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# AN INTEGRATED USER-ORIENTED WEATHER FORECAST SYSTEM FOR AIR TRAFFIC USING REAL-TIME OBSERVATIONS AND MODEL DATA

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## Abstract

*This paper presents the Weather Forecast User-oriented System Including Object Nowcasting (WxFUSION), an integrated weather forecast system for air traffic. The system is currently under development within a new project named "Weather and Flying" under the leadership of the Institute of Atmospheric Physics (IPA) at the German Aerospace Center (DLR). WxFUSION aims at combining data from various sources, as there are weather observations, remote sensing, nowcasting and numerical model forecast data, in order to extract specific information on target weather objects like thunderstorms, icing, or areas with heavy snow fall. The target weather objects are pre-defined including user requirements. The paper gives a short overview on the concept of the system and on-going work.*

## 1 Motivation and goal

Weather has been identified as the primary reason for delays and disruptions in the air transport system [1]. For instance, during the summer months flights are often delayed or even cannot be operated because of thunderstorms in the terminal manoeuvring area (TMA), while during winter operations at the airports might be substantially affected by winter storms and icing conditions. In the U.S. up to 90% of all delays are due to thunderstorms during the summer months [1]. 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]. There is a clear need for integrated systems that analyse and forecast weather hazards for air traffic as precisely as possible in order to enable the mitigation of the weather hazard's effects.

Several such systems have been successfully developed for U.S. airports during the last decade (e.g. [2][3]). The integrated Terminal Weather System (ITWS [2]) provides tailored weather products to Air Traffic Control (ATC) personnel that are immediately usable without further meteorological interpretation. The products include windshear/microburst detection and prediction, gust front detection and forecast, precipitation, storm cell speed, motion and extrapolated position, and lightning, tornado, and storm cell information (e.g. hail and radar echo tops). The NCAR Auto-Nowcast System ([3]) provides nowcasts of convective storm location and intensity by combining observations, a numerical boundary layer model, hazard detection algorithms, and forecaster input. The combination is done through fuzzy logic which provides an efficient manner to combine datasets and apply conceptual models.

In Europe, an important piece of the ACARE (Advisory Council for Aeronautics in Europe) plan has been put in place early in 2005: the FLYSAFE Project (http://www.eu-flysafe.org/). FLYSAFE aims at defining and testing new tools and systems contributing to the safety of flights for all aircraft. It focuses on the development of new on-board systems and of the tools on the ground for feeding them with the information that they require. The development of a thunderstorm weather information management system within

FLYSAFE is described in more detail by Tafferner et al. (presentation ICAS 2008-8.6.2: Nowcasting thunderstorm hazards for flight operations: the CBWIMS approach in FLYSAFE). In Germany, a new project has started in 2008 under the leadership of the Institute of Atmospheric Physics (IPA) at the German Aerospace Center (DLR) in Oberpfaffenhofen. Named "Weather and Flying", this DLR project aims at increasing safety and efficiency of air traffic and to secure the competitiveness of German and European aviation industry. In order to reach this high level goal two main systems are being constructed:

- Integrated airport weather systems for the airports Frankfurt and Munich comprising the components "wake cortices", "thunderstorms" and "winter weather"
- On board systems for steering and monitoring as well as ground based information systems in order to improve flying characteristics in case of turbulence, wake vortices and thunderstorms.

In this paper, we present the central element of the weather systems part by introducing the Weather Forecast User Oriented System Including Object Nowcasting (WxFUSION) which is envisaged to be operationally installed at the airports Frankfurt and Munich after a demonstration phase.

## 2 The components and the concept of the system

Fig. 1 shows the components and the concept of the WxFUSION system ([4][5]). The upper half in Fig. 1 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

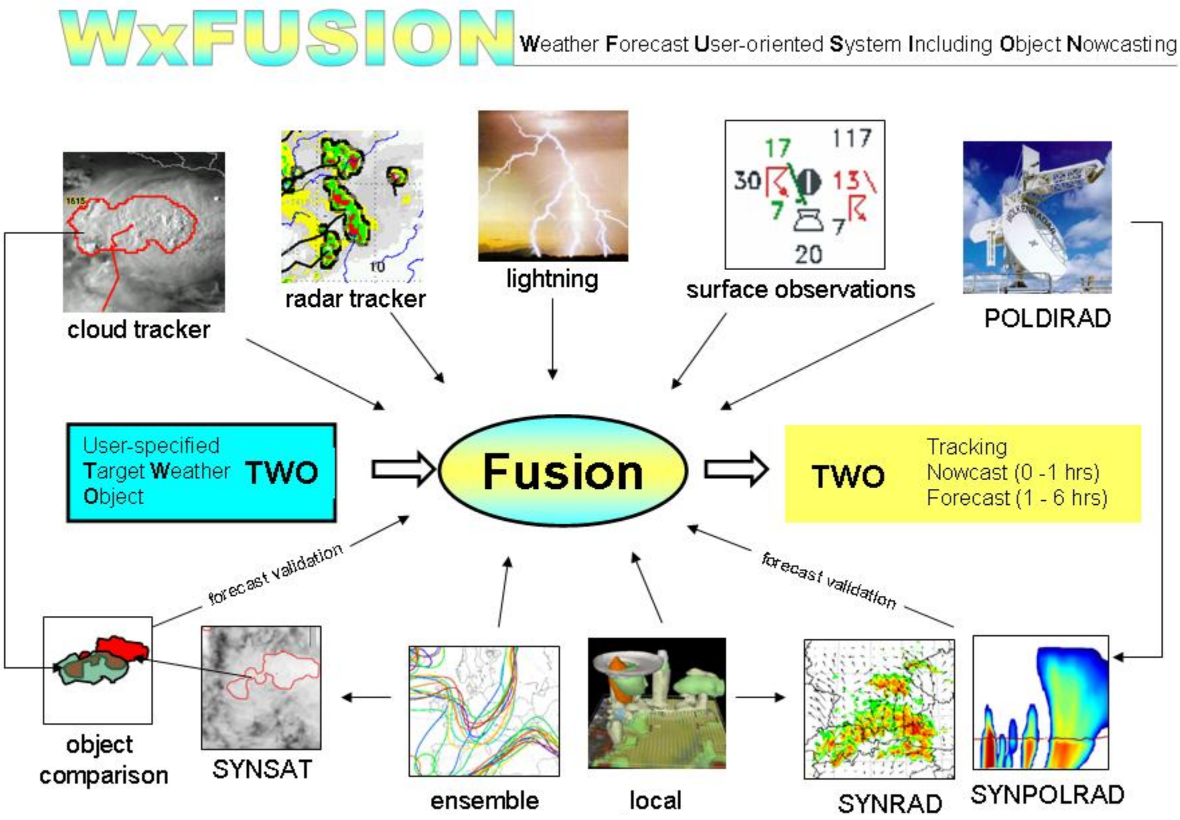


**Fig. 1.** Schematic diagram of the WxFUSION concept. User specified target weather objects (TWO) are characterized by appropriate information through a fusion of selected nowcast information (upper half) and forecast products (lower half).

particular purposes and work independently from each other. They have partly been developed at DLR and are shortly described in the following paragraph. For further details on the individual tools and data sources please refer to the given literature.

The cloud tracker Cb-TRAM (Cumulonimbus TRacking And Monitoring) is a new fully automated algorithm for the detection and nowcasting of convection using Meteosat SEVIRI (Spinning Enhanced Visible and Infra-Red Imager) data ([6]). 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. The HRV is used to identify convective updrafts within thunderstorm complexes by exploring the 'roughness' of the satellite image in the HRV. 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 t-1 (with t = current time) in combination with a new so-called pyramidal image-matching algorithm ([6]). This algorithm 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 and use of the pyramidal image-matching algorithm. For more details on the nowcasting skills of Cb-TRAM please see [6] and Tafferner et al. (presentation ICAS 2008-8.6.2: Nowcasting thunderstorm hazards for flight operations: the CBWIMS approach in FLYSAFE). The pyramidal matcher is also used for tracking and nowcasting of precipitation cells detected by the radar tracker Rad-TRAM (Radar TRacking and Monitoring)([7]). Rad-TRAM makes use of the European radar composite from the German Weather Service (DWD) to identify precipitation cells with more than 37 dBZ reflectivity. Currently, work is going on to apply Rad-TRAM also to data from the DLR polarization diversity Doppler radar (POLDIRAD). POLDIRAD provides 3-D information on precipitation and enables the distinction of hydrometeors ([8]). Lightning data are provided by the Lightning Location Network (LINET) system ([9]) which can distinguish between cloud-to-ground and intra-cloud flashes. In addition it is planned to use surface observations like AMDAR and LIDAR as well as SYNOP and TEMP data, if available in the TMA. The numerical model simulations for both local high resolution and regional-scale ensemble forecasts are performed by the COSMO-DE and COSMO-EU models, respectively, from the DWD ([10], [11]). Both models also generate synthetic satellite imagery and synthetic radar reflectivity indicated as SYNSAT and SYNRAD, respectively, in Fig. 1. Finally, the ability of numerical models to reproduce the formation and interactions of hydrometeors can be assessed with the newly developed synthetic polarimetric radar forward operator (SYNPOLRAD)([12]).

The task within the "Weather and Flying" project is to combine the above described different data sources accordingly in order to detect, nowcast (0-1 hrs) and forecast (1-24 hrs) target weather objects (TWO) which are pre-defined and specified by the user (e.g. weather providers for Air Traffic Management and pilots). The nowcasting up to one hour is primarily based on the tools in the upper half of Fig. 1, while the forecasting up to 24 hours is primarily based on the tools in the lower half of Fig. 1. The TWOs are simplified pictures of rather complex weather hazards like thunderstorms, icing, or areas with heavy snow fall. As an example, Fig. 2 shows a thunderstorm as TWO. There is a top volume representing the upper anvil part and a bottom volume representing the lower part of a thunderstorm. Outer and inner volumes indicate the severity levels moderate and severe of the hazard, respectively (see also Tafferner et al. ICAS 2008-8.6.2: Nowcasting thunderstorm hazards for flight operations: the CBWIMS approach in FLYSAFE). The upper part can be identified by using e.g. the cloud tracker Cb-TRAM in combination with lightning data from LINET. Thereby Cb-TRAM detects and nowcasts the outer top volume, i.e. turbulent areas within the anvil, while the lightning

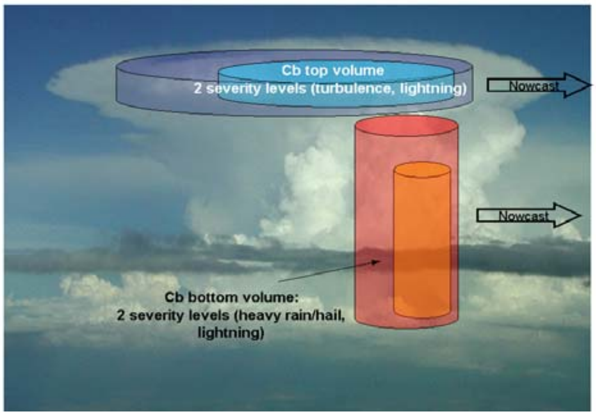


**Fig. 2** A thunderstorm rendered as an idealized target weather object (TWO) with top and bottom volumes

density exceeding a certain threshold marks the inner severe part of the top volume. The outer part of the bottom volume can be detected and nowcasted e.g. by the radar tracker Rad-TRAM. A combination with POLDIRAD and LINET data allows refining the detection by identifying the severe part of the volume with heavy rain, hail, and lightning occurrence. Note that the horizontal shape of the top and bottom volumes does not have to be round or elliptical, but can be polygon shaped.

The combination of data from different sources has the benefit that the assertions of the individual tools, 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 or nowcasting tool could give [4]. In addition, it is planned to use fuzzy logic in the system's core element FUSION (Fig. 1) to combine the information from the different data sources. Fuzzy logic has been used for a variety of applications in meteorology (e.g. [3] [14] [15]). It allows to account for imprecise observations and forecasts and also to deal with parameter ranges instead of fixed thresholds. The binary yes-no decision is eliminated and, instead, mathematical functions based on conceptual models or expert knowledge are used in combination to estimate the probability of a particular weather hazard in a defined region. In addition, local constraints and requirements for safe aircraft operations with respect to certain weather conditions can be accounted for.

The use of numerical model forecasts for the time range one to several hours is accounted for by another part of WxFUSION called "forecast validation", where the quality of the forecasts is checked against observations (Fig. 1). Here, forecasted weather objects are compared to weather objects as detected from observational data. For this, the cloud (radar) tracker is applied to the synthetic satellite (radar) images, and the resulting synthetic cloud (radar) cells are compared to the cloud (radar) cells detected in the real satellite (radar) images. This object comparison enables the assessment of the quality of the forecasted cloud (radar) cells. Another possibility to assess the forecast quality is to apply the novel forecast quality measure (FQM) developed at DLR [13]. Thereby the pyramidal image matching algorithm ([6]) in combination with the local squared difference is used to compare observed and synthetic images, and a FQM for the whole image is calculated. Of course, a forecast will normally not perfectly match an observation. Displacements of forecasted TWOs, i.e. phase errors, must be taken into account as well as errors in existence and intensity. Nevertheless, either the FQM or the object comparison can be used to select the best forecast available, e.g. out of an ensemble, which can then be used for further predictions of the observed patterns. For these further predictions also probabilistic methods will be applied, 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 FUSION of all available data sources has the task to nowcast the position of TWOs up to an hour, to forecast probability measures of occurrence up to 24 hours if possible, and to characterize the TWOs by extracting specific attributes and weather elements describing the history, the current and future state of the TWO. Attributes for nowcasted objects are e.g. moving speed, moving direction, developing stage (growing/decaying), and severity level (moderate/severe). Weather elements are e.g. heavy rain, hail, lightning. For the forecast up to 24 hours, risk areas of heavy precipitation, hail, turbulence, and wind will be output from the system. The final information for the user is then tailored in a short, clear, and precise manner in order to enable quick decision making.

Currently, the system is under development (the Weather and Flying project started in January 2008). The above described data sources, nowcasting tools and forecasting models as well as a graphical user interface (section 3) have already been developed at DLR.

## 3 WxFUSION graphical user interface

A graphical user interface (GUI) enables the overlay of the different observations with the results of the nowcasting tools and the numerical forecasts (Fig. 3). The GUI has been set up in a way that it can be adjusted to local and operational constraints at different TMAs by selecting the respective TMA in the area mode selection. The user can navigate in time, select different backgrounds and superimpose different data sources as well as the tracks, the analyses and the nowcasts of the TWOs. The example in Fig. 3 shows convective cells in the HRV satellite image (grey shading) and the radar reflectivity (colored shading) over the TMA Munich on 12 August 2004 at 17:00 UTC.

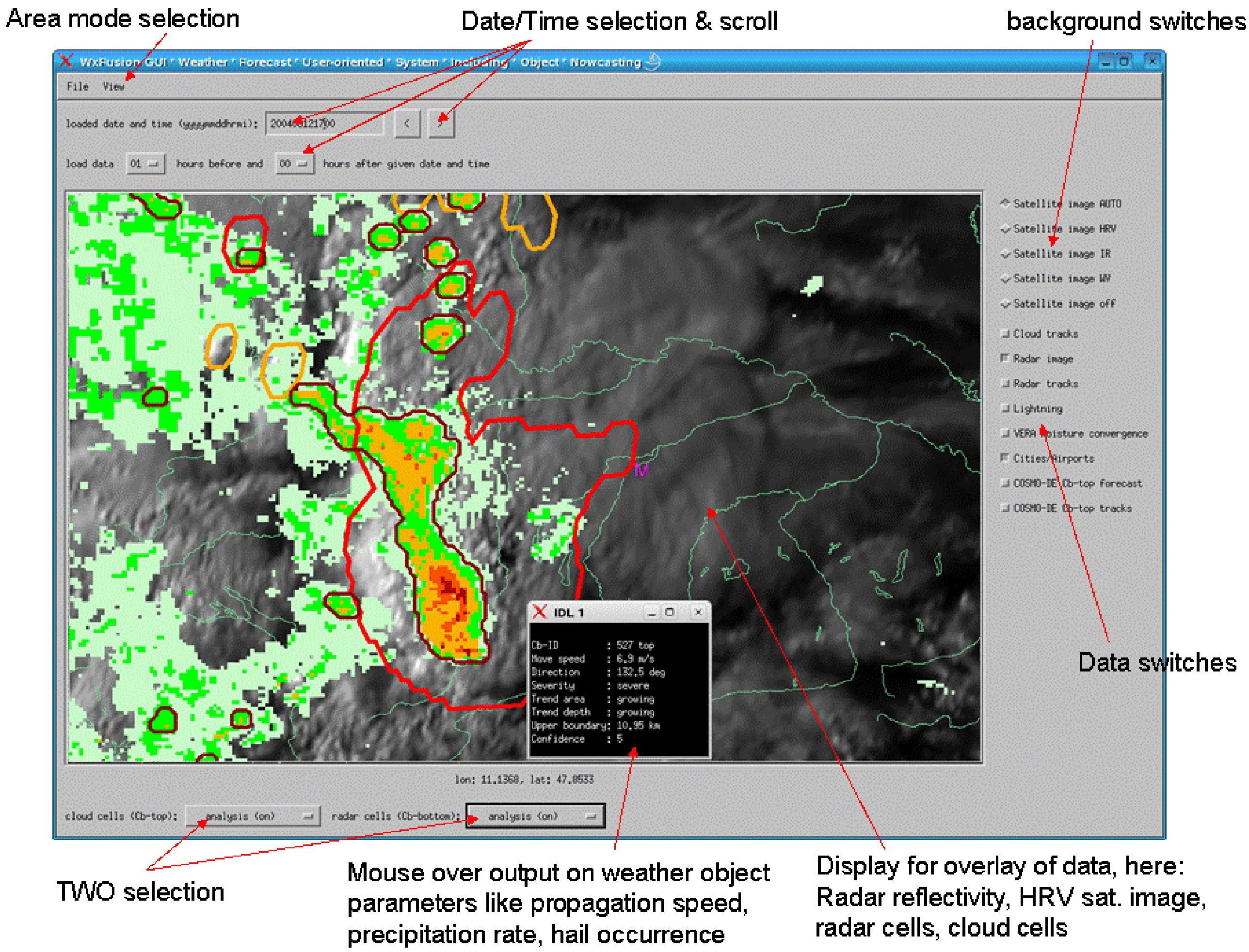


**Fig. 3** WxFUSION graphical user interface displaying radar reflectivity (colored shading), radar cells with reflectivity ≥ 37 dBZ (dark red contours) and cloud cells (orange and red contours) superimposed on the HRV satellite image (grey and shading) for the TMA Munich on 12 August 2004 at 17:00 UTC. Munich airport is marked by a purple M. Rivers and the contours of lakes are indicated in green.

Here, the TMA Munich has been chosen as an area encompassing about 500 km x 300 km around Munich Airport. The dark red contours mark the bottom volumes of the thunderstorm TWOs, while the red (mature thunderstorm) and orange (rapidly growing cumulus cloud) contours mark the top volumes. Generally, the top volumes are larger than the bottom volumes. They do however not encompass the whole anvil, but only the most turbulent regions. In addition, several bottom volumes can be connected to the same top volume. The attributes of the top and bottom volumes extracted from the results of the cloud and radar tracker, respectively, can be displayed in an additional window by moving the mouse inside a contour.

Currently, the GUI is used as a development surface and encompasses a variety of functions. It provides the platform to integrate and test new algorithms for data fusion. However, a similar and presumably simpler GUI will be provided to users like ATC, weather providers for Air Traffic Management, and pilots by accounting for their specific needs for a weather display.

## 4 Forecast validation of TWOs by object comparison

The forecast validation by object comparison is demonstrated in a case study over southern Germany and the Alpine region from 21 July 2007. A cold front was approaching from the south-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 Fig. 4. In the afternoon further convective cells developed over Southern Germany (Fig. 5) leading to considerable obstructions and delays at Munich Airport at later times. Between 19:40 UTC and 20:05 UTC no take-off and landing could be operated because of turbulence, hail and lightning at and around the Airport. Aircraft approaching Munich had to fly holding patterns thereby avoiding regions with heavy rainfall and hail they could detect with their on-board radars. The cell leading to these obstructions is detected for the first time at 16:45 UTC between 10°E and 11°E Fig. 5a) and rapidly develops to a mature thunderstorm within 30 minutes (Fig. 5b). At 18:00 UTC (Fig. 5c) the cell has

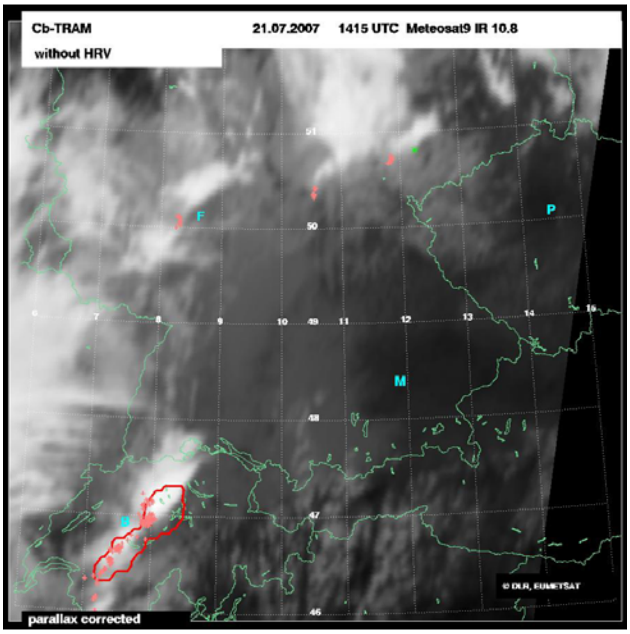


**Fig. 4** Thunderstorm top volumes detected by Cb-TRAM (red contours) and LINET lightning data (pink crosses) superimposed on the IR 10,8 µm METEOSAT image over Germany and the Alpine region on 21 July 2007 at 14:15 UTC. Bern, Frankfurt, Munich Airport, and Prague are marked by the turquoise letters B, F, M, and P, respectively.

substantially grown and the severe weather part (indicated by lightning in Fig. 5) approaches Munich Airport. Still intensifying the severe part reaches the airport at 19:30 UTC (Fig. 5d).

The one hour nowcast by Cb-TRAM at 17:15 UTC (Fig. 5b) indicates that the thunderstorm is heading towards Munich. Already such a short term forecast would enable ATC to adjust flight operations to the expected extreme weather conditions. In addition, if forecasts beyond the nowcasting horizon could be provided, this would be valuable for the long-term planning of flights. A forecast two or more hours in advance would give the ATC the possibility to advise long-range flights from other continents to reduce or increase their speed and to plan flights within Germany in a way that obstructions in Munich are minimized. As mentioned in section 2, forecasts are often not accurate and displacements of the forecasted

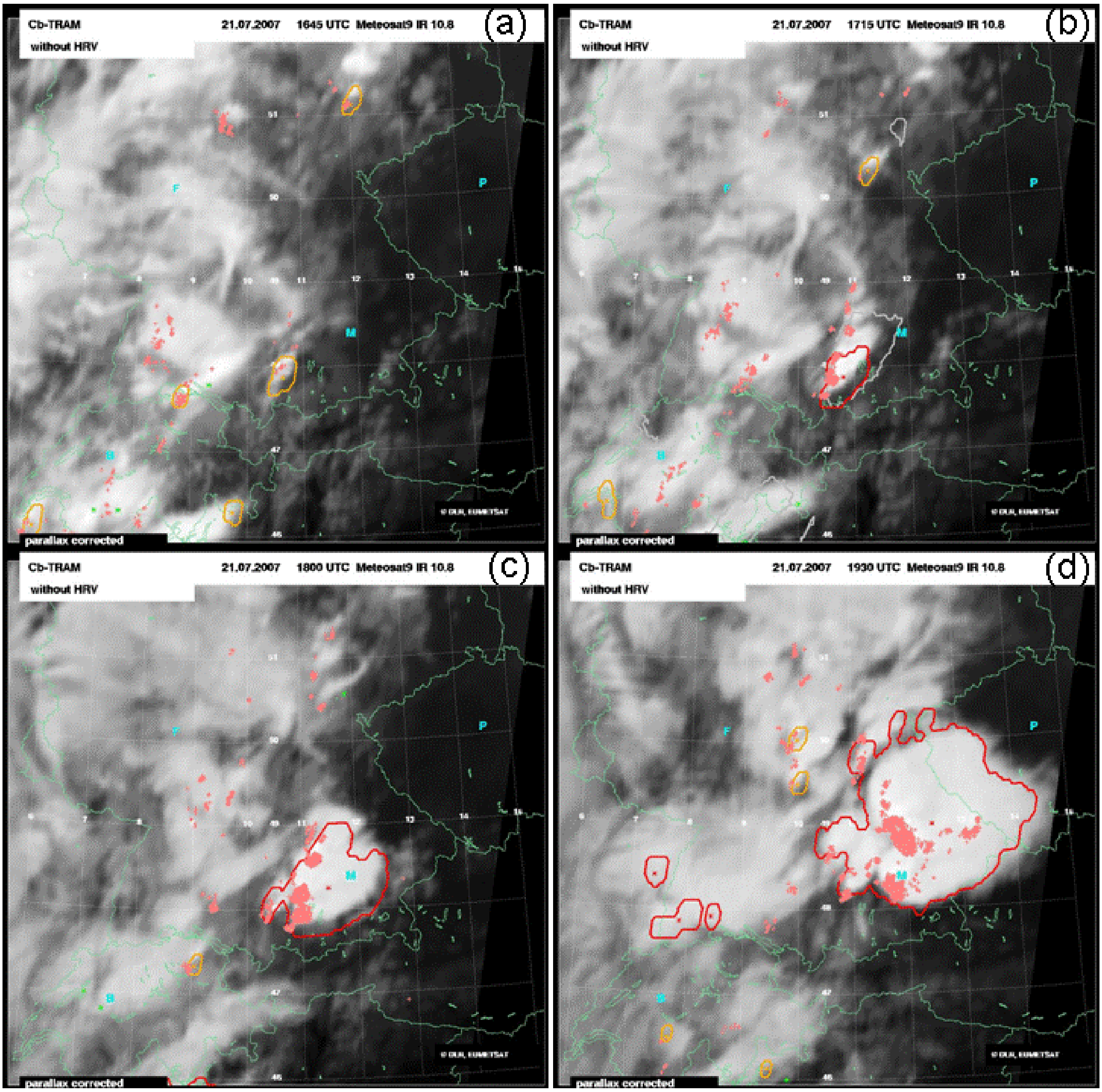


**Fig. 5.** Same as Fig. 4, but at (a) 16:45 UTC, (b) 17:15 UTC, (c) 18:00 UTC, and (d) 19:30 UTC. The orange contours mark rapidly developing cumulus clouds, while the red contours mark mature thunderstorms. The grey contours in (b) indicate the 60 minutes nowcasts.

objects as compared to the observation (phase errors) must be taken into account. Therefore, the forecasts must be compared to observations. If there is reasonable agreement, the respective forecast can be used to extend the nowcasting time horizon, e.g. to predict the probability that thunderstorms will occur over a defined region. In order to enable a comparison of the observed top volumes with the 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 ([10]). This version of CB-TRAM is called Cb-TRAM$_{COSMO}$ in the following.

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 ([11]). Unfortunately, HRV information is not available from this algorithm. Therefore, updraft regions cannot be isolated with Cb-TRAM$_{COSMO}$, and the

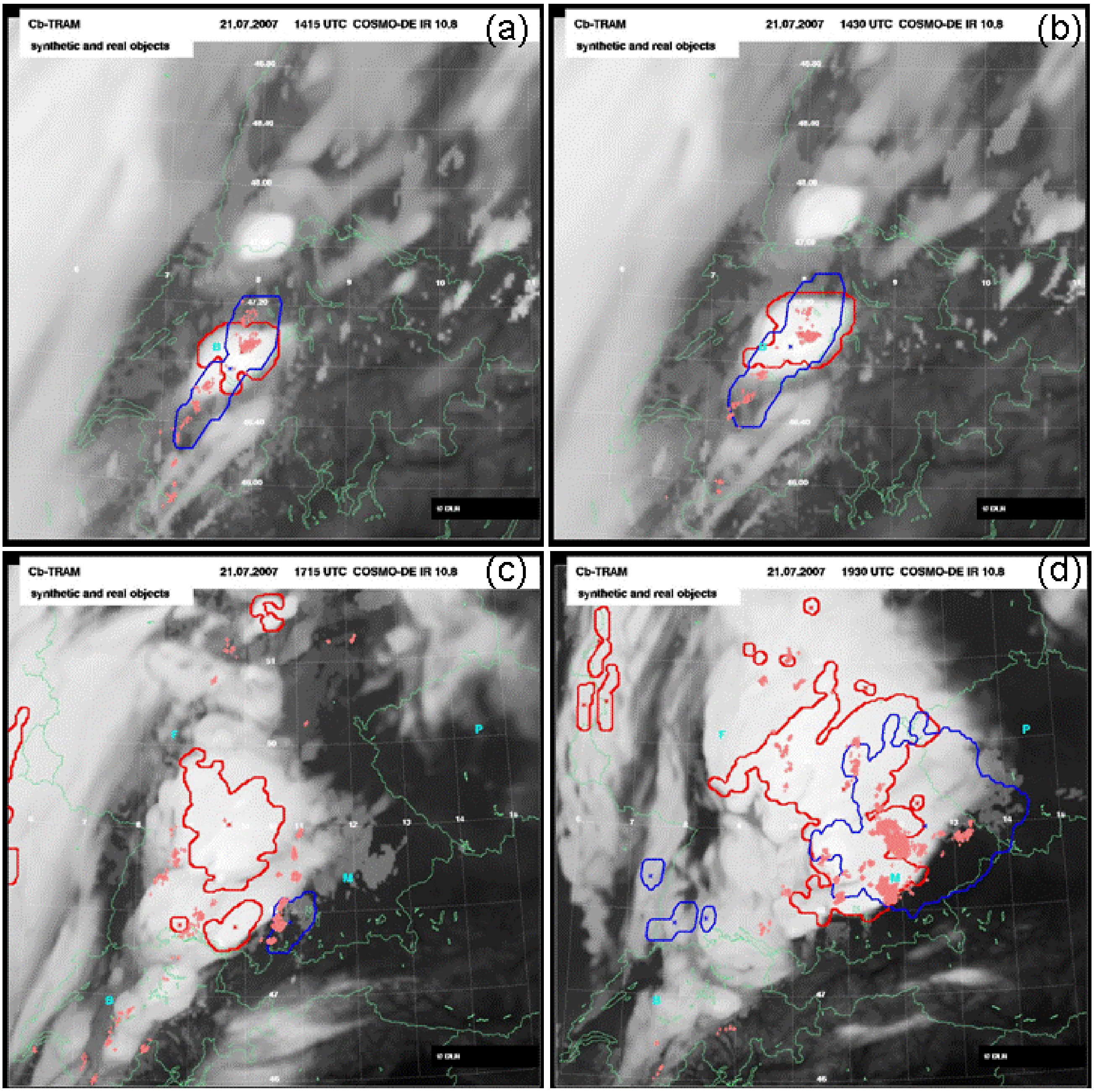


**Fig. 6** Comparison of forecasted synthetic top volumes (red contours) with observed top volumes (blue contours) of mature thunderstorms detected by Cb-TRAM$_{COSMO}$ and Cb-TRAM, respectively, over Switzerland at (a) 14:15 UTC and (b) 14:30 UTC and over Germany and the Alpine region at (c) 17:15 UTC and (d) 19:30 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.

diagnosed top volumes might be somewhat larger than with the usual detection procedure which uses also the visible channel. Please note that the top volumes shown in Fig. 4 and Fig. 5 are detected by Cb-TRAM without using the HRV in order to enable a fair comparison with the synthetic top volumes detected by Cb-TRAM$_{COSMO}$.

Fig. 6 shows a comparison of forecasted synthetic top volumes with observed top volumes for the thunderstorms over Switzerland (Fig. 6a and 6b) and for the thunderstorms leading to the obstructions at Munich Airport (Fig. 6c and 6d) on 21 July 2007. The top volumes are superimposed on the IR 10.8 µm brightness temperatures forecasted by the 00 UTC COSMO-DE model run. Cb-TRAM$_{COSMO}$

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 in Fig. 6. In the case of the top volumes over Switzerland, the shapes of the synthetic and the observed objects are different, but the positions overlap to a great extent. The forecast indicates a growing top volume moving 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. 6c and 6d with Fig. 5). Therefore, the synthetic top volumes are located further west compared to the observed top volumes. The synthetic object at 10°E (Fig. 6c) merges with the larger one north of it, grows substantially and covers a large part of south-east Germany at later times (Fig. 6d). 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. 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. Therefore, this forecast could be used to further predict the evolution of the thunderstorm.

In a next step, it is planned to include a function that enables the user to define a window in space and time surrounding the user's area of interest (like e.g. the area chosen in Fig. 6a and 6b). With the aid of the pyramidal image matcher ([6]) synthetic objects will be searched for that overlap with observed objects within the area. By assessing the degree of overlap and by comparing the size, the moving speed, the moving direction, and the history of the overlapping patterns, the quality of the forecast will be estimated.

## 6 Summary and outlook

WxFUSION is the acronym for Weather Forecast User Oriented System Including Object Nowcasting, a system that is currently under development within the project Weather and Flying (runtime 2008 - 2011) under the lead of DLR-IPA. It aims at combining observational data with data from nowcasting algorithms and numerical model forecasts in order to predict weather hazards as precise as possible for ATC, pilots, and airports. Weather hazards like thunderstorms are represented as target weather objects (TWO) which are pre-defined and specified including user requirments. For each of the TWOs the system extracts individual attributes and weather elements from all available data sources in order to describe the TWO's history, current state, and future. The combination of the different data sources will be based on fuzzy logic and the use of numerical model forecasts, if they exhibit reasonable agreement with observations. This paper summarized the components and the concept of the system as well as on-going work concerning the graphical user interface (GUI) and the validation of numerical forecasts of TWOs with observations. If there is reasonable agreement of a forecasted TWO with an observed one, the forecast can be used to further predict the evolution of the TWO beyond the nowcasting horizon. For these further predictions also probabilistic methods will be applied.

Within the Weather and Flying 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 will be tested in real-time during a summer and a winter campaign at the airports Munich and Frankfurt in order to test its forecasting skills with respect to thunderstorm and winter weather objects. After the testing phase it is envisaged to install it operationally for use at the airports Frankfurt and Munich.

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