2.5 Limited Area Numerical Weather Prediction

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Two limited area model derivatives of the numerical weather prediction model COSMO-DE operated by the German Meteorological Service are introduced. The aim is to obtain frequently updated highly resolved predictions in a limited area as an aerodrome. The predictions include dynamic parameters as wind and turbulence kinetic energy and thermodynamic quantities as temperature and humidity but also the amount of snow, rain and hail. The models are used in the airport environments of Frankfurt (COSMO-*FRA*) and Munich (COSMO-*MUC*) for aircraft wake vortex, thunderstorm activity, and wintry weather warning applications, as detailed in Sections 2.1 to 2.4.

Introduction

The demand for efficient, safe, and environmentally sustainable air traffic is steadily increasing. Major airports already today operate at their capacity limits. With increasing demand the air transport system becomes more vulnerable to distortions of all kinds. One of the major contributors to incidents, accidents, and delays in air traffic are adverse weather conditions, also en-route but especially at and around busy airports. Detailed studies of the impact of weather upon aviation show that there is a need for improved weather forecasts. Short-range wind forecasts with high resolution in space and time will become an important factor in airport operations especially for lead times of 1-2 hours.

An accurate forecast of wind, turbulence and temperature along the glide paths of an airport is also required to predict the transport and decay of aircraft wake vortices, see Section 2.1. The reason is that the atmosphere in terms of wind speed, wind direction, turbulent kinetic energy, eddy dissipation rate, and vertical stability of air surrounding the vortices affects their horizontal and vertical displacement as well as their decay (see Section 6.1).

For high quality predictions a limited area, high-resolution weather forecast model should be the appropriate choice. Such a model should take into account the orographic and land use characteristics at and around the airport in order to correctly balance the levels of energy, driven by turbulence, surface friction and sensible and latent heat of the air masses in the atmospheric boundary layer. In the past DLR has developed the ‘Nowcasting Wake Vortex Impact Variables’ model NOWVIV (Gerz et al. 2005) to forecast wake-vortex affecting weather parameters in airport environments. Recently, we use derivatives of the COSMO-DE model with which the German Meteorological Service, DWD, runs operational weather forecasts for Germany. The two derivatives are COSMO-*FRA* and COSMO-*MUC* for the two aerodromes of Frankfurt and Munich, respectively.

Running the model in a rapid update cycle (RUC) mode results in several forecasts with different forecast initial times for a certain forecast time. This so called Time-Lagged-Ensemble (TLE) is a single-model variant initial-condition ensemble-forecast system where the dynamics, the physical parameterisations and the numerics are the same for all members. It provides an estimate of the forecast uncertainties and reduces errors resulting from initial spin-up. An improvement especially of the short term forecasts up to 6 h is expected which is highly relevant for forecasting wake vortices (Section 2.1), thunderstorms (Section 2.3) and wintry weather conditions (Section 2.4).

The COSMO-DE Model and its Limited Area Derivative COSMO-*FRA*

The non-hydrostatic, fully compressible COSMO model has jointly been developed by the Consortium for Small Scale Modelling and is operationally used by several European Meteorological Services. The COSMO-DE version is the high resolution model of DWD using a horizontal mesh size of 2.8 km covering an area of roughly 1200 x 1300 km^2 in Central Europe (Steppeler et al. 2003).

For the application in the Frankfurt Airport area, we took the COSMO-DE model of version 4.2 as the local area model COSMO-*FRA* which is centred at the Airport encompassing an area of 280 x 280 km^2 (see Figure 1). The vertical resolution of the boundary layer is increased amounting to 16 to 90 m corresponding to 19 levels below 1600 m with a total of 50 vertical levels as in COSMO-DE. The horizontal resolution was kept as in the parent model. The numerics and physics packages follow the operational configuration (Baldauf et al. 2011), using a two time level integration scheme based on the Runge-Kutta method of 3rd order and a prognostic turbulence scheme with 2nd order closure (i.e. a prognostic equation for the turbulence kinetic energy). The roughness length used in COSMO-*FRA* is 0.47 m (forest). COSMO-*FRA* made a 24-hour forecast once a day starting at 00 UTC; initial and hourly boundary data were provided by the larger-scale COSMO-EU model and updated every three hours. COSMO-*FRA* was first applied to predict wake vortex transport and decay parameters, so the vertical profiles of wind, virtual potential temperature, and turbulence kinetic energy were output at a 10 min frequency.

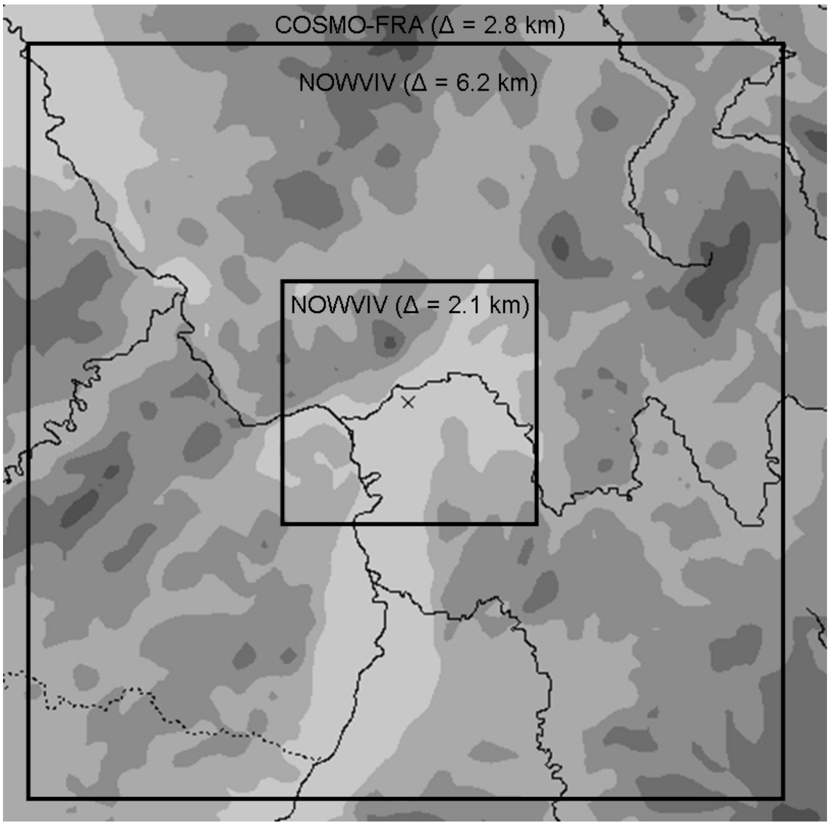


Figure 1. Domain of the high resolution models COSMO-*FRA* and nested NOWVIV centred at Frankfurt Airport. COSMO-*FRA* topography is given in grey shading, rivers in black.

The performance of COSMO-*FRA* has been assessed against NOWVIV predictions and local measurements at Frankfurt Airport by Dengler et al. (2009). One of the outcomes was that an adjusted land use data set for COSMO-*FRA*, possibly combined with higher horizontal and vertical resolutions, to account for specific topographic and land-use features at and around the airport would achieve better forecasts of wind, virtual potential temperature and turbulence kinetic energy in the boundary layer.

The next improvement was to adapt COSMO-*FRA* to version 4.8 of COSMO-DE and start the model hourly in a Rapid Update Cycle (RUC) mode providing short range time-lagged ensemble (TLE) forecasts of up to 6 hours. Figure 2 shows a schematic illustration how the TLE is created showing the available forecasts for an example time of 15:10 UTC. Forecasts starting at 10 UTC (member -5h) to 15 UTC (member -0h) are available with 10-minute output frequency. Therefore, for every 10-minute increment 6 members of the TLE are available. In addition, every full hour a forecast starting 6 hours ago is available creating a 7th member (i.e. for 15 UTC a forecast starting at 09 UTC, member -6h). Finally an equally weighted ensemble mean is calculated from the 6 available members. Further, the spread of the 6 ensemble members indicates the predictability and the related uncertainties of the respective meteorological situation. The model output comprises the three wind components, air density, virtual potential temperature, turbulent kinetic energy, eddy dissipation rate (EDR), and pressure.

The hourly forecasts of the COSMO-*FRA* model were analysed for three cases representing significantly different weather situations as experienced in winter 2006/2007: a frontal passage, stormy conditions and a high pressure system. The results were compared against the reference run starting at 00 UTC with a lead time of 24 hours as used before.

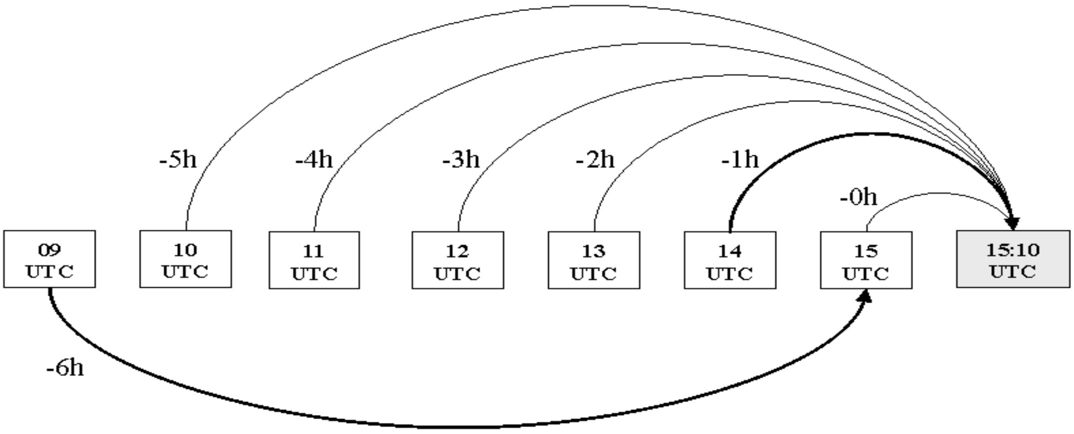


Figure 2. Schematic illustration of the creation of a time-lagged-ensemble (TLE) forecast.

The TLE forecasts were also checked and validated against measurements of vertical profiles of the three wind components, the standard deviation of vertical velocity, and virtual temperature from 60 m up to 1650 m with vertical resolution of 30 m provided by a wind and temperature radar combined with radio-acoustic sounding system run by DFS (Konopka and Fischer 2005) at the airport of Frankfurt.

A detailed discussion of the results is provided by Dengler et al. (2011). It was concluded that TLE forecasts of wind speed and the wind components parallel and perpendicular to the flight/runway direction reduce the mean bias and root-mean-square error in all three cases compared to the reference model run. The improvement of the forecast was most evident in the very short range of 1 - 2 hours as has been found in previous studies (Lu et al. 2007). The 1-hour forecast showed the lowest bias in all cases. In case of the frontal passage all forecasts overestimated the wind speed within the inversion layer up to 1000 m. In the stormy situation forecasts up to 2 hours underestimated the wind speed above 800 m while no consistent trend was observed in case of the high pressure system. The forecasts of turbulence kinetic energy improved below 900 m but not above that altitude. In contrast to the wind forecasts the 1 hour forecast of turbulence kinetic energy showed the largest error caused by initial spin-up effects. Finally, TLE forecasts of virtual potential temperature also improved except in the case of the high pressure system where the root-mean-square error increased significantly compared to the reference run.

No data assimilation had been used in the model runs. This shows that the observed improvement of the forecasts is a result of the hourly rapid update cycle which benefits from more accurate initial- and boundary conditions provided and updated every 3 hour by the COSMO-EU model. The shortest forecast range members of the time-lagged ensemble (forecasts up to 2 hours) were most accurate and the ensemble spread of the members provided useful information about the reliability of the forecasts.

To further improve the forecasts especially on the short range we aimed to assimilate local data measured in the airport environment, e.g., wind and temperature data from profilers or from aircraft (AMDAR) as well as precipitation data from radar (latent heat nudging), into the model. These technical improvements were achieved with another limited area model, this time located at the airport of Munich, COSMO-*MUC*.

The Limited Area Model COSMO-*MUC*

The COSMO-*MUC* setup used a 358 x 358 km^2 domain where the airport of Munich was located in the southeast quarter of the computational domain, i.e. downstream of the main wind direction (see Figure 4 below). The model had a horizontal resolution of 2.8 km and a vertical resolution of 16 to 144 m corresponding to 17 levels below 1100 m above ground. Again, the numerics and physics packages followed the operational configuration of COSMO-DE. The boundary conditions were treated as before with COSMO-*FRA*, COSMO-*MUC* however, calculated the initial conditions by assimilating locally available data from precipitation radar, aircraft (AMDAR), surface synoptic observations (SYNOP), and radio sounding observations (TEMPS) with an hourly update rate (Figure 3). As COSMO-*FRA* also COSMO-*MUC* started every hour instead 3-hourly like COSMO-DE. Forecast parameters included, besides standard model output, also the amount of precipitation which has been used for advanced warning of thunderstorms (Section 2.3) or in winter time (Section 2.4).

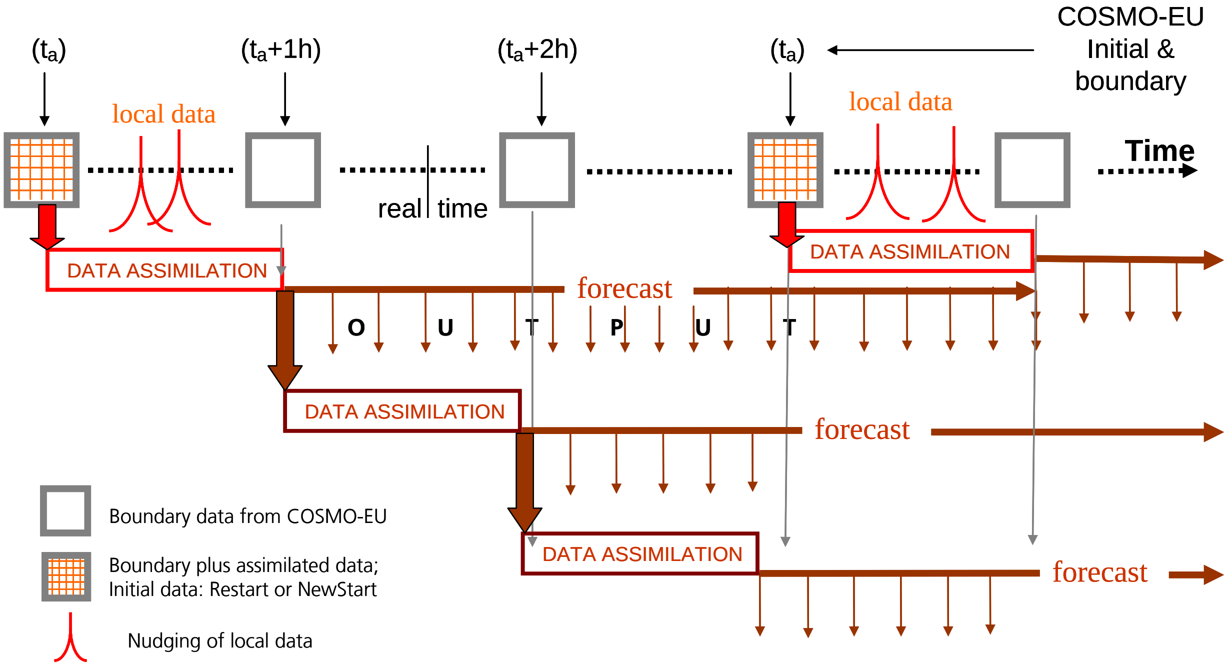


Figure 3: Schematic illustration of the hourly assimilation cycle of the operational mode of COSMO-*MUC*.

Every hour boundary conditions were provided by the operational COSMO-EU model of DWD. New initial data was available every 3 hours from COSMO-EU as indicated by the gridded squares in the upper line of Figure 3 while empty squares indicate the input of boundary data only. Every hour COSMO-*MUC* started from an initial state provided from an analysis run which assimilated local data throughout the past hour (indicated by “local data” and “data assimilation”). In case of a 6-hour forecast run 6 different model outputs were available at any analysis time (see also Figure 2). These TLE forecasts allowed the calculation of probabilities of snow or heavy convective precipitation amount for a certain time. Of course, the configuration could be changed, e.g. by running longer forecasts therefore enabling more members to be combined at any time, or perturbing initial conditions and generate more members. A quite similar approach is undertaken at DWD with the aim to spread an ensemble of 40 members (Schraff et al. 2011).

COSMO-*MUC* has also been used to analyse the improvement of precipitation forecast of convective systems (Figure 4). The predicted reflectivity fields at 850 hPa were compared to COSMO-DE forecasts and reflectivity data from radar (Figure 5) employing the displacement amplitude score (*DAS*) technique (Keil and Craig 2009). *DAS* is a field verification measure for precipitation forecasts that combines weighted distance and amplitude errors:

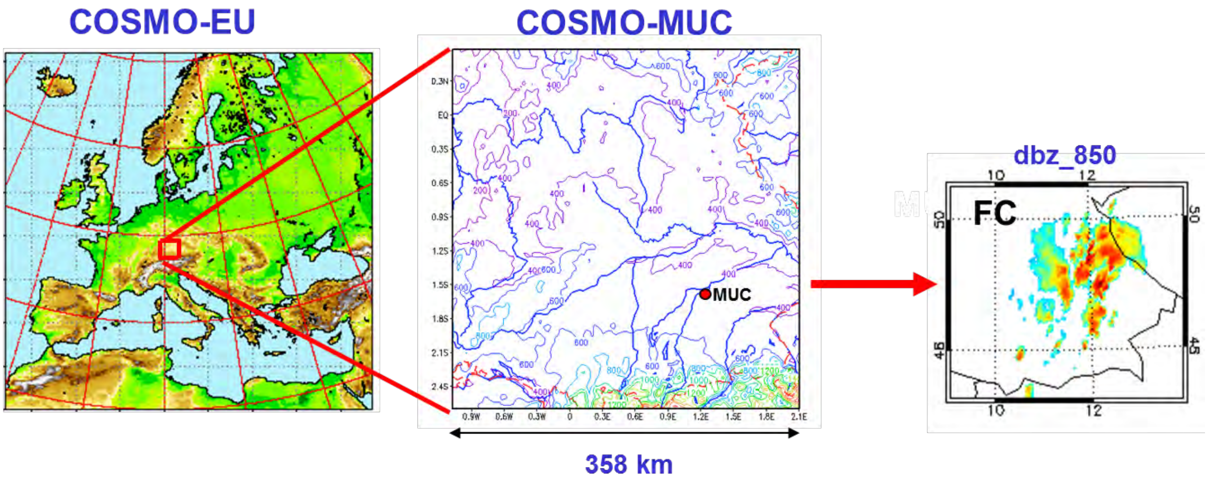


Figure 4: COSMO-*MUC* model chain for Munich Airport (MUC). Hourly boundary conditions updated every 3 hours were provided by COSMO-*EU*. COSMO-*MUC* provided forecasts of the reflectivity at 850 hPa as a guess for the amount of precipitation.

$$DAS = \frac{DIS}{D_{\max}} + \frac{AMP}{I_0}$$

It is based on an optical flow algorithm that defines a vector field that deforms, or morphs, one image to match another. When the forecast field is morphed to match the observation field, then for any point in the observation field, the magnitude of the displacement vector gives the distance to the corresponding forecast object (if any) yielding a “displacement error field” (*DIS*), while the difference between the observation and the morphed forecast is the “amplitude error” (*AMP*); I_0 is a **c**haracteristic intensity averaged out of 5 thunderstorm cases. If observed and forecast features are separated by more than a prescribed maximum search distance (D_{max}), they are not matched to each other, but they are considered to be two separate amplitude errors, i.e. a missed event and a false alarm. *DAS* constitutes a single measure of forecast quality and has the advantage to avoid double penalties. The smaller the values of *DAS*, *DIS* and *AMP*, the better is the prediction.

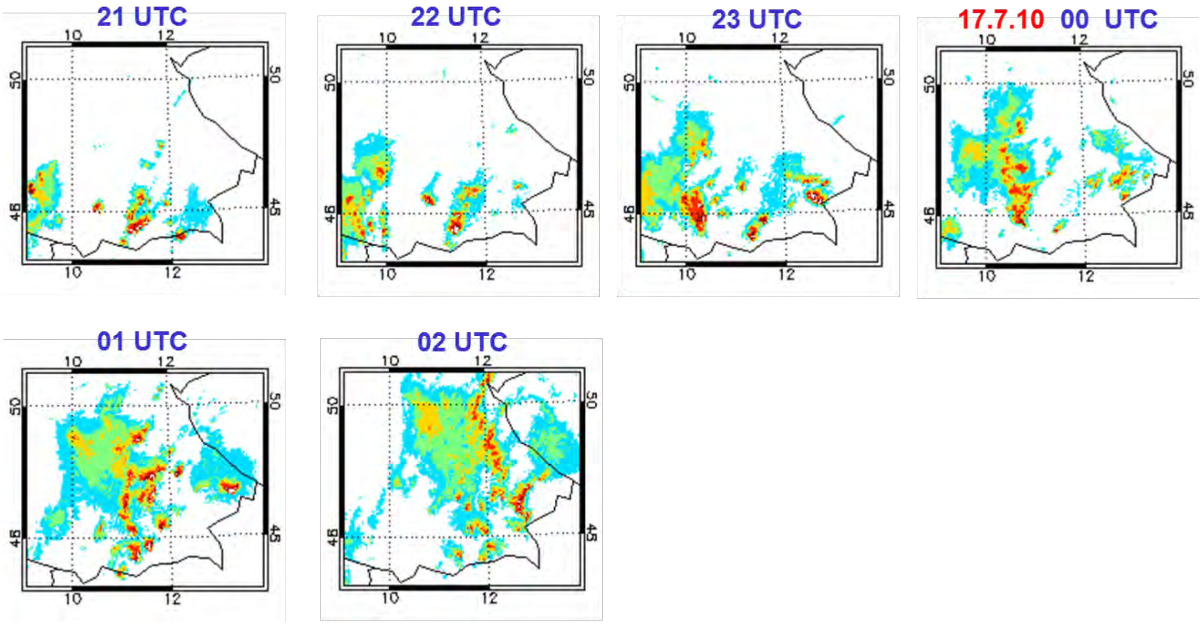
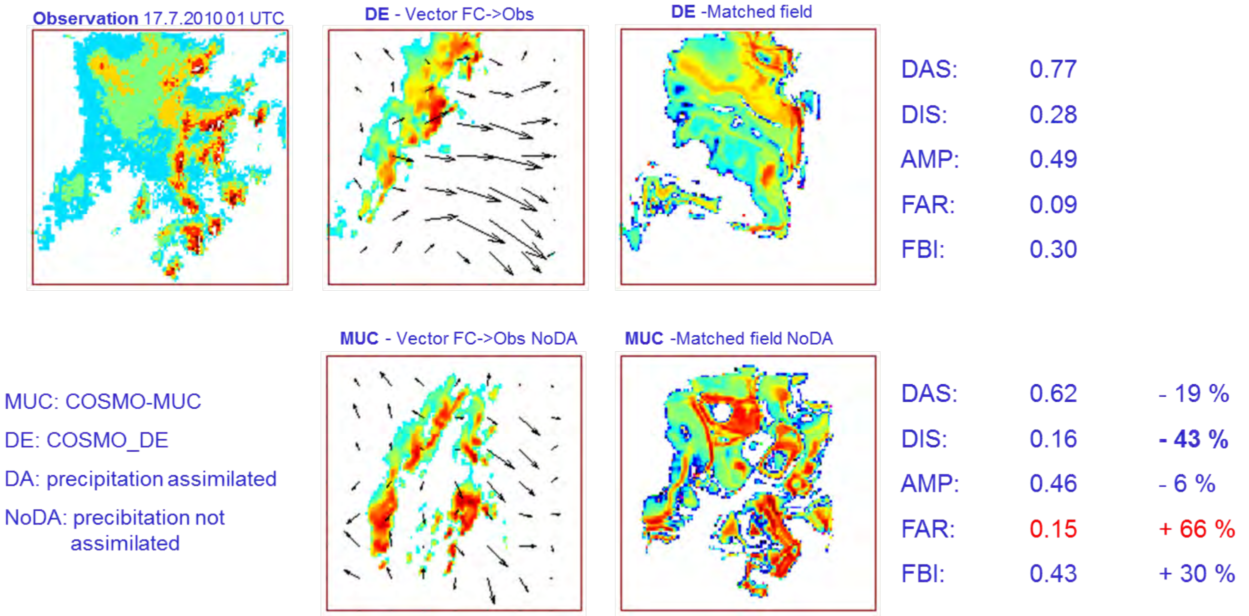


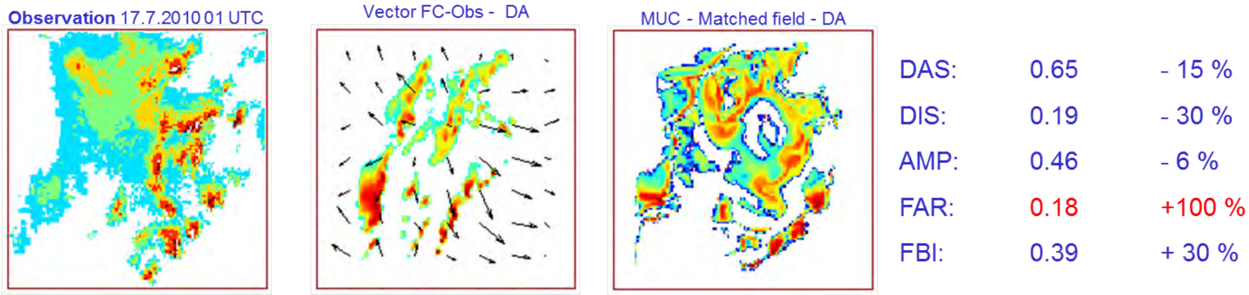
Figure 5: Observed precipitation fields of the passage of a convective system on 17th July 2010.

In our case study of a convective situation over Southern Germany from 16th of July at 21 UTC to 17th of July 2010 at 02 UTC (Figure 5), DAS compared the predicted 850-hPa reflectivity fields from COSMO-DE and COSMO-*MUC* with the observed precipitation field from radar measurements: A vector field was calculated to morph the predicted field on the observed field such that the error was minimised. Thereafter, the vector field was applied to the predicted field and by comparing with radar observations the domain-averaged errors DAS, its components DIS and AMP, as well as the false alarm ratios (FAR) and the biases (FBI) were calculated. This procedure is demonstrated in the figures below; both models started at 21 UTC on 16.7.2010 and forecasts are compared to observations at 01 UTC on 17.7.2010. Figure 6 shows the COSMO-*MUC* forecast without data assimilation, Figure 7 depicts the COSMO-*MUC* forecast including data assimilation.



	DE	MUC NoDA	
DAS:	0.77	0.62	- 19 %
DIS:	0.28	0.16	**- 43 %**
AMP:	0.49	0.46	- 6 %
FAR:	0.09	0.15	+ 66 %
FBI:	0.30	0.43	+ 30 %

Figure 6. Four-hour COSMO-*MUC* (without data assimilation) and COSMO-*DE* runs from 16.7.2010 21 UTC: Observed precipitation from radar (upper left), operational DE-forecast with vector field (upper middle) and the matched DE field (upper right). Below the vector field and matched field for the COSMO-MUC run are shown, respectively. The values of the main error parameters are displayed as well as the change in error when using COSMO-*MUC* instead of the operational COSMO-DE.



DAS:	0.65	- 15 %
DIS:	0.19	- 30 %
AMP:	0.46	- 6 %
FAR:	0.18	+100 %
FBI:	0.39	+ 30 %

Figure 7. As Figure 6 but with data assimilation in COSMO-*MUC*.

Both figures reveal that the forecasts of COSMO-*MUC* (with and without assimilating observation data) improve compared to COSMO-DE forecasts. Although the COSMO-*MUC* runs with data assimilation are somewhat less accurate than the runs without data assimilation on average (compare the DAS values 0.65 and 0.62, respectively), it is worth to note the some details as the strong convective band in the southeast corner of the observed field are very well predicted when including data assimilation. The analysis of five more cases revealed that the displacement error was reduced in the first 3 hours but the amplitude error increased (indicating that the event was underestimated by the model).

These are preliminary results and more cases have to be analysed to get a thorough assessment. The dependency of DAS on the search radius, precipitation threshold and on the domain size and temporal value of the averaging has to be investigated in more detail. Finally, one has also to keep in mind that the comparison of the 850-hPa reflectivity filed with observation from the precipitation radar can have some notable influence on DAS, especially on AMP.

Conclusion

The two limited area models COSMO-*FRA* and COSMO-*MUC*, which were derived from their parent model COSMO-DE of the German Meteorological Service, were used to obtain frequently updated highly resolved predictions in the aerodrome areas of the airports of Frankfurt and Munich in Germany. Tests showed that the prediction accuracy of wind, turbulence kinetic energy and temperature generally improved with time-lagged ensemble forecasts when updated each hour. We then employed the recently developed displacement amplitude score technique to assess the quality of convective precipitation forecasts and confirmed the previous finding of better prediction accuracy by rapid forecast updating also for precipitation patterns. On the other hand, we found that the assimilation of local data (nudging of precipitation, AMDAR, SYNOP, and TEMP data) did not improve the forecast quality further in the statistical mean but provided some accurately forecasted rain pattern locally.

The limited area models will be evolved further in the future. We might advance to finer spatial resolutions of the horizontal and vertical scales requiring adaptations of the sub-grid closures. Also to use adequately resolved data bases of topography and land use at and around the airports is envisaged to ensure a better representation of the local boundary layer physics and energetics.

We will apply COSMO-*FRA* and COSMO-*MUC* to predict aircraft wake vortex separation minima and to combine the forecast of thunderstorms and wintry weather conditions with observations and nowcasting techniques in the WxFUSION environment, see Section 2.2.

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