VALIDATION OF SEVERE WEATHER FORECASTS BASED ON SYNTHETIC SATELLITE DATA AS PART OF AN INTEGRATED THUNDERSTORM FORECAST SYSTEM FOR AIR TRAFFIC

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Abstract

This paper presents on-going work on a new tool that validates severe weather forecasts based on synthetic satellite data against satellite observations. The algorithm Cb-TRAM is used for tracking and monitoring objects of severe convection both in observed satellite imagery from METEOSAT SEVIRI and in synthetic satellite images forecasted by the German Weather Service (DWD) COSMO-DE model. Objects are defined by the area where convection is detected based on certain thresholds in Cb-TRAM, together with the vertical extent of the cloud cell. The validation tool compares size, displacement, overlap, intensity distribution and history of the observed and forecasted objects and thereby assesses the quality of the forecast. The functioning of the method is demonstrated for case studies of severe thunderstorms. If several forecasts of one object are available (e.g. from an ensemble forecast), this method enables the selection of the forecast that agrees best with the observation and that could then be used to estimate the future thunderstorm evolution. In particular, this method has the potential to close the gap between nowcasting and forecasting. It is part of an integrated thunderstorm forecast system for air traffic named WxFUSION (Weather Forecast User Oriented System Including Object Nowcasting) which is currently under development within the framework of the DLR project “Wetter & Fliegen”, in close collaboration with the DWD.

1. MOTIVATION AND INTRODUCTION

During the summer months thunderstorms are the major reason for delays and disruptions in the air transport system [Quon, 2006]. In the U.S. up to 90% of all delays are due to thunderstorms [Quon, 2006], and at Munich Airport in Germany more than 80% of the delays are due to weather with thunderstorms and fog as the primary reasons [German Air Traffic Control (DFS), personal communication]. It is therefore necessary to develop integrated systems that analyse and forecast weather hazards for air traffic as precisely as possible in order to enable the mitigation of the hazard's effects.

Several such systems have been successfully developed for U.S. airports during the last decade, e.g. the Integrated Terminal Weather System (ITWS) [Evans and Ducot, 1994] and the NCAR Auto-Nowcast System [Mueller et al. 2003]. Both systems combine different data sources like observations, model simulation output, hazard detection algorithm output, and interactive forecaster input in order to provide tailored products on specific weather hazards to Air Traffic Control (ATC) personnel. As ATC personnel has to make quick decisions, the information given by these products is short, precise and immediately usable without further meteorological interpretation.

Within the framework of the Advisory Council for Aeronautics in Europe (ACARE) plan, the FLYSAFE project [http://www.eu-flysafe.org/] aims at defining, developing, and testing new on-board and ground-based systems contributing to the flight safety for all aircraft. The ground-based tools feed the on-board systems with the information the on-board systems require. One of these ground-based tools is a thunderstorm weather information management system that has successfully been tested during summer 2008 [Tafferner et al. 2008b]. In January 2008, a new project named “Wetter & Fliegen” (“Weather and Flying”) has started under the leadership of the Institute of Atmospheric Physics (IPA) at the German Aerospace Center (DLR) in Oberpfaffenhofen, Germany. The main goal of this project is to increase the safety and efficiency of air traffic by developing

- integrated airport weather forecast systems for the airports Frankfurt and Munich with the components “wake vortices”, “thunderstorms” and “winter weather” and
- on-board systems for automated flight control and surveillance and information strategies as well as hazard detection sensors to improve the behaviour of the aircraft when confronted with wind gusts, wake vortices and thunderstorms.

The central element of the weather systems part is the Weather Forecast User Oriented System Including Object Nowcasting (WxFUSION) [Forster and Tafferner, 2008; Tafferner et al., 2008a]. In the system’s core element “FUSION” it is planned to combine available data from observations, nowcasting algorithms and numerical model simulations accordingly in order to detect, nowcast (0-1 hrs) and forecast (1-24 hrs) user-defined target weather objects (TWO) like thunderstorms or icing.

While the analysis and the nowcasting of a TWO is primarily based on observations and nowcasting algorithms, the forecasting for the time range one to several hours is based on numerical model simulations. Numerical model forecasts often fail to produce observed weather features and even a good forecast will not perfectly match an observation. Phase errors must be taken into account as well as errors in existence and intensity. It is therefore useful to introduce a forecast validation that checks the quality of the forecasts against observations. One possibility to assess the forecast quality is to apply the novel forecast quality measure (FQM) developed by Keil and Craig [2007]. They use an image matching algorithm in combination with the local squared difference to compare observed and synthetic satellite or radar images, and a FQM for the whole image is calculated. A second method is to compare single observed TWOs with their forecasted synthetic counterparts and assess the quality of each TWO forecast. This method is currently under development at DLR, and in a first step will be applied to thunderstorms as TWOs. It is described in more detail in this paper which is structured as follows: section 2 introduces the definition and detection of TWOs, section 3 demonstrates the forecast validation by object comparison with the aid of a case study, and section 4 gives a summary and an outlook.

2. RENDERING THUNDERSTORMS IN THE FORM OF TARGET WEATHER OBJECTS

Thunderstorms can appear in various sizes from small convective cells to meso scale convective systems and convective lines with corresponding life times from a few minutes to several hours. Remote sensing with satellite, radar, and lightning measurements gives detailed information on initiation, life cycle and dissipation of thunderstorms, but this detailed information is not very useful for ATC personnel or pilots for decision making. Therefore, the strategy is not to describe thunderstorms to any observable detail, but reduce them to simplified target weather objects (TWO) representing the hazard levels “moderate” (avoid, if possible) and “severe” (no go area) for aircraft. Figure 1a shows a photography of a real thunderstorm with its idealized simplification as TWO depicted as cylinders. There is a top volume representing the upper anvil part of the thunderstorm with the hazards turbulence and lightning. The bottom volume covers the hazards wind shear, heavy rain, hail, and lightning at mid-tropospheric and near ground levels. Outer and inner volumes indicate the hazard levels “moderate” and “severe”, respectively. The top volume can be identified by using the Cumulonimbus TRacking And Monitoring (Cb-TRAM) algorithm based on satellite data (described in more detail below) in combination with lightning data. Cb-TRAM detects and nowcasts the outer top volume, i.e. turbulent areas within the anvil, while the lightning density exceeding a certain threshold marks the inner severe part of the top volume. Bottom volumes describing two severity levels can be detected and nowcasted with the aid of radar data exceeding certain thresholds, e.g. 33 and 41 dBZ as has been used in the CONO software [Hering et al., 2005] by Météo-France during the FLYSAFE campaign [Tafferner et al., 2008b]. If polarimetric radar information and/or lightning data are available in addition, the detection of the severe part can be refined as regards to occurrence of hail and/or lightning. Note that the horizontal shape of the top and bottom volumes does not have to be circular or elliptical, but can be polygon shaped as indicated in Figure 1b which displays the top and bottom volumes as detected for a real situation. Note that the three pillars to the right of the large TWO are convective cells which have not yet produced the characteristic thunderstorm cloud anvil, therefore they appear without top volume.

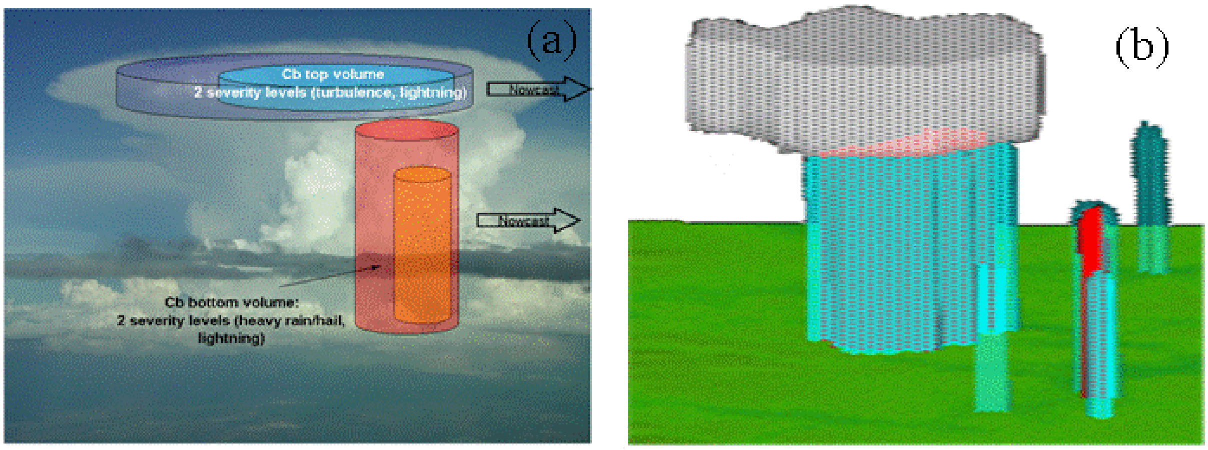

Figure 1: **A thunderstorm rendered as a target weather object (TWO) with top and bottom volumes. (a) Photography of a thunderstorm with its idealized TWO. (b) 3-dimensional view of a TWO as produced from a real thunderstorm by using detection algorithms based on satellite and radar data. Grey indicates top volumes, bluish colors indicate bottom volumes with level "severe" in red. Green is the surface.**

As mentioned before, the outer top volumes are detected from space by using the cloud tracker Cb-TRAM, a new fully automated algorithm for the detection and nowcasting of convection using Meteosat SEVIRI (Spinning Enhanced Visible and Infra-Red Imager) data [Zinner et al. 2008]. Three different channels (broad-band high-resolution visible (HRV), water vapour (WV) 6.2 µm, and infra-red (IR) 10.8 µm) are combined to identify three different stages of thunderstorm development: areas with convection initiation, with rapid vertical development, and with mature thunderstorm cells. Mature thunderstorm cloud tops are detected using WV data in combination with atmospheric profile information from ECMWF forecasts. The HRV is then used to limit the detection to the convective updrafts within the larger thunderstorm complexes by exploring the gradients in reflectivity of the satellite image in the HRV during daytime. This has been shown to improve the detection considerably with regard to the isolation of active cells within thunderstorm clouds. The tracking is based on the geographical overlap between current detections and first guess patterns of cells detected in preceding time steps. The first guess patterns are retrieved by using the approximate moving direction and velocity of a detected cloud pattern at a previous time step (15 minutes before). The motion information is provided by a so-called pyramidal image-matching algorithm which extracts the general transformation vector field from two consecutive satellite images thereby describing the cloud motion and local cloud developments. Similar to the first guess patterns, nowcasts up to 60 minutes are generated by extrapolation using these transformation fields.

3. FORECAST VALIDATION

The forecast validation by object comparison is demonstrated with the use of Cb-TRAM in a case study over southern Germany and the Alpine region from 21 July 2007. A cold front was approaching from the west in the afternoon, and severe thunderstorms with heavy rainfall and hail were triggered ahead of the front. At 14:00 UTC first mature thunderstorms were observed over Switzerland as shown by the tracking and monitoring of the top volumes with Cb-TRAM in Figure 2a. Lightning data from the LINET network [Betz et al., 2004] indicate the most active areas. In the afternoon further convective cells developed over Southern Germany, grew rapidly until the evening (Fig. 2b), and lead to considerable obstruction and delays at Munich Airport. Between 19:40 UTC and 20:05 UTC no take-off and landing procedures could be operated because of turbulence, hail, and lightning at and around the Airport.

In order to enable a comparison of the observed top volumes with forecasted synthetic top volumes, Cb-TRAM has been adapted to detect top volumes in synthetic satellite images, e.g. as forecasted by the COSMO-DE model of the German Weather Service (DWD) [Steppeler et al., 2003]. This version of CB-TRAM is called Cb-TRAM$_{\mathrm{COSMO}}$ in the following. The COSMO-DE has a grid spacing of 2.8km on

50 levels up to about 22km altitude. Convection is not parameterized, but explicitly resolved in the model physics.

The COSMO-DE model provides WV 6.2 µm and IR 10.8 µm brightness temperatures derived with the aid of the radiative transfer model RTTOV-7 [Saunders et al., 1999; Keil et al., 2007]. Unfortunately, no solar channels (e.g. HRV) are available from this algorithm. Therefore, updraft regions cannot be isolated with Cb-TRAM$_{\mathrm{COSMO}}$, and the diagnosed top volumes might be somewhat larger than with the standard detection procedure which uses also the visible channel. Thus the top volumes shown in Figure 2 are detected using a Cb-TRAM version not using the HRV in order to enable an adequate comparison with the synthetic top volumes detected by Cb-TRAM$_{\mathrm{COSMO}}$.

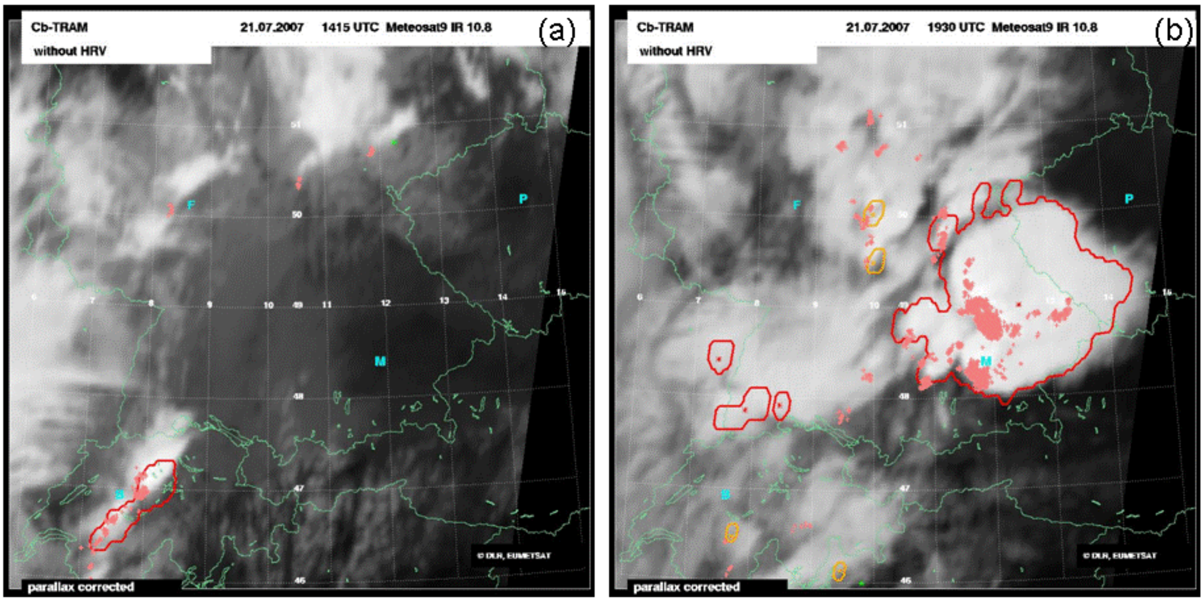

***Figure* 2: Thunderstorm top volumes detected by Cb-TRAM (orange contours for rapidly developing clouds and red contours for mature thunderstorms) and LINET lightning data (pink crosses) superimposed on the IR 10,8 µm METEOSAT image over Germany and the Alpine region on 21 July 2007 at (a) 14:15 UTC and (b) 19:30 UTC. Bern, Frankfurt, Munich Airport, and Prague are marked by the turquoise letters B, F, M, and P, respectively.**

The left column in Figure 3 shows a comparison of forecasted synthetic top volumes with observed top volumes for the thunderstorms over Switzerland. The top volumes are superimposed on the IR 10.8 µm brightness temperatures forecasted by the 00 UTC COSMO-DE model run. The corresponding observed METEOSAT IR 10.8 µm images with observed objects are displayed in the right column of Figure 3. A visual inspection of the synthetic and observed satellite images already indicates that the COSMO-DE forecasts capture the thunderstorms over Switzerland quite well. Cb-TRAM$_{\mathrm{COSMO}}$ could successfully be applied to the synthetic data. The comparison of the synthetic with the observed objects is quite good keeping in mind the forecast times (more than 14 hours). Please note that the observed objects are corrected for the parallax error caused by the viewing angle of METEOSAT in order to be able to compare them to the synthetic objects that do not suffer from the parallax error. The parallax error was determined for the highest cloud top within the observed object. Therefore, the observed objects appear somewhat shifted to the south-west with respect to the cloud seen in the METEOSAT IR images (which are not parallax corrected). The shapes of the synthetic and the observed objects are different, but the positions overlap to a great extent. 60% (Fig. 3a), 50% (Fig.3c), and 40% (Fig.3e) of the synthetic object's area lie within the observed object. The horizontal coverage of the synthetic objects (named "size" in the left column of Figure 3) is about one third to one half of the observed object's horizontal coverage. The forecast indicates a top volume growing in size (named "trend" in the left column of Figure 3) and moving slowly in a north-eastern direction in good agreement with the observation.

At later forecast times, it can be seen that the front moves somewhat slower in the forecast than in the observation (compare Fig. 2b with Fig. 4b). Therefore, the synthetic top volumes are located further west compared to the observed top volumes. The synthetic object at 10°E (Fig. 4a) merges with the larger one north of it, grows substantially and covers a large part of south-east Germany at later times

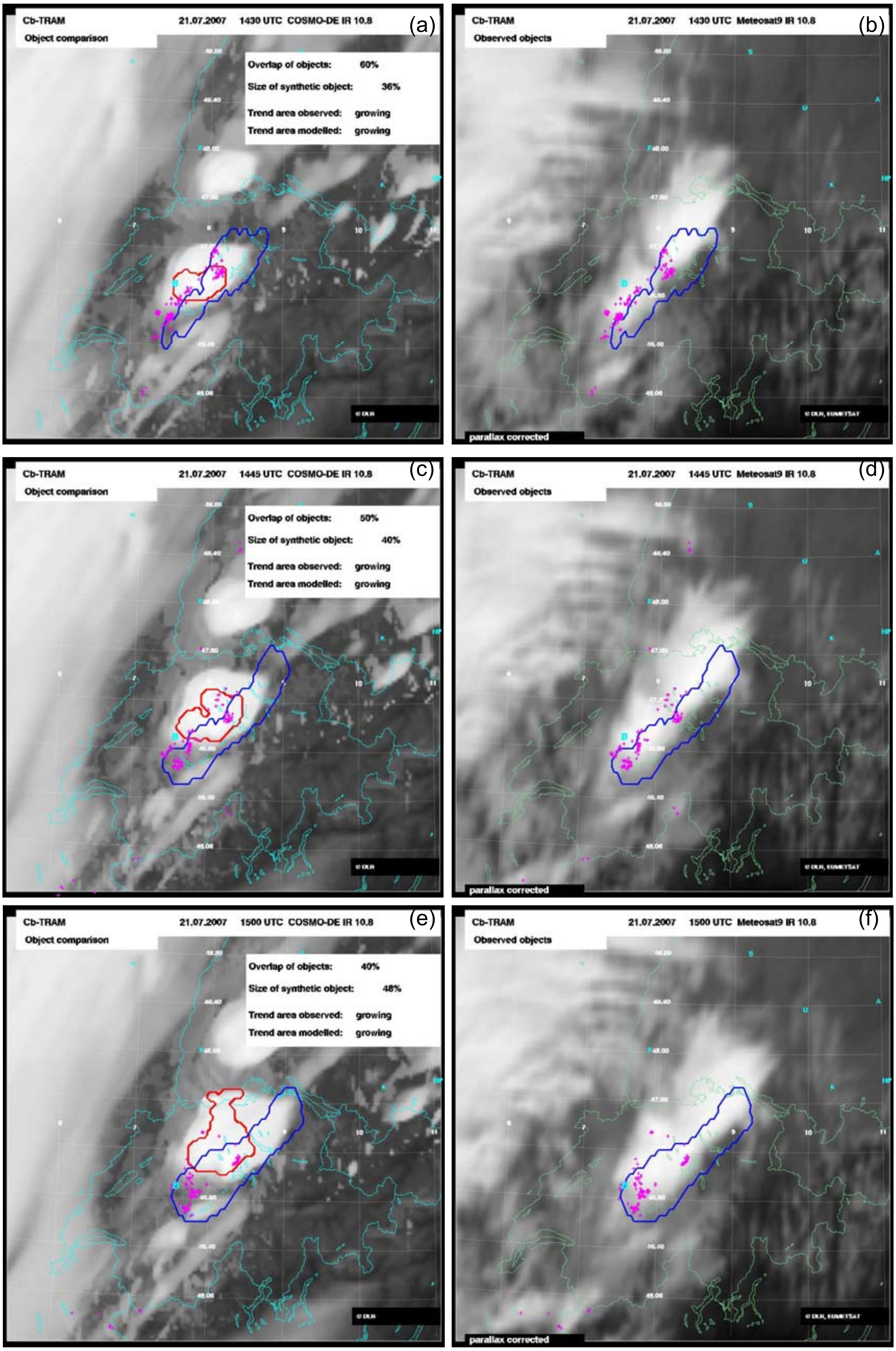

***Figure* 3: Left column: Comparison of forecasted synthetic top volumes (red contours) with observed top volumes (blue contours) of mature thunderstorms detected by Cb-TRAM$_{\mathrm{COSMO}}$ and Cb-TRAM, respectively, over Switzerland at (a) 14:30 UTC, (c) 14:45 UTC, (e) 15:00 UTC on 21 July 2007. The background is the IR 10.8 µm synthetic satellite image forecasted by the 00 UTC COSMO-DE model run. Right column: Observed METEOSAT9 IR 10.8 µm image at (b) 14:30 UTC, (d) 14:45 UTC, and (f) 15:00 UTC with corresponding observed top volumes (blue contours) detected by Cb-TRAM. The pink crosses in the figure indicate lightning detected by LINET. Bern is marked with a turquoise letter.**

(Fig. 4b). The observed top volume does not merge with another cell, but continuously grows to a cell of the size comparable to that in the forecast. Hence, although the history of the forecasted and the observed top volumes are different, the forecast of the track and the trend in size agrees well with the observation.

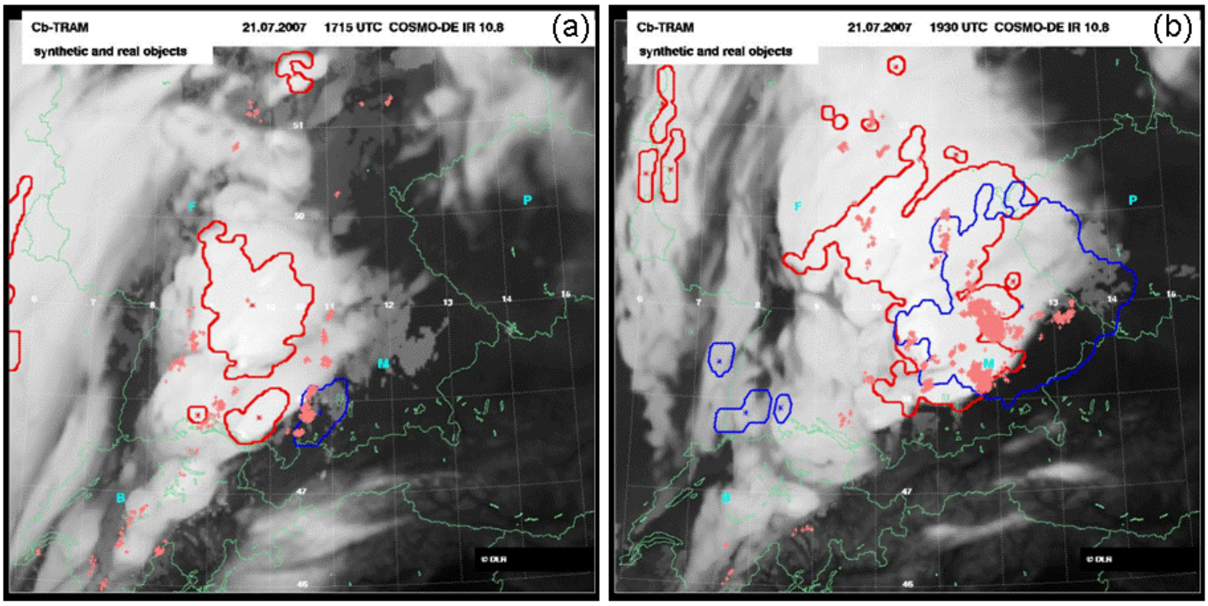

***Figure* 4: Same as left column of Figure 3, but for Southern Germany and the Alpine region at (a) 17:15 UTC, and (b) 19:30 UTC.**

4. OUTLOOK

In a next step, it is planned to combine the parameters overlap, size, trend, moving speed, moving direction and intensity of each object adequately into a quality measure describing the agreement of the forecast with the observation thereby accounting for the history of the object and phase errors in its forecast. The object comparison method can then be used to select the best forecast available, e.g. out of an ensemble. The final aim is to use this best forecast for further predictions of the observed patterns beyond their nowcasting horizon. For these further predictions it is planned to apply also probabilistic methods, i.e. instead of forecasting the future position of a TWO, the probability that a weather hazard will occur in a defined region is calculated.

The forecast validation by object comparison is part of the Weather Forecast User Oriented System Including Object Nowcasting (WxFUSION; Figure 5), a system that is currently under development within the project “Wetter & Fliegen” (runtime 2008 - 2011) under the lead of DLR-IPA. WxFUSION aims at combining observational data with data from nowcasting algorithms and numerical model forecasts in order to predict weather hazards as precisely as possible for ATC, pilots, and airports. The combination has the benefit that the assertions of the individual data sources, e.g. with regard to the exact location of a particular weather system, its intensity and movement, can be processed and contrasted. Thus, the system provides a more reliable interpretation of the future state of a weather system than only one data source could give [Tafferner et al., 2008a]. Figure 5 shows the components and concept of the system (reprinted from Forster and Tafferner, 2008). The upper half in Figure 5 represents data sources from observations and nowcasting tools, while the lower half represents data sources from numerical model simulations. These tools have been developed as stand-alone tools for particular purposes and work independently from each other. A description of the tools and their respective references can be found in Tafferner et al. [2008a] and Forster and Tafferner [2008]. In the core element “FUSION”, it is planned to combine the different data sources by using fuzzy logic and also with numerical model forecasts, if they exhibit reasonable agreement with observations. Here, the object comparison method will have its central role. It will be used to determine the best forecast available out of an ensemble. Weather hazards like thunderstorms are represented as target weather objects (TWO) which are pre-defined and specified including user requirements. For each of the

TWOs WxFUSION extracts individual attributes and weather elements from all available data sources in order to describe the TWO's history, current state, and future.

Within the "Wetter & Fliegen" project WxFUSION will be developed for two kinds of weather hazards: thunderstorms and winter weather. For winter weather a TWO might be an area with heavy snowfall or icing. Work is going on for finding the exact definition of such a TWO and adjusting nowcasting algorithms based on polarimetric radar data.

In 2010, WxFUSION is envisaged to be run in real-time during a summer and a winter campaign at the airports Munich and Frankfurt in close cooperation with the DWD in order to test its forecasting skills with respect to thunderstorm and winter weather objects. After the testing phase an installation for operational use at the airports Frankfurt and Munich is intended.

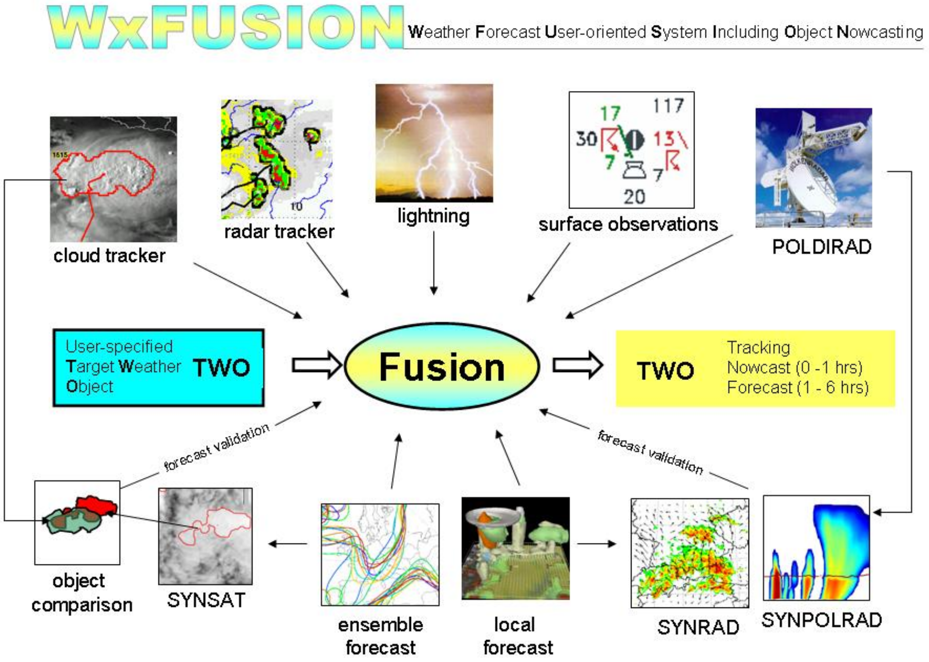

***Figure* 5: Schematic diagram of the WxFUSION concept. User specified target weather objects (TWO) are characterized by appropriate information through a fusion of selected nowcast information (upper half) and forecast products (lower half). Reprinted from Forster and Tafferner, 2008.**

5. ACKNOLEDGEMENT

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