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ASSIMILATION OF HIGH-RESOLUTION DIAL WATER VAPOR DATA INTO THE MM5 4DVAR SYSTEM: EXPERIMENTS AND VALIDATION

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ABSTRACT

In this paper the assimilation of high-resolution water vapor profiles from the NASA LASE instrument with the MM5 4DVAR system for a case study during the International water vapor experiment (IHOP 2002) is described. Experiments demonstrated that the assimilation of only these water vapor profiles strongly influences the 4d-distribution of water vapor far beyond the assimilation window. Furthermore a beneficial influence on the development of the precipitation fields is demonstrated.

1. INTRODUCTION

The distribution and intensity of precipitation is the most important parameter in today's weather forecasts. At the same time its prediction is very difficult since the development of precipitation occurs at the end of a long chain of processes which are only crudely represented even in high-resolution numerical weather prediction (NWP) models. Another reason for the bad performance of quantitative precipitation forecasts is that the observed 4-d distribution of water vapor is not very accurate. The main source for today's water vapor observations is the operational radiosonde network associated with different problems as coarse horizontal resolution, horizontal drift, or measurement inaccuracies above 300 hPa. The assimilation of those observations introduces large errors in the water vapor distribution at the beginning of the forecast. They accumulate to large errors in the depending distribution of precipitation. This is especially problematic for rapidly developing, severe, and small-scale precipitation events.

Lidar systems are admittedly qualified for closing gaps in the existing observational network, since they are able to observe parameters like temperature, wind and water vapor with high temporal and spatial resolution and concurrently high accuracy.

In this paper the influence of high-resolution water vapor profiles observed by the NASA LASE instrument on the development of a convective situation in the mesoscale NWP model MM5 is investigated. To assimilate the observations a continuous and physically consistent assimilation scheme is necessary. Here the new 4DVAR system based on MM5 version 3.4 was selected.

The paper is organized as follows. In the second section the synoptic situation for the selected case study is described. The third section describes the model configuration, the assimilation system, as well as the experimental setup before the LASE data used for the assimilation is described in section 4. In the next section some results of the assimilation experiments are shown in which simulations with and without assimilation are compared with independent observations collected during IHOP. The last section finally summarizes first results and ends up with an outlook on future plans.

2. CASE STUDY: 24 MAY 2002

Several cases during IHOP_2002 were analyzed with respect to a potential impact of DIAL data on the quantitative precipitation forecast. On the one hand DIAL data of good quality, coverage, and long duration must be available. On the other hand interesting atmospheric processes must occur such as initiation of convection and precipitation. In addition, the DIAL measurements must be performed in a region which is sensitive to a better forecast of these processes. From the analyzed cases we selected May 24 2002 as the best choice regarding the criteria mentioned above.

The large-scale weather conditions over the southern Great Plains region were dominated by three major features. In the upper troposphere a well defined short-wave trough moved from west to east over the Great Plains during the day. It was associated with a cold frond pushing southward across Oklahoma during the evening and night. At the same time a strong southerly low-level jet transported hot and moist air from the Gulf of Mexico northward into the region of interest. Together this led to strongly increased gradients of geopotential height, temperature, and deep-layer wind shear. The associated large-scale ascent and the already strong mid-level vertical temperature gradients of 8-9 K/km resulted in high values of convectively available potential energy (CAPE). Moreover, a significant dryline moved eastward from New Mexico into Texas during the day. Together these features lead to a classical situation for the development of severe thunderstorms in the southern and central Great Plains. The general synoptic situation is illustrated by Fig. 1. The top panel illustrates the situation in the upper troposphere showing the 300 hPa wind field with a strong upper level

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trough over the central plains. The lower panel shows the 2m dew point temperature. Here the well developed dryline over western Texas as well as the cold front are clearly seen.

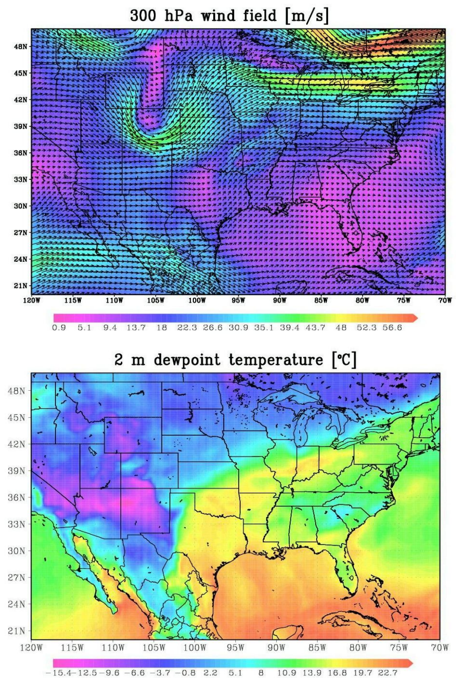

FIG. 1: Horizontal wind velocity [m/s] at 300 hPa overlaid by the vector field (top) and 2 m dew point temperature field [$^{\circ}C$] (bottom) from the ECMWF operational analysis (approx. 14 km horizontal resolution).

3. MODEL AND METHOD

3.1 *Model*

For this study version 3 of the MM5 model is used. It is described in more detail by Grell et al. (1995) and solves the non-hydrostatic dynamics in a terrain-following sigma coordinate system. Two nested model domains are used for the simulations. Their horizontal grid box sizes are 14 km, and 4.7 km. The corresponding domain sizes are 85x85, and 202x202 grid points covering areas of 1200x1200 km, and 950x950 km. The time steps used for the simulations were 30s, and 10s, respectively.

The initial and lateral boundary conditions necessary for the model simulations were obtained from the operational analysis of the European Centre for Medium Range Weather Forecasts (ECMWF). They are available every 6 hours (00, 06, 12 and 18 UTC) and were retrieved from the archive at a horizontal resolution of 14 km and 17 vertical pressure levels between 1000 and 1 hPa.

3.2 *Assimilation Method*

The MM5 model has been chosen for this data assimilation study as it provides convenient tools for ingesting measurements of different observing systems. This is a good starting point for lidar data assimilation. The 4DVAR data assimilation scheme is described in more detail by Ruggiero et al. (2001) and Ruggiero et al. (2002). For this study the 4DVAR method is used, since we expected the largest impact on the forecast due to the assimilation of the DIAL data at the times and locations they were recorded.

3.3 *LASE data*

LASE is an extensively characterized airborne DIAL system which provides water vapor profiles in the entire troposphere using two online and one offline wavelength (Browell et al., 1996). The power of the DIAL technology is not only its high horizontal and vertical resolution but also the capability to specify system errors very accurately (e.g.,Wulfmeyer and Walther, 2001a; Wulfmeyer and Walther, 2001b). This is particularly important when the data should be used for data assimilation.

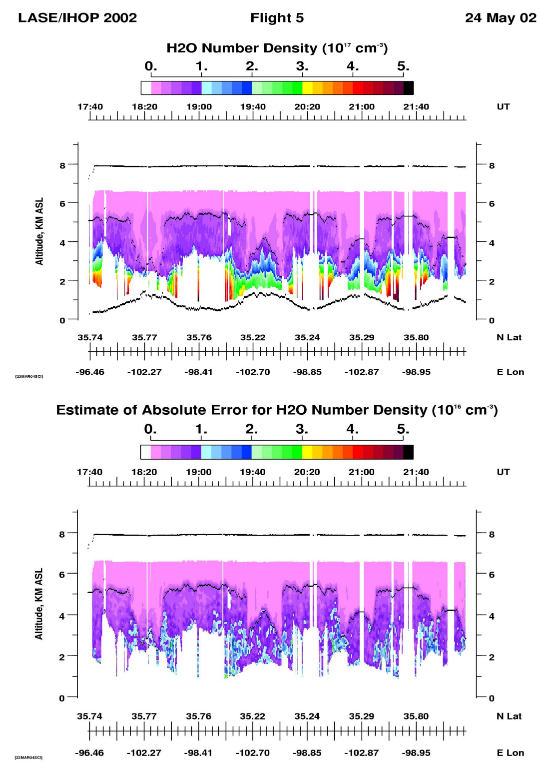

FIG. 2: LASE water vapor number density [$10^{17} cm^{-3}$] profiles (top) and the corresponding profiles of the absolute errors (bottom) [$10^{17} cm^{-3}$] along the flight track of flight 5 on the 24^{th} of May 2002.

Fig. 2 shows the vertical profiles of water vapor taken during this day flight and the corresponding error profiles. White areas indicates either clouds which could not be penetrated by the LASE transmitter or, when no data exists in the whole profile, periods where the LASE system was not operational. However, the dryline was easily detected by the LASE system as a strong gradient of moisture with dry conditions to the west and very moist conditions to the east. Fig. 3 shows the flight track of the NASA DC-8 on 24 May 2002 including marks where the aircraft was at distinct times.

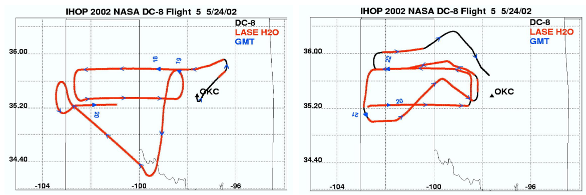

FIG. 3: Track of flight 5 on the 24th of May 2002. On the red track the LASE system was working. Blue marks show the aircraft location at distinct times.

During IHOP data were collected with a horizontal resolution of 14 km and a vertical box average of 330 m. Because of this vertical averaging no data was available in the lowermost 330 m of the troposphere. In the meantime a newly calibrated data set is available in which the atmosphere is profiled down to 60 m. It should be used for future studies. On May 24 2002, LASE performed measurements between 5:30 and 10:30 PM UTC. For data assimilation the time frame 6:00 to 9:00 UTC was used. During that period LASE performed several west-east transects so that it probed the complex water vapor distribution on both sides of the dryline. The coverage was only partly limited by clouds. This gives rise to optimism that the data will have a significant impact on model forecasts.

3.4 *Observation operator*

In this study the water vapor mixing ratio m derived from observations of the LASE instrument is assimilated with the MM5 4DVAR system. This quantity can be ingested more or less completely with the existing code of the public release of the system. A more optimal way to assimilate directly the water vapor number density N_W, the primary quantity observed by the LASE system is subject of later studies, since its implementation is more complicated and nothing is known so far about the improvements this additional effort would give. Furthermore, a more complex implementation of the observations is expected to lead to a longer tuning phase. However, observed water vapor number densities are used to avoid the use of non-model temperatures and pressures. The relation between the mixing ration m and the water vapor number density N_W is given by:

$$N_W = \frac{N_L}{M_W R_L T} \frac{p}{T} \frac{m}{1 + 1.608\, m} \qquad (1)$$

where N_L is Loschmidt's number, M_W is the molecular weight of water vapor, and R_L is the gas constant of dry air. Pressure p and temperature T were taken from the model at the corresponding height to perform the inversion described above.

In this study only the observations of the LASE system are assimilated to demonstrate the effect of this observing system only. In later studies additional observations should be assimilated at the same time to further improve the general performance of the system. Observation operators for radiosondes and GOES radiances are still available. Developments for other observing systems as e.g. Raman lidar which directly observes the water vapor mixing ratio, Doppler lidar, measuring the line of sight component of the wind velocity, or dropsondes are planned.

3.5 *Experiment setup*

Fig. 4 summarizes the experimental setup. After installation of the system on the super computer at the German Climate Computing Center (DKRZ) in Hamburg and the preparation of the initial conditions from the ECMWF operational analysis, a lase decoder was developed. This piece of software processes the LASE data and error files, and does all the necessary computations and interpolations between the model grids and the observed locations. Finally, a file is written which is read by the 4DVAR system. Main aim was to use the data assimilation system as is. Therefore the radiosonde operator of the 4DVAR system is used during the assimilation and the LASE data is processes as if it is a data set with 173 radiosonde ascents.

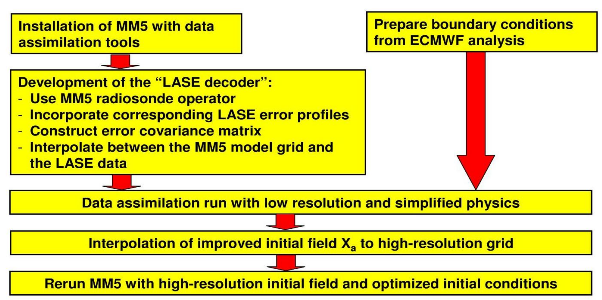

FIG. 4: Flowchart illustrating the setup of the data assimilation system and the experiments done for this study.

The simulations were split into the assimilation run which is done only in the coarse model domain using 20 vertical levels and the free forecasts from two different initial conditions using both model domains in a 1-way nesting mode with 36 vertical levels. This separation is done for three reasons. First, the used LASE data, described later in this section, is available every 14 km. Secondly, the used 4DVAR needs a large amount of computational resources which makes it not feasible to assimilate in the higher resolution configurations. Thirdly, different sets of physical parameterizations are used for the assimilation and the forecast simulations. The latter is necessary since the necessary adjoints are only available for parts of the existing parameterization schemes. The initialization time for all simulations was 18 UTC 24 May 2002.

The assimilation was done for the assimilation window 18 to 21 UTC, while the free forecasts runs where done over 12h from 18 UTC 24 May 2002 until 06 UTC 25 May 2002.

After the low resolution data assimilation run with simplified physics the fields are interpolated to the higher horizontal and vertical resolution with the NESTDOWN utility. The results shown later in this paper are from the higher resolution simulation. On the one hand control simulations were done without the use of the LASE date (hereafter referred to as NOASSIM) and a second set of simulations were done from initial conditions optimized by the assimilated LASE data (hereafter ASSIM).

4. RESULTS

In the following some results of the simulations are shown. Figure 5 shows the difference (ASSIM-NOASSIM) of the mixing ratio at the initial time for different heights in the troposphere (14 km horizontal resolution, 20 vertical levels). It illustrate the influence of the assimilation on the initial condition of the following simulations.

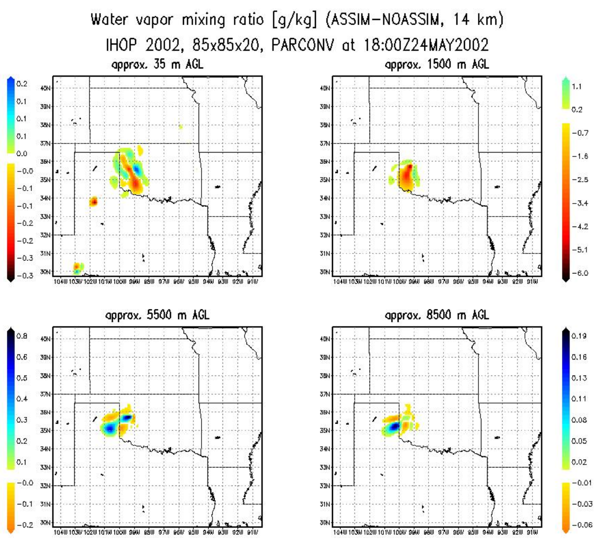

FIG. 5: Differences ASSIM-NOASSIM of the water vapor mixing ratio [g/kg] at different levels of the troposphere ranging from 35m above ground level (AGL) to about 8500 m AGL for the initial time 18 UTC 24 May 2002.

It is, as expected, clearly seen that the water vapor field in the whole depth of the troposphere is strongly influenced by the assimilation. It is also seen that there is a tendency to moisten the upper troposphere, whereas the lower troposphere is instead getting dryer due to the assimilation. A view on the temporal development of that difference during the course of the forecast (not shown) demonstrates that the signal in the water vapor field stays in the forecast until long after the assimilation is switched off. Even after a 24 h forecast strong differences are seen between the two simulations. In the following more results of the free forecast simulations are shown. They all are from simulations of domain D1 (202x202x36 grid points, 4.7 km horizontal resolution).

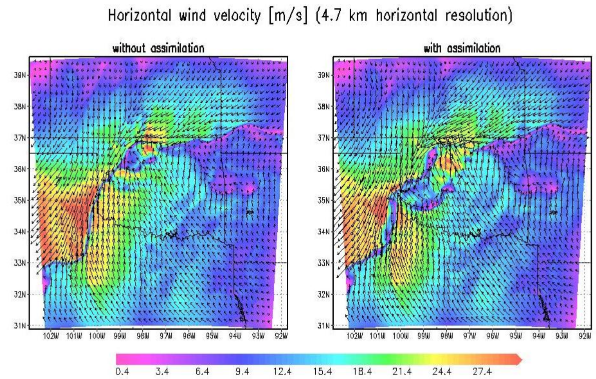

FIG. 6: Horizontal wind velocity [m/s] of the simulations without (left) and with (right) the assimilation of LASE water vapor profiles with overlaid vector field at 00 UTC 25 May 2002.

The next important question is whether other processes which are only indirectly influenced by the water vapor field are influenced by only assimilating water vapor profiles. This is demonstrated with two more Figures. Fig. 6 shows the near surface wind fields three hours after the end of the assimilation window for the NOASSIM (left) and ASSIM (right) simulations. The horizontal wind velocity is color shaded whereas the wind direction is shown by the vector wind field. The frontal boundary is clearly seen as a region of low wind velocity, since in this region the vertical wind component is the largest of the three components. It is seen that the dynamics are clearly affected by the assimilation. In the assimilated simulation a region with low horizontal wind velocity, corresponding to a developing convective system, is moving to the southeast. This is not seen in the simulation without assimilation.

The most difficult quantity to predict for a numerical weather prediction model is precipitation. This situation is particularly difficult since most of the observed convection was triggered locally e.g. by temperature and/or moisture differences at the surface, and not synoptically. For this, local factors as cloudiness or surface moisture are most important which are very difficult to initialize correctly. Therefore we do not expect improvements of the precipitation in regions south of the observation region. Fig. 7 compares the NOASSIM (left) and the ASSIM (right) simulation with a radar observation at the same time. As expected no improvement in northern Texas occur due to the assimilation. However, the distribution of precipitation is clearly improved in the region where the water vapor profiles were assimilated and leeward of this region to the east and northeast as seen in the occurrence of precipitation further to the south as compared to the NOASSIM simulation.

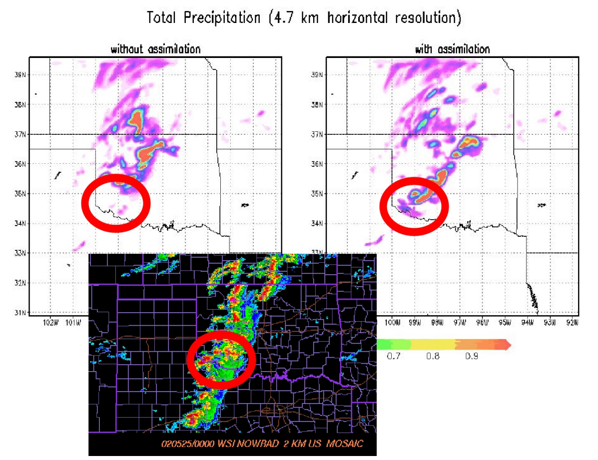

FIG. 7: Qualitative comparison of half hourly accumulated precipitation from the simulations without (left) and with assimilation (right) and a corresponding image of the observed radar reflectivity at 00 UTC 25 May 2002.

5. SUMMARY AND OUTLOOK

The influence of high-resolution water vapor profiles from the NASA LASE instrument into the MM5 version 3.4 4DVAR system has been investigated. For this purpose an observation operator was developed and results of experiments with and without 4DVAR data assimilation were shown and compared to independent observations collected during the IHOP field campaign.

The results clearly demonstrate the strong influence of the water vapor observations on the developing water vapor, wind and precipitation fields. The developing convection occurs further to the south compared with the control simulation. This compares much better with radar observations. This positive signal is seen in the forecast hours after the end of the assimilation window.

Future work will contain a careful quantitative validation of the results as well as the investigation of the influence of the LASE data in the different assimilation systems MM5 provides. A further refinement to a resolution of less than 2 km is also planned. Then a parameterization of convection will no longer be necessary. In addition it is planned to include further observations as Raman Lidar, Doppler Lidar, or dropsondes.

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