

2.3 Nowcasting Thunderstorms for Munich Airport

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The successful demonstration and assessment of the DLR thunderstorm nowcasting algorithms at Munich Airport during two campaigns in the summers of 2010 and 2011 are described. The algorithms Cb-TRAM and Rad-TRAM, that detect, monitor, and forecast up to one hour (nowcast) thunderstorm cells from satellite and radar data, run in real time and provided new thunderstorm products for users at the airport. The products were presented on displays the users were already familiar with as well as on webpages designed by DLR. On the webpages, also additional information like measurements with DLR's polarimetric radar and model forecasts was shown. Moreover, thunderstorm warnings were issued and sent via email to the users whenever a thunderstorm was detected in the terminal manoeuvring area of the airport of Munich. The nowcasting skills of Rad-TRAM and Cb-TRAM are encouraging, especially for lead times up to 30 minutes, and the user feedback on the DLR thunderstorm products was very positive. The Rad-TRAM and Cb-TRAM products provide a good overview on the situation and its future development, and the thunderstorm warnings were very helpful for the collaborative decision making at the airport. However, some suggestions for improvements were made like the demand for nowcasts beyond one hour. This will be considered within the integrated weather forecast system, WxFUSION, which has been further developed during the campaigns.

Introduction

Thunderstorms are related to hazardous phenomena like turbulence, icing, hail, heavy rain, lightning and reduced visibility that can lead to considerable obstructions in the air transport system. For instance, if a thunderstorm passes an airport, ground operations might have to be stopped and flights have to be re-routed in holding patterns or even diverted because of hazardous weather phenomena in the airport's terminal manoeuvring area (TMA). It is clear that delays and diversions at one airport lead to delays and diversions at other airports as well. According to Quon [2006], adverse weather is the primary reason for disruptions in the air transport system in the U.S. Over Europe, adverse weather is responsible for 40-50% of all delays [EUROCONTROL, 2007], and according to the German air navigation safety provider DFS (personal communication), more than 80% of the delays at Munich Airport (MUC), Germany, are due to weather with thunderstorms and fog as the primary reasons. These numbers indicate that there is a clear need for weather information systems that help all air space users to plan well in advance and enable the mitigation of the weather hazard's effects. If all decision makers in the air and at the ground have access to the same weather information systems, the collaborative decision making process can be accelerated considerably.

Many of the weather data and tools available to date have to be interpreted by the user before any action can be triggered. However, as air space users often have to make quick decisions especially during thunderstorm situations, they need simple and easy to read information which does not need any interpretation. Recently, the algorithms Cb-TRAM (Cumulonimbus Tracking and Monitoring) [Zinner et al., 2008; Zinner and Betz, 2009] and Rad-TRAM (Radar Tracking and Monitoring) [Kober and Tafferner, 2008] have been developed at DLR. They provide thunderstorm detections and forecasts up to one hour (nowcast) especially for aviation purposes. Hazardous areas for aircraft are represented by simple contours, see Section 5.2 for details. In addition, an integrated weather forecast system named WxFUSION (Weather Forecast User-Oriented System Including Object Nowcasting) [Forster and Tafferner, 2009b] is currently under development at DLR with the aim to combine different data from observations and numerical models in order to detect, nowcast (up to 6 hours), and forecast (beyond 6 hours) weather phenomena like thunderstorms as precisely as possible.



For the development of such algorithms and systems, feedback of the users is needed in order to optimise the output of the algorithms in terms of the user's requirements. Therefore, two summer campaigns have been initiated and performed at MUC airport during 2010 and 2011. One of the aims of these campaigns was the demonstration and test of the DLR nowcasting products at MUC in close cooperation with the German Meteorological Service (DWD) and users from DFS, the Lufthansa Hub Control Center (DLH-HCC), and the Munich Airport operations (FMG). This paper will present the results of these campaigns with regard to thunderstorm nowcasting and outline recent developments with regard to WxFUSION. Other activities during the campaigns like wake vortex forecasts and air traffic operational concepts will be described in other contributions of this report [Holzäpfel et al. 2011; Mollwitz and Korn, 2011]. In the following, we introduce the DLR nowcasting algorithms Cb-TRAM and Rad-TRAM; we describe the activities and specific goals of the two campaigns in more detail; we present an example of a typical thunderstorm situation at MUC and the products provided by DLR; then, the user feedback and the quantitative evaluation of the nowcasting products during the campaigns are discussed before we conclude our study and give an outlook.

The DLR Nowcasting Algorithms

Cb-TRAM

Cb-TRAM (Cumulonimbus Tracking and Monitoring) is a fully automated algorithm for the detection, tracking, and nowcasting of thunderstorms by using satellite data from METEOSAT SEVIRI (Spinning Enhanced Visible and Infra-Red Imager) [Zinner et al., 2008; Zinner and Betz; 2009]. The four different spectral channels high resolution visible (HRV), infra-red (IR) 10.8 μm , IR 12.0 μm , and water vapour (WV) 6.2 μm are combined in order to identify three different stages of thunderstorm development: (1) convection initiation, (2) rapid vertical development, and (3) mature stage (Figure 1). Note that Cb-TRAM is able to detect the most active parts within huge cloud systems. Over Europe, METEOSAT data have a spatial resolution of about 5x5 km² and are available either every 15th minute (METEOSAT-9 normal scan) or every 5th minute (METEOSAT-8 rapid scan). The tracking in Cb-TRAM is based on the geographical overlap between current detections and first-guess patterns of cells detected in preceding time steps. At a time, the first-guess patterns are retrieved by using the approximate propagation direction and velocity of a detected cloud pattern during the previous 30 minutes in combination with an image-matching algorithm [cf. Zinner et al., 2008]. This algorithm extracts the general transformation vector field from several consecutive satellite images, thereby describing the cloud motion and local cloud developments. Similar to the first-guess patterns, nowcasting intervals from 5 to 60 minutes are generated by extrapolation and exploitation of the pyramidal image-matching algorithm. Additional details as well as application and validation studies of Cb-TRAM were provided by Zinner and Betz [2009], Tafferner et al. [2008], Forster et al. [2008], Dotzek and Forster [2010], and Zinner et al. [2011].

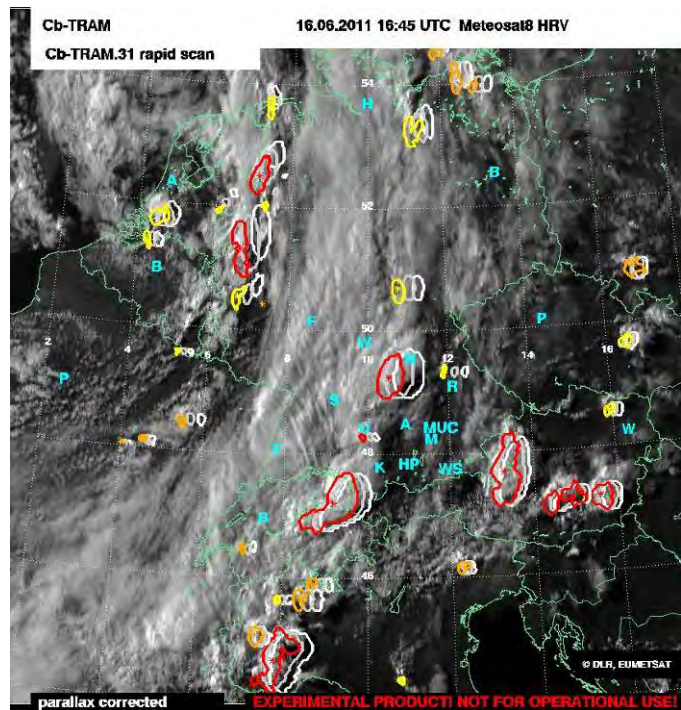


Figure 1. HRV image from METEOSAT-8 over middle Europe with Cb-TRAM objects as polygons; yellow, orange, and red indicate detected development stages 1, 2, 3. Grey and white contours indicate the 15 and 30 minutes nowcasts.

Rad-TRAM

Rad-TRAM (Radar Tracking and Monitoring) is a detection, tracking, and nowcasting algorithm for heavy precipitation cells by using weather radar data [Kober and Tafferner, 2008]. A reflectivity threshold of 37dBZ is used in order to identify hazardous precipitation areas for air traffic (Figure 2). This threshold has been chosen, as precipitation with reflectivity ≥ 37 dBZ often corresponds to lightning activity within the most active parts of thunderstorms. In addition, experience has shown that pilots often avoid flying through precipitation with reflectivity ≥ 37 dBZ. During the summer campaign 2010, Rad-TRAM was based on the European radar composite (PM product)

provided by the DWD. It has a spatial resolution of 2km x 2km and a temporal resolution of 15 minutes. For the summer campaign 2011, Rad-TRAM was set up on a new DWD product, the EURADCOM composite which covers Central Europe with a spatial resolution of 1km x 1km and a temporal resolution of 5 minutes. The EURADCOM product has been especially developed for aviation purposes in the Functional Air Space Block European Central (FABEC). Rad-TRAM's tracking and nowcasting is based on the same principle as in Cb-TRAM. For more details on Rad-TRAM applications see Kober and Tafferner [2008] and for details on the tracking and nowcasting technique see Zinner et al. [2008].

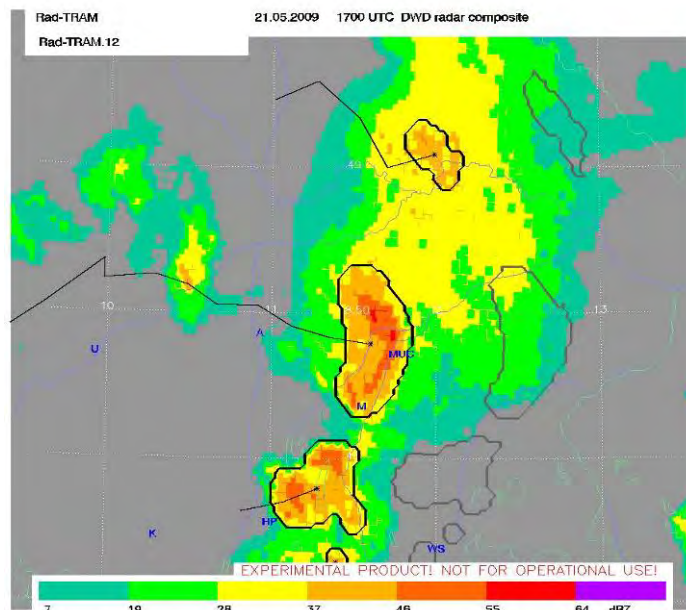


Figure 2. DWD weather radar composite (colored shading) over TMA MUC with detected Rad-TRAM Cb cells (black polygons); grey polygons indicate 60 minutes nowcast; black lines are the tracks of the objects.

The Summer Campaign 2010

During 2010, the campaign was performed within the Wetter & Fliegen project. It took place from 1 June until 15 August 2010. The focus of this first campaign was the demonstration of the products to the users who should test them and give feedback on their benefits and disadvantages. The DWD provided input data for the DLR nowcasting tools as well as other observational and forecast data and acted as an observer of the activities during the campaign. In case of a positive user feedback with regard to the DLR nowcasting tools, the DWD considers to implement Cb-TRAM and Rad-TRAM in its operational service.

Cb-TRAM and Rad-TRAM products were provided in real time directly from DLR to the DFS Center at MUC, the DFS Tower MUC, the DLH_HCC, and the FMG. They were presented on a website from DLR (<http://www.pa.op.dlr.de/nowcasting/>) which was updated whenever a new Cb-TRAM or Rad-TRAM product was available. During 2010, the refresh rate was 15 minutes. Both Cb-TRAM and Rad-TRAM were displayed also in real time in the Weather Image Information System (WIIS) by the company WIIS GmbH. WIIS was already well-established at LH HCC, FMG, and DFS Center MUC, i.e. the users could test the DLR products in displays they were familiar with. Feedback of the users was collected via e-mail and via a questionnaire.

In addition to the nowcasting tools, also products from the DLR polarimetric Doppler radar POLDIRAD were provided to the users. POLDIRAD is a C-Band radar with polarisation agility for transmitting, dual-channel receiving, and Doppler capability. It was operated during thunderstorm situations only, but provided the advantage that vertical scans through specific thunderstorm clouds could be performed manually if necessary and that hydrometeors could be distinguished due to the polarisation capability. These



skills were very helpful to estimate the echo top of a thunderstorm and the location of hail within the cloud. If operated, POLDIRAD can provide its products in 10 minutes intervals. They were available for the users on a website (<http://www.pa.op.dlr.de/poldirad/>).

From the DWD COSMO-DE model, parameters important for take-off and landing procedures as well as for airport operations like wind, total precipitation, and temperature were extracted and graphically prepared for the TMA MUC (COSMO-MUC). The COSMO-MUC forecasts were updated every hour and products were displayed in 15 minutes intervals at <http://www.pa.op.dlr.de/MUCSOMMER2010/>.

In order to draw the attention of the users to our products during thunderstorm situations, thunderstorm warnings were issued by DLR via e-mail to all users involved in the campaign whenever thunderstorms were detected and forecast in the TMA MUC. The warnings were simple and short text messages describing the situation and giving an overview of the situation by an attached image displaying Cb-TRAM and/or Rad-TRAM output. As these warnings were issued by hand, it was necessary to permanently monitor the weather and especially the thunderstorm situation. For this, not only the nowcasting tools Cb-TRAM and Rad-TRAM, but also other weather information and tools from the DWD within in the Ninjo Workstation were used.

LH HCC offered DLR a working place in the HCC area during the whole campaign period, i.e. whenever there was a thunderstorm situation, DLR staff had the possibility to be directly in contact with the people responsible for operations at the airport and with air traffic controllers. For instance, the director of operations at the LH HCC could explain his work and its dependence on the current weather situation, while DLR staff could in turn explain the thunderstorm products and how they can be used at LH HCC. Within the course of the campaign it turned out that these conversations and discussions were very valuable for both sides. The DLR staff learned much about the chain of operations at the airport and the related needs with regard to thunderstorm information, while the users learned about modern weather information and how it can facilitate their work.

For a later evaluation of the campaign, it was necessary to collect information and establish a documentation of all thunderstorm days during the campaign period. This has been done on a campaign website, where different links to the documentation and the products offered by DLR are available (<http://www.pa.op.dlr.de/MUCSOMMER2010/>).

Finally, the integrated weather information system WxFUSION has been tested and further developed during the campaign period. As the system is still under development, the WxFUSION products have not yet been presented to the users at the airport, but have been tested internally.

The Summer Campaign 2011

As the summer campaign in 2010 was successful and resulted in a very positive user feedback (see below), the DFS requested a repetition of the campaign in 2011 with slightly different and additional activities described below. Since a second summer campaign could not be supported within Wetter & Fliegen, the DFS was prepared to sponsor the summer campaign 2011 within the LuFo IV project iPort. The campaign took place from 1 June until 30 September 2011. Its focus was again the demonstration of the nowcasting products and their test by the users (this time users at DFS only) as well as the collection of further and more detailed user feedback.

This time, Cb-TRAM and Rad-TRAM were test-wise installed and running at the DWD, i.e. Cb-TRAM and Rad-TRAM output was directly provided in real time to the users by the official weather data supplier for aviation in Germany. This is an important step towards an implementation of the DLR algorithms in the operational service by the DWD. It could be shown that the installation of the algorithms in the environment at DWD is not complicated, and that the algorithms were running stable over the whole campaign period. In addition, Cb-TRAM and Rad-TRAM output could easily be included in the Ninjo test version and was tested by the DWD at MUC.

The Rad-TRAM and Cb-TRAM output data were provided every 5th minute and were collected and stored by the DFS during the whole campaign period. They are used for evaluation purposes and for the test-wise integration in DFS displays like MetFROG and PHOENIX, a special weather information display for air traffic controllers and the controller display in the tower, respectively. Rad-TRAM could already be demonstrated in real time in the MetFROG test display during summer 2011. It was tested at several places within the DFS, e.g. Tower MUC, Tower Köln/Bonn, Tower Düsseldorf, and Center Operation Support. So far, detailed feedback has been received from the Tower MUC (see below).

Similar to the campaign in 2010, the DLR products were also displayed on the DLR nowcasting site (<http://www.pa.op.dlr.de/nowcasting/>), a documentation of all thunderstorm days has been established (<http://www.pa.op.dlr.de/MUCSOMMER2011/>), and DLH-HCC kindly offered the working place in the HCC again. As the thunderstorm warnings turned out to be very helpful, they have been issued again on demand of the DFS Tower MUC. In addition, new POLDIRAD products were presented to the users on a website (<http://www.pa.op.dlr.de/poldirad/rainbow.html>). This includes vertical cross sections through thunderstorm cells along the glide path at MUC as well as Doppler velocities and vertical wind profiles.

Finally, the Bayerische Rundfunk (BR) prepared a documentary about clouds for the series "Faszination Wissen" in which thunderstorm clouds and aviation were one of the key topics. A BR team visited DLR on 19 July 2011 in order to document the DLR activities for the nowcasting of thunderstorms for aviation. Fortunately, this day was a thunderstorm day at MUC airport, and the DLR team could demonstrate the skills of their nowcasting tools to the film team in real time. The shooting was done both at the working place in the DLH HCC at MUC and in the office of the DLR team at Oberpfaffenhofen. The documentary has been shown on the Bavarian TV on 6th of November 2011.

An Example Case: The 19th of July 2011

As an example of how the DLR nowcasting products were presented to the users, the thunderstorm case on 19th July 2011, when a BR team filmed at DLR, will be shown here. Ahead of a low pressure system, warm and humid air masses were advected to Bavaria. At 16:15 UTC, the vortex of the low pressure system over France can clearly be seen in the HRV satellite image with Cb-TRAM contours superimposed (Figure 3a). Convection initiation (yellow contours) is detected near the center of the low pressure system, and a mature thunderstorm (red contour) has already developed between Kempten and Hohenpeissenberg (marked by K and HP). It is predicted to move in a north-easterly direction (grey and white contours in Figure 3a and b) and is related to lightning activity, heavy precipitation, hail (reflectivity >55dBZ, Figure 3b). A first thunderstorm warning was sent to the users at this time with Figure 3b as attachment. The thunderstorm intensified and slowly moved towards MUC. At around 16:30 UTC, POLDIRAD scans show echo tops at 10 to 12 km height within the cell (Figure 4a), and the vertical structure with the overhanging strong reflectivity indicates strong dynamical development within the cell (Figure 4b). At 18:15 UTC the thunderstorm had crossed the river Lech and reached lake Ammersee (Figure 3c). A second warning was sent to the users at this time with Figure 3c attached. Finally, the thunderstorm reached MUC at 19:45 UTC (Figure 3d).

On this day, the DLR team was present at the working place at LH HCC and could show and discuss the DLR products with the director of operations at LH HCC who asked from time to time for an update of the situation during the afternoon. It was especially important for him to know when the thunderstorm will hit MUC. At 19:30 UTC there was a peak in departing long distance flights scheduled, and LH's interest was the departure of these flights before the thunderstorm arrived at MUC. If necessary, LH would try to accelerate the dispatch of these flights in order to avoid that they were stuck on the ground because of lightning and heavy precipitation over MUC. The DLR nowcasting products finally predicted about one hour in advance that the thunderstorm will likely hit MUC after 19:30 UTC. This information was very helpful for the dispatch at LH HCC. Unfortunately, it was not possible to talk to users from the FMG or DFS on this day, as they were under pressure because of the thunderstorm situation. However, feedback on the DLR nowcasting products from DFS and FMG was given at a later time and is presented in the following.

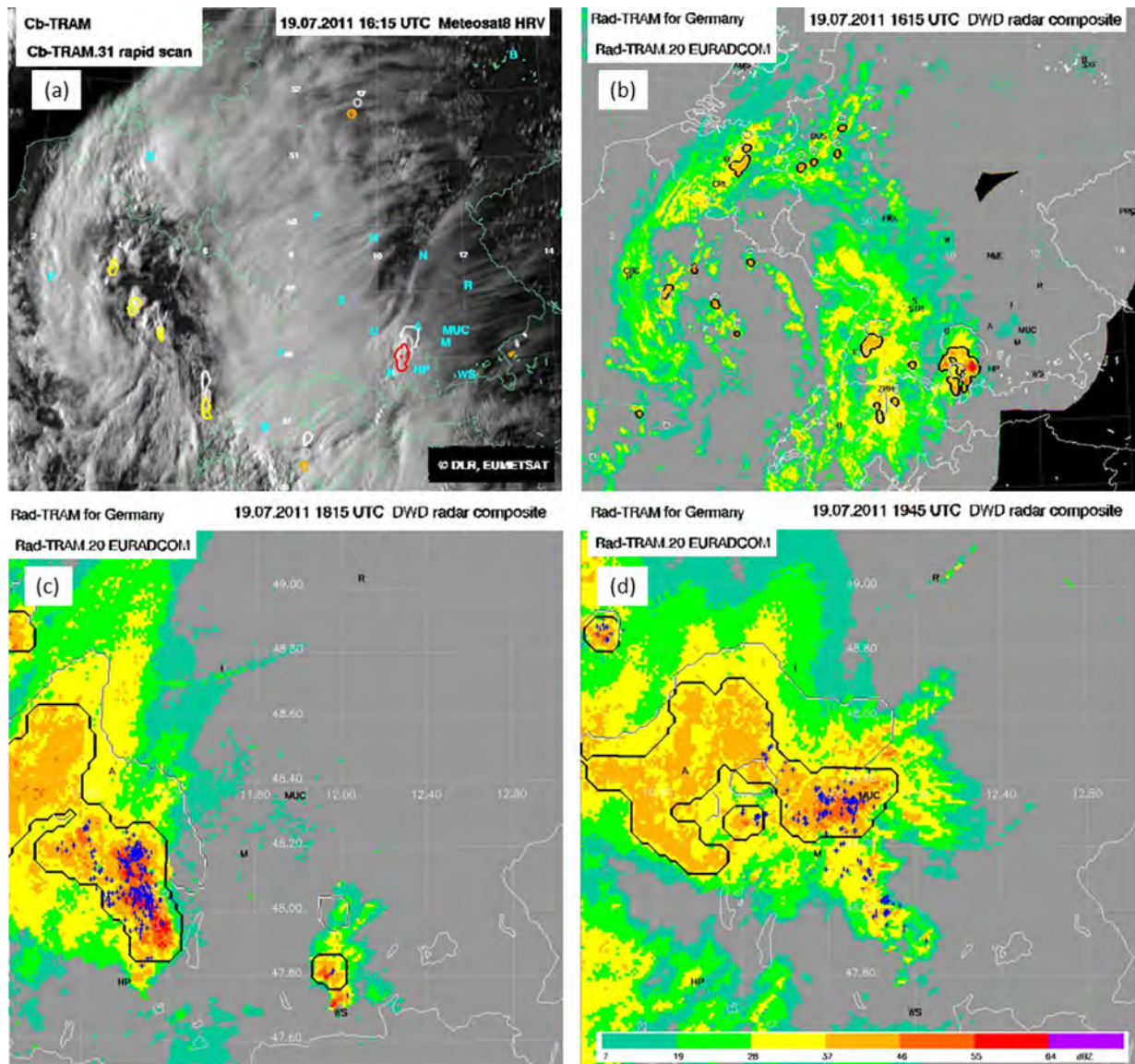


Figure 3. Thunderstorm situation on 19 July 2011. (a) METEOSAT-8 HRV image at 16:15 UTC with Cb-TRAM contours; yellow, orange, and red contours indicate the detected development stages 1, 2, 3. (b) EURADCOM radar composite with black Rad-TRAM contours at 16:15 UTC. (c, d) As (b), but for the TMA MUC at 18:15 UTC (c) and 19:45 UTC (d). The grey and white polygons in (a) and (b) are the 30 and 60 minutes nowcasts. The thin black contours in (c) and (d) are the 60 minutes nowcasts. Blue crosses in (c) and (d) represent lightning detections from the LINET system (Betz et al., 2008).

Users' Feedback

Feedback of the users on the benefits and disadvantages of new weather information products is very important for the development of these products. Based on user feedback the user's requirements can be accounted for in the output and in the presentation of the products. In addition, it can be assessed whether the application of new weather information tools help improving coordination through common situational awareness of the convective weather impacts among all affected users. For instance, in the U.S., MIT Lincoln assessed the user feedback with regard to innovative integrated terminal weather systems [Robinson et al., 2006, 2008]. They got co-ordinated feedback from traffic managers and area supervisors on convective weather impact mitigation decisions made using the new systems, on the time to monitor existing convective weather impact mitigation initiatives, and on the time associated with

the mitigation plan development and execution process in relation to expected workload for similar convective events prior to the new systems [Robinson et al., 2006]. Important results of this assessment were that it took less time for the users to develop and implement operationally effective plans and that the number of such plans implemented per convective weather day significantly increased.

During the summer campaigns 2010 and 2011 at MUC, the user feedback on Cb-TRAM and Rad-TRAM was obtained via informal e-mails, personal conversations, and a questionnaire with the questions:

1. Are the thunderstorm forecasts correct (e.g. extrapolated cells, moving direction) ?
2. Is the way of displaying the products appropriate? (e.g. clear, readable, free of interpretation) ?
3. Is the thunderstorm product helpful? (e.g. for the planning and for the co-ordination of the operations) ?

In total 8 questionnaires were filled in and 18 e-mails were obtained from about 20 persons involved in the campaigns. In-

cluding the numerous comments and suggestions from personal conversations with supervisors at DFS Tower and Center MUC, directors of operations at LH HCC, and traffic managers from FMG, the evaluation of the questionnaires and e-mails resulted in a very positive feedback. Most of the users found the depiction of the products clear and intuitive. They appreciated the simple display of hazardous areas for air traffic as contours and the indication of the future development and moving direction. The 5 minutes updates of the products in 2011 were considered as much better than the 15 minutes updates in the year before. With the 5 minutes updates rapidly changing situations could easier and earlier be assessed. The nowcasting up to one hour was found to be accurate enough to enable a reasonable planning, e.g. the deployment of additional staff or the ordering of overtime, and it was useful to estimate how long the airport will be affected by a thunderstorm. The DFS appreciated the display and availability of data also from neighbouring countries. Thunderstorms moving towards Germany could then be recognized early and actions could be triggered with less time pressure. In general, the nowcasting products turned out to be very helpful for the planning.

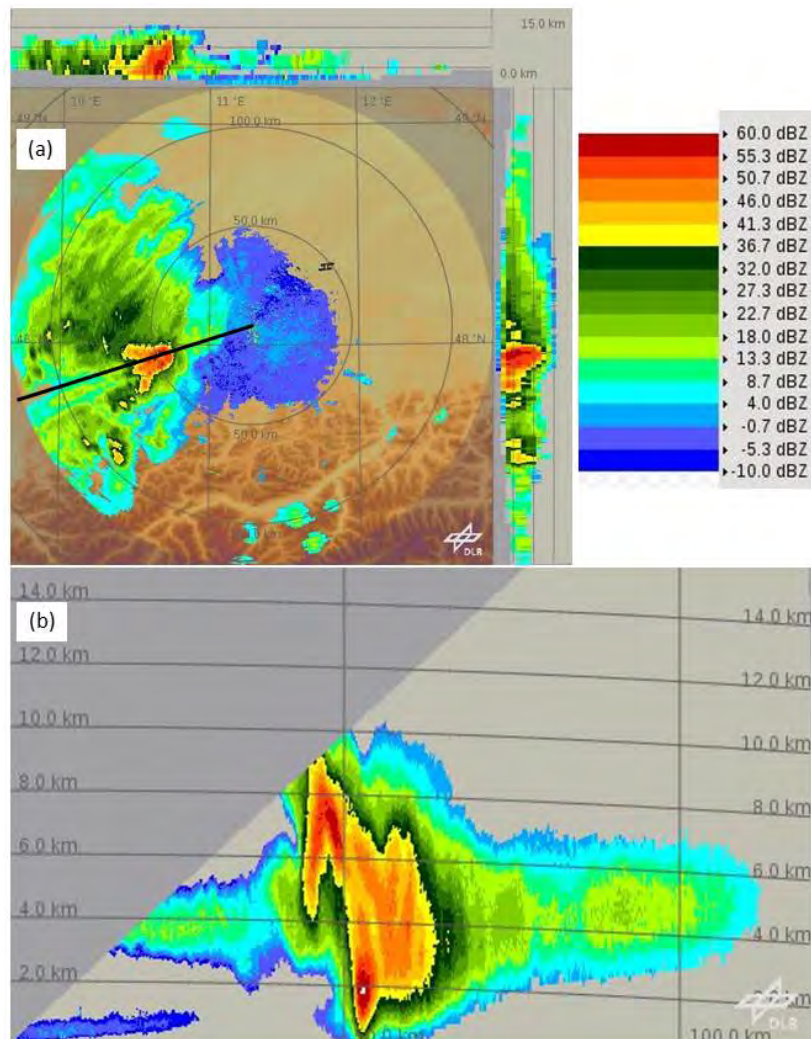


Figure 4. POLDIRAD measurements on 19 July 2011. (a) Maximum reflectivity scan at 16:31 UTC. POLDIRAD is located in the center of the image. The circles indicate the radii of 50km and 100km around POLDIRAD. MUC is indicated by a black symbol on the 50km radius north-east of POLDIRAD. (b) Reflectivity for a vertical cross section (black line in (a)) at 16:27 UTC through the thunderstorm cell at 249° azimuth.



However, in some cases it became clear that different users have different requirements with respect to weather information. For example on 24 August 2010 at 14:15 UTC, the 60 minutes nowcast predicted that a thunderstorm cell will directly affect MUC. One hour later, however, the cell passed just south of the airport. For the airport operations FMG, this was a wrong forecast, because the cell missed the airport and the operations on the movement area did not have to be shut down. In contrast, the DFS Tower MUC was satisfied with the forecast. Although MUC was not directly hit by the thunderstorm, there were severe obstructions in the approach, and with the help of the nowcast, the DFS could plan accordingly.

Another issue were heavy precipitation cells in Rad-TRAM close to the threshold of 37dBZ. Such cells appear and disappear from time step to time step, as their maximum reflectivity alternates between above and below the threshold. This is very confusing for the user, especially in cases when the cell clearly shows lightning activity also at time steps where it was not detected by Rad-TRAM. From these cases it is evident that a combination of different data sources (e.g. lightning and Rad-TRAM information) could guarantee a more continuous tracking of thunderstorm cells. The fusion of different data sources will be considered in WxFUSION (see below).

The DFS suggested some improvements with respect to the weather information and its presentation to the users. For instance, an indication of the height of a thunderstorm cell on the display would be very helpful in order to assess how many of the upper air sectors are affected by the cell. In addition, forecasts up to two hours would be of great advantage, as this is the timeframe for actions with regard to coordination at the central flow management unit (CFMU) in Brussels. Moreover, it would be a great advantage to have available and displayed all the innovative weather information products demonstrated during the summer campaigns in one visualization system only. At DFS, this would preferably be Met-FROG.

Finally, it turned out that the thunderstorm warnings were very useful for the collaborative decision making at the airport. During 2010, they were issued by DLR just to draw the attention of the users to the DLR products. However, as all users obtained the same warning at the same time, they all had the same situational awareness and could make decisions and trigger actions within a much shorter time period than without the warnings. Therefore, the thunderstorm warnings were also issued in 2011 on demand of the DFS. Currently, an automation of the thunderstorm warnings is discussed.

Quantitative Evaluation of the Nowcasting Products

Several evaluations of Rad-TRAM and Cb-TRAM have been performed and are still in progress based on the data collected during the summer campaigns. An economic assessment has been performed and is described by Lau [2011] within this report and by Lau et al. [2011]. These studies investigate delay data at MUC, and determine the potential for a delay reduction, if weather information from Rad-TRAM is used for the pre-tactical planning of flights. In a complementary study, the DFS plans to estimate the potential for a delay reduction, if Rad-TRAM is used by the air traffic controllers for tactical regulations. It is envisaged to perform real time simulations with controllers to assess their actions with and without the Rad-TRAM information.

In order to assess the detection and nowcasting quality of the DLR algorithms two different methods have been applied. The first method compares the nowcasting of Cb-TRAM and Rad-TRAM for different lead times with the detection in Cb-TRAM and Rad-TRAM, respectively. The second method compares the detection and nowcasting of Cb-TRAM or Rad-TRAM with the observation by an independent data source. While the first method assesses the nowcasting quality only, the second method also assesses the ability of the algorithm to detect thunderstorms at the correct location.

Comparison of Nowcast with Observation

In case of the first method, we distinguish a pixel-based from an object-based analysis, see Figure 5. The pixel-based analysis checks how many pixels of an observed Rad-TRAM (Cb-TRAM) object overlap with pixels of a Rad-TRAM (Cb-TRAM) nowcast. These are counted as hits (Figure 5a). The pixels of an

observed object that do not overlap with a nowcast one are regarded as misses, and the pixels of a nowcast object that do not overlap with an observed one are regarded as false alarms. Skill scores like the probability of detection (POD) with $POD = \text{hits} / (\text{hits} + \text{misses})$ and the false alarm ratio (FAR) with $FAR = \text{false alarms} / (\text{hits} + \text{false alarms})$ are calculated and interpreted. The perfect nowcast would have a $POD = 1$ and a $FAR = 0$. Figure 6 shows the results of the POD and FAR for the pixel-based analysis of Rad-TRAM nowcasts over the whole summer period 2011 (39 thunderstorm days). As expected the POD decreases, and the FAR increases with nowcast lead time. The mean POD value over all days is 0.65 for the 15 minutes nowcast and declines to 0.27 for the 60 minutes nowcast with standard deviations between 0.06 and 0.03, respectively (Table 1). The mean FAR over all days increases from 0.36 for the 15 minutes nowcast to 0.73 for the 60 minutes nowcast with standard deviations between 0.03 and 0.06, respectively. These numbers are quite encouraging keeping in mind that the pixel-based analysis requires an exact match of observation and nowcast.

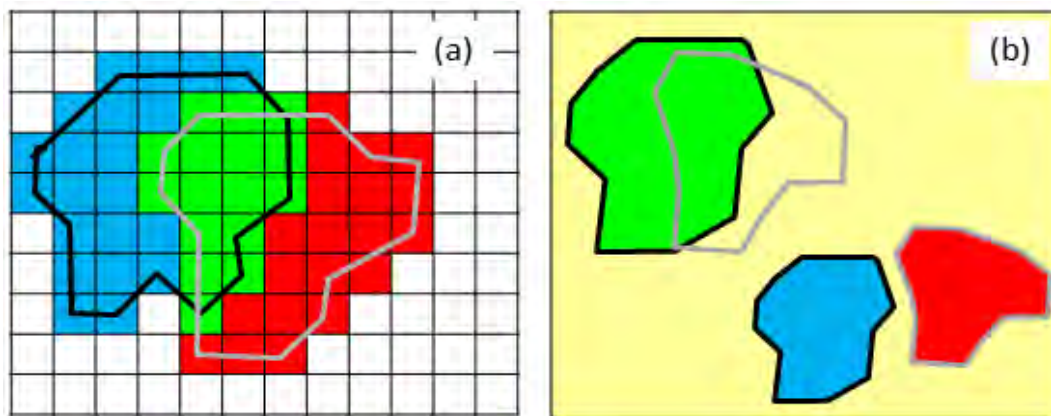


Figure 5. Observed (black) and nowcast (grey) objects. (a) Pixel-based analysis: the pixels covered by the observed and nowcast objects are counted. (b) Object-based analysis: the observed and nowcast objects are counted. Green are the hits, blue the misses and red the false alarms.

Table 1: Mean values of POD and FAR and the respective standard deviations (STD) for all thunderstorm days in 2011 for the 15, 30, 45, and 60 minutes nowcasts.

	15 min.	30 min.	45 min.	60 min.
POD / FAR	0.65 / 0.36	0.47 / 0.53	0.34 / 0.65	0.27 / 0.73
POD STD / FAR STD	0.06 / 0.03	0.04 / 0.05	0.03 / 0.05	0.03 / 0.06

The object-based method, however, requires just an overlap between observed and nowcast object (Figure 5b). Overlapping observed and nowcast objects are counted as hits, non-overlapping observed objects are counted as misses, and non-overlapping nowcast objects are counted as false alarms. In Figure 7 POD and FAR for the object-based analysis are shown. As only an overlap between observed and nowcast objects is required, the skill is better than for the pixel-based analysis. The mean values of the POD vary between 0.74 for the 15 minutes nowcast and 0.48 for the 60 minutes nowcast with standard deviations between 0.06 and 0.04, respectively (Table 2). FAR increases from 0.25 for the 15 minutes nowcast to 0.52 for the 60 minutes nowcast with standard deviations between 0.02 and 0.04.

Table 2: Same as Table 1, but for the object-based analysis.

	15 min.	30 min.	45 min.	60 min.
POD / FAR	0.74 / 0.25	0.65 / 0.35	0.56 / 0.43	0.48 / 0.52
POD STD / FAR STD	0.06 / 0.02	0.05 / 0.03	0.05 / 0.04	0.04 / 0.04



An issue with the presented pixel- and object-based analyses is the fact that observed objects that appear for the first time are not nowcast and counted as misses, because Rad-TRAM cannot predict the formation of a new heavy precipitation cell. Therefore, the object-based evaluation has been repeated for only those objects that also have a nowcast. This evaluation can be considered as the best case scenario, as the weakest criteria for obtaining a hit (overlap only) and filtering misses (only objects are considered that have a nowcast) are applied for the evaluation. The main results are summarized in Table 3. From the evaluations presented here, it can be concluded that the nowcasting performance of Rad-TRAM is somewhere between the pixel-based analysis and the best case scenario. The nowcasting for lead times greater than 30 minutes has to be considered with care because of the low POD and high FAR.

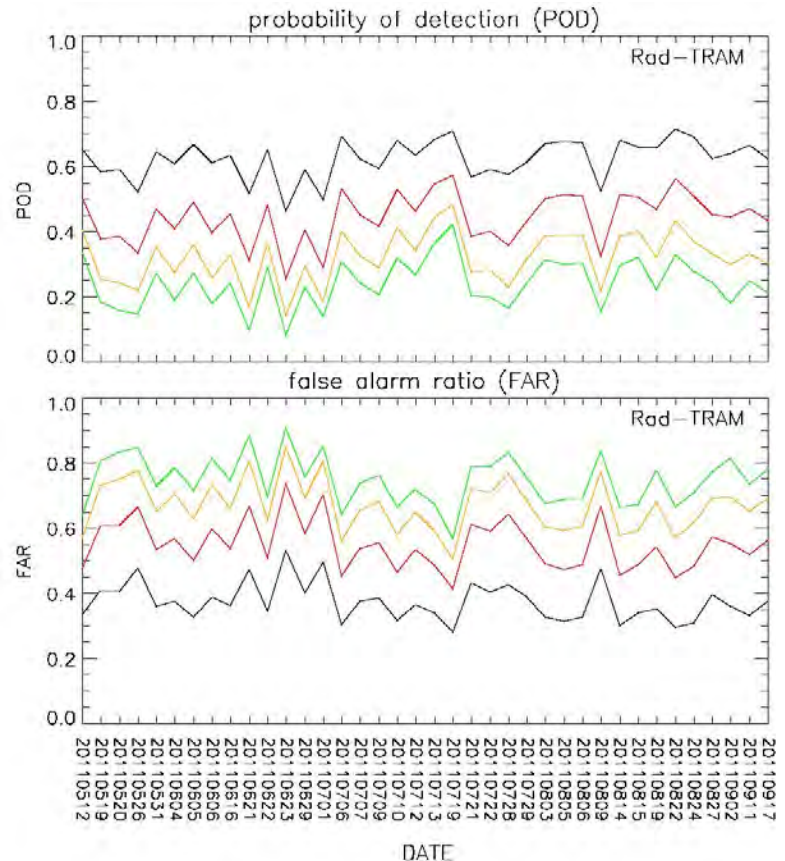


Figure 6. POD and FAR for the pixel-based analysis for all thunderstorm days in 2011. The black, red, yellow and green curves indicate the daily mean values for the 15, 30, 45, and 60 minutes nowcast

Table 3: Same as Table 2, but only for objects that also have a nowcast.

	15 min.	30 min.	45 min.	60 min.
POD / FAR	0.98 / 0.01	0.95 / 0.03	0.89 / 0.09	0.75 / 0.23
POD STD / FAR STD	0.06 / 0.004	0.06 / 0.007	0.06 / 0.01	0.05 / 0.03

One disadvantage of the presented evaluation is the fact that it is biased towards large objects. It is evident that an overlap of the nowcast and the observation of large objects is more likely than for small objects. In addition, it can happen that an observation overlaps with two different nowcast objects which have different sizes and cell centers than the observed one. The overlaps are counted as hits, although from an eyeball inspection the observed object does not match very well with the nowcast objects. In order to get a feeling on the ability of Rad-TRAM to nowcast the correct size of the objects as well as the correct location of their cell centers, further skill scores have to be evaluated like the location error of the cell centres and the area bias of the cells. Work is currently in progress to calculate such skill scores and perform additional analyses for the thunderstorm days in 2011. Similarly, work on the pixel-based and object-based analysis as well as the calculation of location errors and area bias for Cb-TRAM nowcasts is currently in progress.

Comparison with an Independent Data Source

In contrast to precipitation, lightning activity is an exclusive feature to thunderstorms. Therefore, lightning data from the LINET network [Betz et al., 2008] has been the data source of choice for the comparison with Cb-TRAM detections and nowcasts [Zinner et al., 2011]. Only Cb-TRAM cells of the mature stage have been considered here, as the other two development stages in Cb-TRAM are early warning stages and therefore not necessarily connected to lightning activity. The lightning data were clustered to

lightning objects, and the overlap between Cb-TRAM detected and nowcast cells with lightning objects is determined by both a pixel-based and an object-based analysis as illustrated in Figure 5. This time, the grey contours in Figure 5 are the lightning objects, and the black contours represent either Cb-TRAM detections or nowcasts. As example, results of the object-based analysis show that for the Cb-TRAM detections the POD is around 61% and the FAR is around 29%, if an overlap of at least one pixel is required. The POD decreases to 33.4% and the FAR increases to 60.8% for the 60 minutes nowcast. These numbers are encouraging keeping in mind that some of the lightning cells are counted as misses, as they are related to another Cb-TRAM detection of stage. Sensitivity studies including all Cb-TRAM detection stages confirmed this. However, the FAR got worse because many of the Cb-TRAM stage one and two cells do not contain lightning and are counted as false alarms. Further details and results can be found in Zinner et al. [2011].

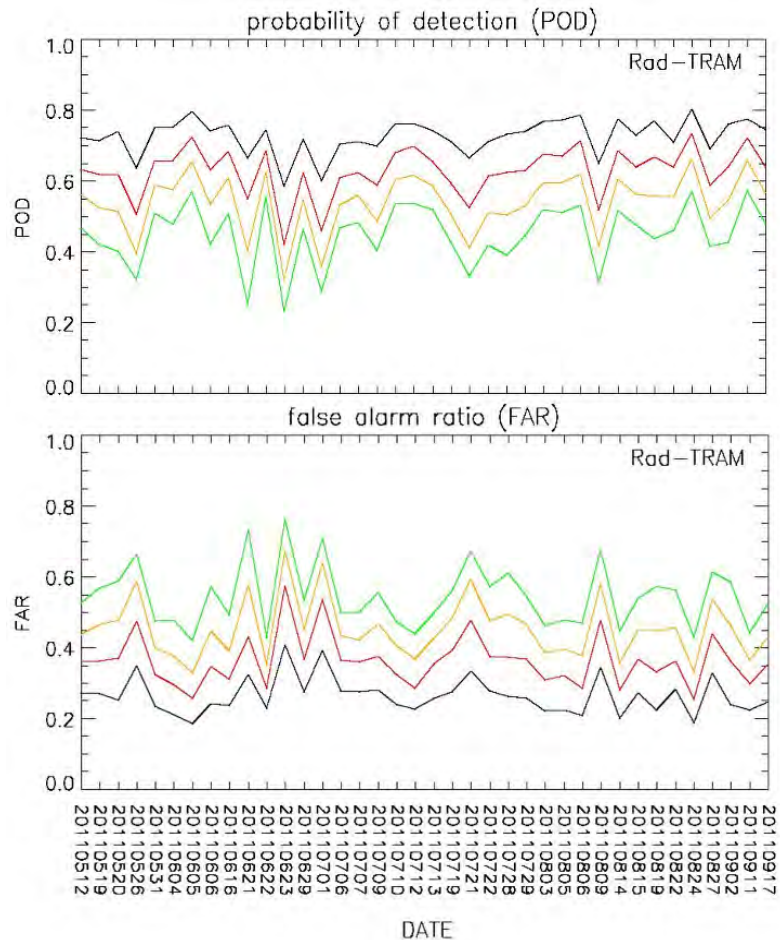


Figure 7. Same as Figure 6, but for the object-based analysis.

A study by Dotzek and Forster [2010] compared Cb-TRAM detections and nowcasts with data from the European Severe Weather Data base (ESWD). With six case studies they showed that up to 47% of all ESWD reports were located within a Cb-TRAM detection contour, and about 7% more reports were located close by these contours. The POD for an ESWD report corresponding with a Cb-TRAM detection was 24% on average in the whole summer season 2008 with maximum values up to 58% on intense thunderstorm days. These numbers are encouraging, as ESWD reports do not necessarily have to correspond exactly with a Cb-TRAM cell due to storm morphology. In addition, if a detected Cb-TRAM cell is not related to an ESWD report, this does not falsify the Cb-TRAM detection, but the convective storm might simply have not been reported to the ESWD. Likewise, the absence of a Cb-TRAM cell cannot be regarded as a proof that there was no thunderstorm. The ESWD report then might be related to storms that cannot be seen from space like small or low-topped convective storms, or those developing below cirrus layers.

Developments beyond the Nowcasting Horizon

The nowcasting quality of thunderstorms rapidly deteriorates with nowcast lead time. For lead times beyond roughly one hour they are no longer reliable and reasonable, as discussed above. On the other hand, forecasts from numerical weather prediction models are not reliable for the first hours, but have better forecast skills for longer lead times.

To fill that gap between nowcasts based on observations only and forecasts based on model data only, the concept of WxFUSION (see Section 2.2 above) is used. The graphical user interface of WxFUSION



where the different data sources can be superimposed and the fuzzy logic and the numerical forecast selection algorithms can be tested has been run in real time during the summer campaigns. Work has been done and is currently going on to evaluate the results of these algorithms and to gain further knowledge on the formation and life cycle of thunderstorms that can be used in the fusion algorithm. Examples are given in the following.

One study investigated the ability of the COSMO-DE model to forecast the location of thunderstorm cells. For this, Cb-TRAM was applied to synthetic satellite images from COSMO-DE which are available up to 21 hours in 15 minute intervals. Comparing the Cb-TRAM_{COSMO} forecasts to Cb-TRAM observations revealed that 50% of all Cb-TRAM_{COSMO} forecasts overlap with an observation. The forecasts are updated every 3 hours. That means for each 15 minute interval 7 different forecasts with different initial times exist and build a so-called time lagged ensemble with ensemble member 1 as the most recent forecast and ensemble member 7 as the oldest forecast. If the different Cb-TRAM_{COSMO} forecasts from this time lagged ensemble are compared to the observation, it turned out that member 1 and member 4 are the best members in the majority of all cases, i.e. the Cb-TRAM observations overlap most often with a Cb-TRAM_{COSMO} forecast from member 1 or 4.

Another study investigated the initiation of thunderstorms by exploring the vertical velocity, the equivalent potential temperature, and CAPE (convective available potential energy) in the synoptic scale model COSMO-EU [Köhler, 2011]. It was found that in most of the areas where thunderstorms were observed COSMO-EU forecasts showed constant upward motion above 1000hPa, potential lability and elevated values for CAPE. These large scale parameters from COSMO-EU agreed better with observed thunderstorms than the thunderstorm probabilities from the high resolution COSMO-DE model.

The time series of different observational data like cloud top height, maximum radar reflectivity, lightning activity, and size of a thunderstorm as well as forecast data from the COSMO-DE model were inspected in combination in order to learn about the life cycle of thunderstorms [Bretl, 2010]. It was found that the time series of the trend of the inspected variables show a typical behaviour during the formation, mature, and decay phase of a thunderstorm. For instance, the formation phase is characterized by a growth of all inspected variables, while the decay phase is characterized by a decline of these variables.

A further study deals with the detection and nowcasting of convection initiation (CI) [Stich et al., 2011]. The aim is to improve the CI stage-1 detection and nowcasting in Cb-TRAM by a combination with different data sources from observations and numerical models. First results show that the high FAR of the Cb-TRAM's stage 1 can be considerably lowered by excluding detections and nowcasts that occur in regions with low surface equivalent potential temperatures and downward motion at 500hPa. At the same time, the POD hardly changes.

Finally, surface observations of temperature, humidity, and pressure from SYNOP observations and data from the Vienna Enhanced Resolution Analysis (VERA) System were explored to find out whether they exhibit typical characteristics along thunderstorm tracks monitored by Cb-TRAM [Klötzke, 2011]. It was found that thunderstorms related to frontal systems exhibit high pressure gradients and gradients of equivalent potential temperatures.

Conclusions and Outlook

The demonstration of the DLR products for thunderstorm detection and nowcasting at MUC during the summer campaigns in 2010 and 2011 showed the usefulness of these products for the collaborative decision making process at the airport. As all users received a thunderstorm warning at the same time and could get an overview on the current weather situation by inspecting the DLR nowcasting products, they had the same situational awareness and could make decisions and trigger actions with less time pressure than without the warnings and products. In general, the user feedback was very positive, but with suggestions for improvements of the products like an indication of the height of the thunderstorm cells in the display or the demand for nowcasts beyond one hour. The latter will be considered within

WxFUSION (see Section 2.2) which has been further developed during the campaigns, but is not yet ready to be presented to the users. Still, effort has to be made in order to integrate the knowledge gained from the studies made so far. A quantitative assessment of the nowcasting performance of the DLR tools revealed that the algorithms have good forecast skills, but for lead times greater than 30 minutes the nowcasting has to be used with care because of the increasing number of missed observations and false alarms. These results indicate that it is more suitable for longer lead times to combine observational and nowcasting data with numerical model results and express the forecasts with probabilities, e.g. the probability of the occurrence of a thunderstorm in a specific area. This will also be considered within WxFUSION.

It is envisaged to initiate another summer campaign in 2012. Not only Rad-TRAM but also Cb-TRAM products will then be available in the MetFROG display in real time. In addition, Rad-TRAM can also be tested by the controllers within the PHOENIX test display. Since the thunderstorm warnings turned out to be very important, it is planned to automate the production of such warnings on the basis of Rad-TRAM. Whenever a Rad-TRAM cell is detected and/or nowcast within the TMA MUC a text message will be issued automatically and sent to the users. As the DFS wishes to present all the information in one display, it is discussed to integrate the thunderstorm warnings in the MetFROG display. As a further activity during the summer campaign 2012, it is planned to demonstrate the link of Cb-TRAM and Rad-TRAM data into the cockpit of light aircraft. DLR is currently in contact with the companies Atmosphere (<http://www.atmosphere.aero/>) and TriaGnoSys (<http://triagnosys.com/>) in order to discuss and prepare a concept for such a demonstration.

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References

- Betz, H. D., K. Schmidt, W. P. Oettinger, and B. Montag (2008), Cell-tracking with lightning data from LINET, *Adv. Geosci.*, 17, 55–61.
- Bretl, S., 2010: Untersuchung des Lebenszyklus von Gewittern in Mitteleuropa mit Hilfe von Fernerkundungs- und Modelldaten, Diplomarbeit in Meteorologie, Ludwig-MaximiliansUniversität München, 31. März 2010.
- Dotzek, N., and C. Forster, 2010: Quantitative comparison of METEOSAT thunderstorm detection and nowcasting with in situ reports in the European Severe Weather Database (ESWD), *Atmos. Res.*, 100 (2011), 511-522, doi:10.1016/j.atmosres.2010.12.013.
- Eurocontrol, 2007: Performance Review Report 2006 of the Performance Review Commission, May 2007.
- Forster, C., A. Tafferner, C. Keil, T. Zinner, 2008, Validation of severe weather forecasts based on synthetic satellite data as part of an integrated thunderstorm forecast system for air traffic, Proceedings of the EUMETSAT Meteorological Satellite Conference, Darmstadt, Germany 8 - 12 September 2008, EUMETSAT P. 52, ISBN 978-92-9110-082-8, ISSN 1011-3932, 8 pages.
- Forster, C., and A. Tafferner, 2009a: Nowcasting and forecasting thunderstorms for air traffic with an integrated forecast system based on observations and model data, WMO Symposium on Nowcasting, Whistler, B.C., Canada, 30 August - 4 September 2009.
- Forster, C., and A. Tafferner, 2009b: An integrated user-oriented weather forecast system for air traffic using real-time observations and model data, Proceedings of the European Air and Space Conference (CEAS), Manchester, UK, 26 - 29 October 2009
- Holzäpfel, F., K. Dengler, T. Gerz, C. Schwarz, Prediction of Dynamic Pairwise Wake Vortex Separations for Approach and Landing, AIAA Paper 2011-3037, 3rd AIAA Atmospheric Space Environments Conference, 27-30 June 2011, Honolulu, Hawaii, 15 pages.



- Klötzke T., 2011: Signaturen von Gewitterzugbahnen in SYNOP-Beobachtungen, Bachelorarbeit in Meteorologie, Freie Universität Berlin, 28. September 2011.
- Köhler, M., 2011: Untersuchung der Auslösung von Gewittern während der „Wetter & Fliegen“ Sommerkampagne 2010, Masterarbeit in Meteorologie, Ludwig-Maximilians Universität München, 6. Oktober 2011..
- Kober and Tafferner, 2008: Tracking and nowcasting of convective cells using remote sensing data from radar and satellite, Meteorol. Zeitschrift, 1 (18), 75 - 84.
- Lau A., C. Forster , A. Tafferner, N. Dzikus and V. Gollnick, Assessment of a Convective Weather Nowcasting and Tracking Algorithm Based on Delay Reduction Potential at Munich Airport (Part I), 11th AIAA Aviation Technology, Integration and Operations (ATIO) Conference, Virginia Beach, Virginia, USA, 20-22 September 2011.
- Lau A.; Economic assessment of enhanced information on convective weather tracking and nowcasting based on the delay reduction potential, this issue.
- Mollwitz V., Korn B. 2011: Concept of operations for arrival traffic in the terminal area under the influence of thunderstorms – Description of concept and first validation, this issue.
- Quon, 2006: L. Modeling and Simulation Needs for Next Generation Air Transportation System Research. AIAA Modeling and Simulation Technologies Conference and Exhibit, 21-24 August 2006, Keystone, Colorado, AIAA 2006-6109, p 1-8.
- Robinson, M., DeLaura, R. A., Evans, J. E., McGettigan, S., Operational Usage of the Route Availability Planning Tool During the 2007 Convective Weather Season, Project Report ATC-339, MIT Lincoln Laboratory, Lexington, MA, 2008. http://www.ll.mit.edu/mission/aviation/publications/publication-files/atc-reports/Robinson_2008_ATC-339_WW-15781.pdf.
- Robinson, M., Evans, J. E., Assessment of Air Traffic Control Productivity Enhancements from the Corridor Integrated Weather System (CIWS), Executive Summary, Project Report ATC-325-1, MIT Lincoln Laboratory, Lexington, MA, 2006. http://www.ll.mit.edu/mission/aviation/publications/publication-files/atc-reports/Robinson_2006_ATC-325-1_WW-13782.pdf.
- Stich, D., C. Forster , T. Zinner, A. Tafferner, 2011: Convection Initiation - Nowcasting by data fusion and its Verification, European Conferences on Severe Storms (ECSS 2011) Palma de Mallorca, Balearic Islands, Spain, 3 - 7 October 2011
- Tafferner, A., Hagen, M., Keil, C., Zinner, T. and Volkert, H., 2008, Development and propagation of severe thunderstorms in the upper Danube catchment area: Towards an integrated nowcasting and forecasting system using real-time data and high-resolution simulations, Meteorology and Atmospheric Physics, 101, 211-227, DOI 10.1007/s00703-008-0322-7.
- Zinner, T., Betz, H.D., 2009. Validation of Meteosat storm detection and nowcasting based on lightning network data. Proc. 2009 EUMETSAT Meteorological Satellite Conference, Bath, 21–25 September 2009. 9 pp. Available at http://www.eumetsat.int/Home/Main/AboutEUMETSAT/Publications/ConferenceandWorkshopProceedings/SP_201001515267179.
- Zinner, T., C. Forster, E. de Coning, and H.-D. Betz, 2011: Validation of the METEOSAT storm detection and nowcasting system Cb-TRAM with lightning network data, in preparation for Atmos. Chem. Phys.
- Zinner, T., H. Mannstein, A. Tafferner, 2008: Cb-TRAM: Tracking and monitoring severe convection from onset over rapid development to mature phase using multichannel Meteosat-8 SEVIRI data. – Meteor. Atmos. Phys. 101, 191–210, DOI 10.1007/s00703-008-0290-y.