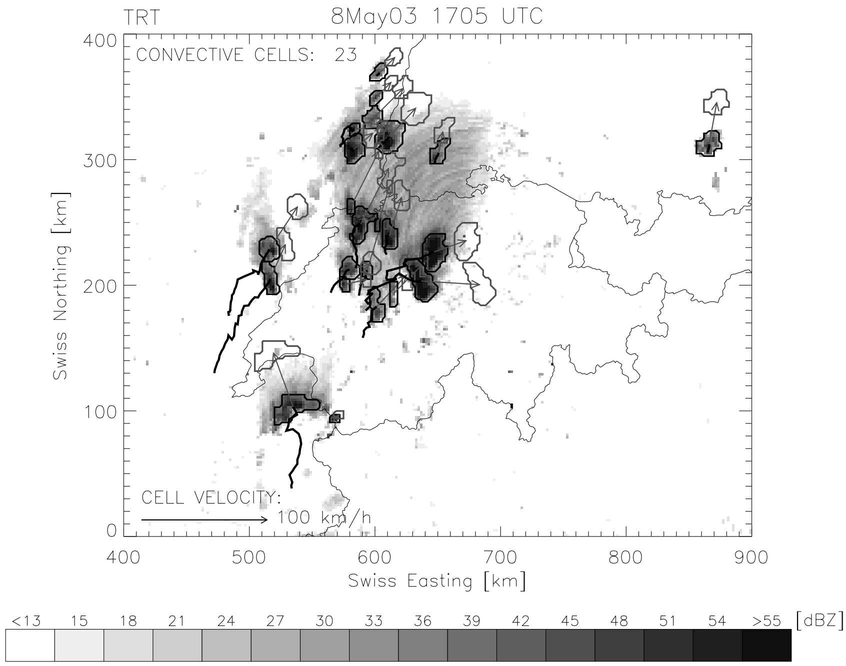

Fig. 3. Visualisation of the real-time TRT-product (8 May 2003, 17:05 UTC) over the Alpine region. Superposition of the composite image of 3 radars (2 north and 1 south of the Alps), detected cells (black contours), trajectories (black), velocities (grey vectors), and extrapolated cells positions (+ 1h; grey). The Swiss border is also represented. Centre of image: LON=8.1 E, LAT=46.9 N.

overlapping is found, the size of these cells is artificially increased adding pseudo pixels along their edges, to facilitate the search for an overlapping.

The evaluation of cells velocity is based on the displacement of the cells centres of gravity (Fig. 2b). If no displacement can be found (e.g. in case of first detection), the velocity is estimated from cross-correlation technique (Morel et al., 2000). To determine the cell displacement velocity, instead of simply using that from the latest time step, a weighted average of all previous velocities is calculated recursively with a decreasing weight beginning with the latest time step. Up to a 1 h thunderstorms movement forecast is performed extrapolating the motion of individual cells by means of their weighted displacement velocity, to give a guess for the expected position. This linear extrapolation forecast method may be reliable for some tens of minutes, depending on the meteorological situation.

4 Case study: 8 May 2003

The performance of the TRT-tool is illustrated by means of a case study from 8 May 2003 recorded during real-time test operational activities. The synoptic situation was characterized by a flat pressure distribution over central Europe with a shallow low-pressure system moving from Spain to France. With the approach of a weak cold front, warm and humid air was advected from the southwest to western Switzerland. This further increased the instability of the atmosphere. Thunderstorms activity started in the afternoon in western Switzerland, with a slow movement to northeast and hail tracks extending to eastern Switzerland.

Figure 3 shows an example of a TRT-visualisation with a superimposition of the composite radar image and the detected convective objects. Three precipitation areas can be distinguished; they correspond to three large convective cloud systems on the satellite image (not shown). On the radar image 23 cells of different sizes (from a few pixels up to a size of about 50×20 km) and intensities are detected, with maximum reflectivities in the range 42 dBZ to >55 dBZ (the highest reflectivity class in our pictures). Pixels >55 dBZ indicate also a certain hail probability at ground.

Detected cells are represented by their contours, which delineate the effective detection thresholds (dB_{th}). These values, as well as additional cell properties such as maximum reflectivity, trajectory duration, velocity and area are available through a popup window selecting the desired cell. Trajectories (black) are displayed on the same image indicating historical, as well as actual cell positions. They represent the connection of cell centres i.e. the tracks.

Grey arrows in Fig. 3 show the weighted displacement velocities in km/h (the 100 km/h vector is drawn on the left bottom). They are used to forecasts thunderstorms motion extrapolating cells contours by 1 h (grey cells). This gives a guess for the expected future cell position. Since the extrapolation depends on velocities, the regularity in the latest time steps from the history of this attribute is determinant for a successful forecast. Regular vectors indicate a useful extrapolation for some tens of minutes, whereas vectors strongly varying in direction and speed indicate an unreliable forecast and the future cell position is thus uncertain. This is best seen in the TRT animation loop (at 5 min time step) containing at least a few pictures of the same trajectory. In Fig. 3 reliable vectors are characterized by a direction continuity with the trajectories (speed quality can not be evaluated in this static image).

As indicated by the tracks, the dominant movement direction in this case study is from southwest to northeast. The trajectory with the longest duration (155 min, 31 time steps) belongs to the cell at position [515;205] (W-E,S-N) with an area of 156 km^2 and maximum reflectivity >55 dBZ.

Another interesting cell is the intense one located about at [645;225]: this is probably a supercell with its movement turning to the right of the main precipitation field displacement. Highest reflectivity values (>55 dBZ) cover an area of about 180 km^2. Hail was also observed at ground with hailstones up to 4 cm in diameter. The cell belongs to a trajectory that lasts from 15:20 to 23:00 UTC and extends from central Switzerland to southern Germany (Fig. 4). The track shows a quite regular development, although some jitter indicates past cell splittings and mergings, as well as detection threshold changes. Sometimes these threshold changes, due mainly to the large spatial and temporal dynamics of the radar pixels field, cause some stability problems in cell detection that remain to be solved.

The direction of the velocity vectors from the cell forming the trajectory, correspond quite good with the effective cell track. However, one recognizes a few outliers that correspond to jitter points in the trajectory. The quality of the cell speeds will be the subject of further investigations.

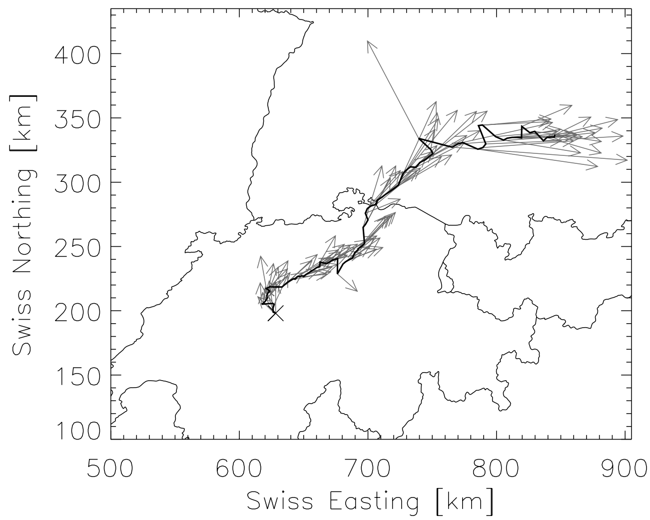

Fig. 4. Trajectory starting near Langnau in central Switzerland (8 May 2003, 15:30 UTC) end ending near Augsburg in southern Germany (23:00 UTC). An "X" marks the starting point. The velocity vectors (time step 5 min) of the whole trajectory are represented as well.

5 Operational use

MeteoSwiss uses the TRT algorithm as a nowcasting tool in pre-operational mode since May 2003. It provides objective quantitative information's about cells characteristics and movements. The forecaster receives thus automated cells activity information in real-time, which he can use as a decision-making aid for convection warning. The use of an automated methodology for cells detection and tracking, as well as for position extrapolation, is a considerable improvement with respect to the mainly subjective visual evaluation of the radar image done till now.

In Switzerland the summer 2003 was characterized by a long dry period with relatively stable high pressure conditions and only a few interesting intense convective situations. This fact, combined with the short operation period, has not allowed a full use of the TRT-tool by all MeteoSwiss forecasters and thus a statistically significant analysis of their statements is not yet possible. However, the evaluation performed by means of a form filled in at the end of a shift during convective situations, showed some interesting qualitative preliminary results.

Main complains from users concern the visualisation of the product, and therefore this point was substantially improved for summer 2004.

One of the main uses of TRT was the forecast of thunderstorm movement in convective situations. The cell displacement velocity vectors used to this purpose (see Sect. 3.2) were considered as generally correct and well organized (in some cases they were used for wind gust warnings) but sometimes also inconsistent, especially in low wind situations with nearly stationary cells, for large cells with rather weak intensity and in case of several rather small and weak cells. This shows the limits of the linear extrapolation method based on the weighted cell displacement velocity. A different approach is presently under test: the motion of individual cells is extrapolated using the velocity estimated for each one from cross-correlation process, as already done if tracking fails (Sect. 3.2).

It appears that cells with rapid development are rather precociously detected and followed relatively well in the majority of the cases (see also Sect. 4). Best tracking performance is achieved in case of isolated, not too small cells. Weak points were indicated in case of frontal passage. The TRT-tool was considered as generally useful for decision-making aid, but with the weakness described above that must be improved in a new version. Especially the prognostic aspect must be enhanced, and this can probably be achieved with the cross-correlation cell motion extrapolation method currently under development.

6 Summary and outlook

TRT is a new promising tool, derived from the RDT, for the automatic identification, tracking and monitoring of intense convective cells in complex orography, based on radar composites. It is used at MeteoSwiss in a pre-operational mode for nowcasting activities since May 2003 showing an encouraging performance and acceptance of routine forecasters.

In order to detect and track cells in an early development stage, as well as mature systems, an adaptive thresholding scheme is used, allowing an individual detection threshold for each cell, depending on the stage of their life cycle. TRT is also able to handle rather small cells, actually down to 16 km^2 (4 pixels), allowing the observation of thunderstorms formation. The detected cells are tracked in successive images based on their geographical overlapping. Splits and merges are accounted for and trajectories indicating cells displacement are created from a sequence of radar images. Future storm position is estimated extrapolating the motion of individual cells up to 1 h, by means of their weighted cell displacement velocity, i.e. information's on past location and speed, to give a tendency for the expected position.

TRT calculates also time histories of several cell attributes (e.g. area of various reflectivity surfaces). At present, this capacity has not yet been fully exploited for nowcasting purposes and will be subject of further investigations in order to improve the skill of the system. Another open point is the determination of the development phase of a thunderstorm. The ingest of lightning data could be a useful improvement in this context, allowing the unambiguous discrimination of convective systems and thus give a complementary hint at thunderstorms phase.

At present the vertical maximum projection of reflectivity is used for TRT. This allows it to maintain the core of the algorithm developed for the RDTproduct and applied to 2D satellite images. A more extensive use of 3D reflectivity data could be useful for an improved characterization of convective cells and of their development, but seems un-necessary for the tracking phase.

TRT allows an automatic identification and tracking of convective cells. This feature will be used for an automatic long-term (e.g. 1–3 years) climatological study of thunderstorms properties. Applying TRT to many radar images we could thus get a large sample of cells and trajectories in the Alpine region, and investigate for instance their lifetime, origin, typical tracks as well as other thunderstorms characteristics, as a function of mesoscale environment, orography etc. This could be very useful for convection nowcasting purposes as well.

Acknowledgement. We want to thank Dr. U. Germann from MeteoSwiss for the valuable discussions and suggestions.

References

Crane, R. K.: Automatic cell detection and tracking, IEEE Trans. Geosci. Electron., GE-17-(4), 250–262, 1979.

Dixon, M. and Wiener, G.: TITAN: Thunderstorm identification, tracking, analysis and nowcasting – a radar-based methodology, J. Atmos. Oceanic Tech., 10, 785–797, 1993.

Germann, U. and Joss, J.: Operational measurement of precipitation in mountainous terrain, in P. Meischner (Ed), Weather Radar: Principles and Advanced Applications, vol. XVII of Physics of Earth and Space Environment, chap. 2, pp. 52–77, Springer-Verlag, 2003.

Golding, B. W.: Nimrod: A system for generating automated very short range forecasts, Meteorological Applications, 5, 1–16, 1998.

Golding, B. W.: Quantitative precipitation forecasting in the UK, J. Hydrol., 239, 286–305, 2000.

Handwerker, J.: Cell tracking with TRACE3D – a new algorithm, Atmospheric Research, 61, 15–34, 2002.

Johnson, J. T., MacKeen, P. L., Witt, A., DeWayne Mitchell, E., Stumpf, G. J., Eilts, M. D., and Thomas, K. W.: The Storm Cell Identification and Tracking algorithm: an enhanced WSR-88D algorithm, Wea. Forecasting, 13, 263–276, 1998.

Keenan, T., Joe, P., Wilson, J., et al.: The Sydney 2000 World Weather Research Programme Forecast Demonstration Project: Overview and Current Status, Bull. Amer. Meteor. Soc., 84, 1041–1054, 2003.

Lang, P.: Cell tracking and warning indicators derived from operational radar products, Proc., 30th Int. Conf. on Radar Meteorology, Munich, Germany, Amer. Meteor. Soc., 245–247, 2001.

Mecklenburg, S., Joss, J., and Schmid, W.: Improving the nowcasting of precipitation in an Alpine region with an enhanced radar echo tracking algorithm, J. Hydrol., 239, 46–68, 2000.

Morel, C., Sénési, S., Autones, F., and Labatut, L.: The Rapid Developing Thunderstorms (RDT) product of the nowcasting SAF. Prototyping activities and quality assessment using GOES images, Proc. The 2000 Meteorological Satellite Data Users' Conference, Eumetsat and CNR, Bologna, Italy, 698–705, 2000.

Morel, C., Sénési, S., and Autones, F.: Building upon SAF-NWC products: Use of the Rapid Developing Thunderstorms (RDT) product in Météo-France nowcasting tools, Proc. The 2002 Meteorological Satellite Data Users' Conference, Eumetsat and Met Eirean, Dublin, Ireland, 248–255, 2002.

Morel, C. and Sénési, S.: A climatology of mesoscale convective systems over Europe using satellite infrared imagery. Part I: Methodology, Q. J. R. Meteorol. Soc., 128, 1953–1971, 2002.

Mueller, C., Saxen, T., Roberts, R., Wilson, J., Betancourt, T., Dettling, S., Oien, N., and Yee, J.: NCAR Auto-Nowcast System, Wea. Forecasting, 18, 545–561, 2003.

Pierce, C. E., Collier, C. G., Hardaker, P. J., and Hagged, C. M.: GANDOLF: A system for generating automated nowcasts of convective precipitation, Meteorological Applications, 7, 341–360, 2000.

Roberts, R. and Rutledge, S.: Nowcasting storm initiation and growth using GOES-8 and WSR-88D data, Wea. Forecasting, 18, 545–561, 2003.

Steinacker, R., Dorninger, M., Wölfelmaier, F., and Krennert, T.: Automatic tracking of convective cells and cell complexes from lightning and radar data, Meteorol. Atmos. Phys., 72, 101–110, 2000.

Warner, T. T., Brandes, E. A., Sun, J., Yates, D. N., and Mueller, C. K.: Prediction of a flash flood in complex terrain. Part I: a comparison of rainfall estimates from radar, and very short range rainfall simulations from a dynamic model and an automated algorithmic system, J. Appl. Meteor., 39, 797–814, 2000.

Weather and Forecasting: Sydney 2000 special issue, Wea. Forecasting, 19, 1, 7–178, 2004.

Wilson, J. W., Crook, N. A., Mueller, C. K., Sun, J., and Dixon, M.: Nowcasting thunderstorms: a status report, Bull. Amer. Meteor. Soc., 79, 2079–2099, 1998.