Evaluation of Modeled Water Vapour Profiles Using Raman Lidar Data

Franz H. Berger[1,2], Jens Reichardt[1*], Anton Beljaars[2], Jürgen Güldner[1], and Claudia Heret[1]

[1] *German Meteorological Service (DWD), Lindenberg Meteorological Observatory - Richard Aßmann Observatory, Am Observatorium 12, D-15848 Tauche/Lindenberg, Germany*

[2] *European Centre for Medium Range Weather Forecast, Shinfield Park, Reading, RG2 9AX, England*

ABSTRACT

During the Lindenberg Upper-Air Measurement Intercomparison (LUAMI) campaign intensive comparison flights with various routine and research radiosondes were carried out. To complement these measurements surface-based active and passive remote sensing systems were operated. In this study, the remote sensing observations were compared to the routine DWD water vapour forecasts, using the measurements of the water vapour Raman lidar RAMSES as a reference. A number of conclusions can be drawn. First, the general humidity patterns are reproduced rather well in the models. Second, the observed water vapour variability shows clear information that can be used for future model improvements. Third, for November 2008 the comparison of monthly lidar measurements with radiosonde, microwave profiler and model data shows good overall agreement. Specifically, there is a good agreement between the radiosonde and the lidar profiles. The microwave profiles have a larger spread. The comparison with modeled data indicates that the COSMO-EU water vapour is more mixed/smoothed than the COSMO-DE water vapour. The difference between the lidar and the COSMO-DE model can be as large as 2 g/kg.

1. INTRODUCTION

Water vapour feedback is the most important feedback enhancing the climate sensitivity. The strength of this feedback varies among the global and regional climate models (Randall et al., 2007). This supports the need for precise observations of atmospheric humidity with enhanced quality assurance / quality control procedures. Another aspect is the importance of clouds and their representation in models. The last IPCC report also indicates that the use of observations will narrow the current spread in model projections of climate change. If so, regional aspects of the energy and water cycle as well as hydrological processes can be predicted with higher accuracies as shown in recent studies (Hagemann et al., 2004; Jacob and Hagemann, 2005; Kotlarski et al., 2005; Hagemann and Jacob, 2007). Similar arguments can be found for numerical weather prediction.

To evaluate current numerical weather prediction and global/regional climate models, routinely measured surface properties, like temperature at 2 m height or precipitation, were used to quantify the uncertainties (e.g., Bachner et al. (2008); Feldmann et al. (2008); Kotlarski et al. (2005)). However, even if these investigations show good agreement between the modeled and observed parameters, this could be for the wrong reasons, i.e., various atmospheric processes could compensate each other under specific atmospheric conditions. Therefore, as indicated by Randall et al. (2007), the observation of vertical profiles of atmospheric state parameters, especially of water vapour including cloud and aerosol information, plays a significant role in future improvements.

To ensure the highest possible accuracy of water vapour observations, the Lindenberg Upper-Air Measurement Intercomparison (LUAMI) campaign took place in Lindenberg in November 2008. During this campaign, an intensive comparison of routine and research radiosonde data was realized. These in situ observations were complemented by high temporal resolution remote measurements (both active and passive). This data set is used here to evaluate model-predicted water vapour fields.

2. DATA DESCRIPTION

In this section different data sets will be described very briefly:

- Raman-lidar (RAMSES) measurements as the reference for the water vapour mixing ratio
- microwave-profiler measurements for all sky conditions
- radiosonde measurements as routine observations of a global network
- two regional model forecasts (COSMO-EU and COSMO-DE)

2.1. Raman Lidar RAMSES

The water-vapour Raman lidar system RAMSES (Raman lidar for atmospheric moisture sensing) in Linden-

* *Corresponding Author*: Jens Reichardt, German Meteorological Service (DWD), Lindenberg Meteorological Observatory - Richard Aßmann Observatory, Tauche/Lindenberg, Germany, E-Mail: `jens.reichardt@dwd.de`

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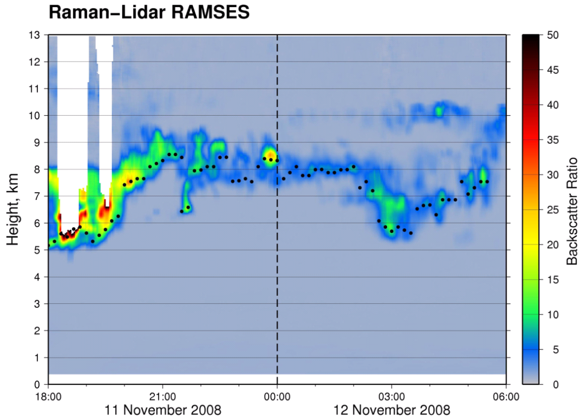

Figure 1: RAMSES - backscatter ratio in color shading. White areas indicate rejected low-quality data, the black dots indicate 10-minute averages of cloud base measurements from a ceilometer on site

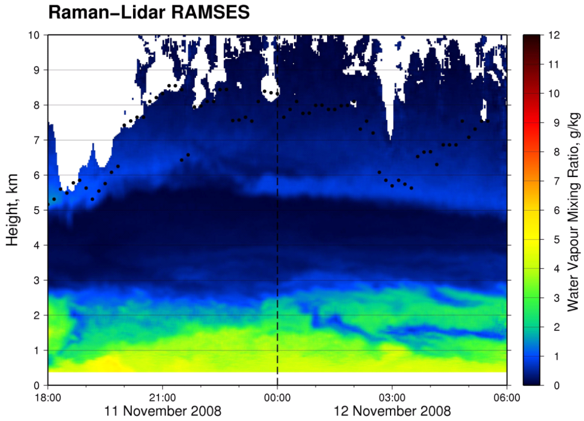

Figure 2: Raman-Lidar RAMSES - water vapour mixing ratio

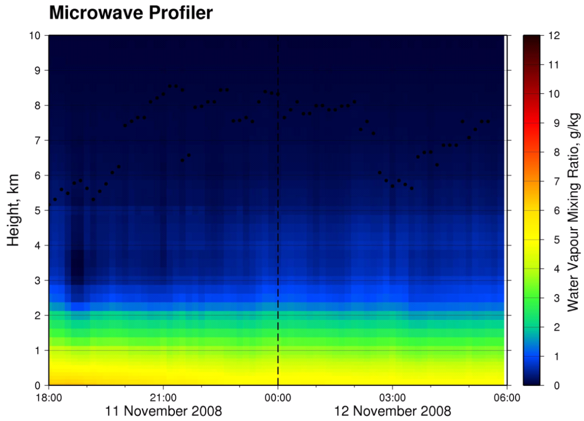

Figure 3: Microwave Profiler - water vapour mixing ratio

berg complements the suite of remote-measurement instruments at the Richard Aßmann Observatory with respect to water-vapour reference sounding. Starting with the LAUNCH-2005 campaign at Lindenberg (Lindenberg campaign for the assessment of humidity and cloud profiling systems and its impact on high-resolution modeling) in the late summer of 2005, RAMSES participated in several measurement campaigns, the last being the WMO campaign LUAMI in November 2008. Until March 2009, RAMSES was restricted to automatic, nighttime observations. Currently, RAMSES is upgraded to daytime measurements with emphasis on water vapour. Measurement capability of depolarization ratio, and of temperature (using the rotational Raman technique) is also added.

Figure 1 shows as an example the RAMSES measurement during the night of 11–12 November 2008. An ice cloud was detected between 5 and 9 km. Figure 1 illustrates that the lidar can penetrate thin ice clouds, whereas in the case of thicker clouds the signal gets extinguished.

Water vapour mixing ratios are determined following a stringent analysis and quality control procedure. In our example, two distinct layers were measured (Figure 2), the first, highly variable, in the boundary layer up to 3 km, the second around 6 km where the cirrus cloud evolved. Note that the water vapour measurement extends well into the cloud layer for small cirrus optical depths (see Figure 1).

2.2. Microwave Profiler

Since 1998, the microwave profiler TP/WP 3000 from Radiometrics Corporation operates continuously at the Lindenberg site. The detailed description of the monitoring and analysis principles are in Güldner and Spänkuch (2001).

Figure 3 depicts the water vapour field as inferred from the microwave observations during the night of 11 November 2008. Comparison to the simultaneous lidar measurements (Figure 2) shows that the water vapour profiles derived with the passive sounder have smoothed features, but still represent the broadscale water vapour variability, especially in the boundary layer. The second layer at 6 km cannot be resolved.

2.3. Radiosonde

As part of the routine observational program, VAISALA RS-92 radiosondes were launched every six hours. Additionally for the LUAMI campaign, research sondes like the cryogenic frost-point hygrometer sonde CFH (Vömel et al., 2007) were launched to quantify measurement accuracies. For this study, the profiles from the routine radiosonde were considered.

2.4. COSMO-DE and COSMO-EU Models

The COSMO-EU/DE model is a nonhydrostatic limited-area atmospheric prediction model (Doms et al., 2008) based on primitive, hydro-thermodynamical equations preserving mass, momentum and energy. The basic version has been developed at Deutscher Wetterdienst to describe compressible flow in the moist atmosphere and runs operationally since 1999. Together with the

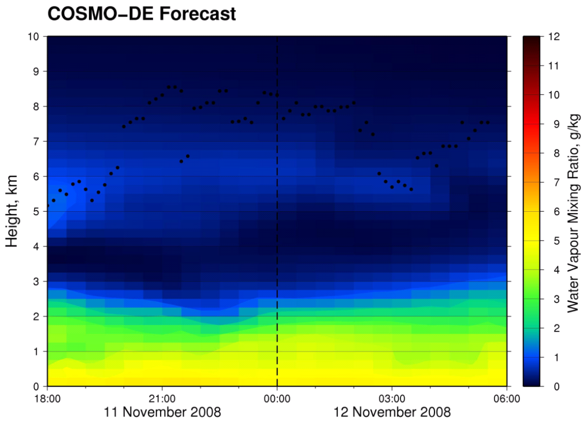

Figure 4: COSMO-DE - water vapour mixing ratio

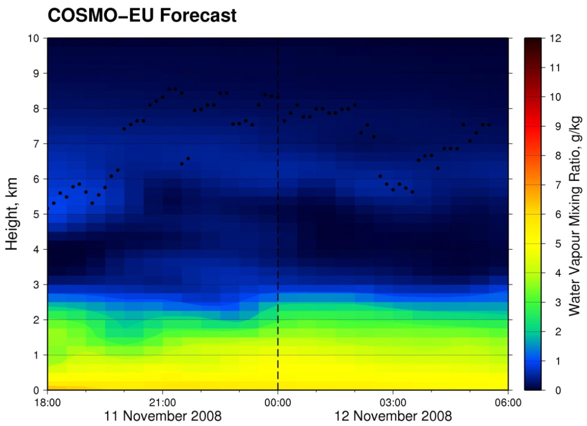

Figure 5: COSMO-EU - water vapour mixing ratio

hydrostatic global model GME, both models form the present numerical weather prediction system at DWD.

The operational application of the COSMO-EU model (formerly known as *Lokalmodell*) proceeds on the meso-β scale using grid spacing of 7 km and 40 layers. Covering Europe, the model is designed to accurately predict the fundamental meteorological processes near the surface up to 72 h in advance. During computation the COSMO-EU receives GME forecasts as lateral boundary values. The atmospheric prognostic variables are pressure, horizontal and vertical wind components, temperature, specific contents of water vapour, cloud water and cloud ice, rain and snow and turbulent kinetic energy. The cloud and convection schemes are based on the Tiedtke formulations (Tiedtke, 1989, 1993).

The COSMO-DE model (formerly known as *LMK*) is the high-resolving version of the basic model with a resolution of 2.8 km (meso-γ) and 50 layers, and resolves deep convection explicitly. The model is running eight times a day, delivering 18-h forecasts, and provides guidance for warning of dangerous weather in Germany. The lateral boundary values are derived from COSMO-EU forecasts.

In Figure 4 and Figure 5 the water vapour fields forecasted for the night of 11 November 2008 are plotted. Good agreement is found between these modeled data

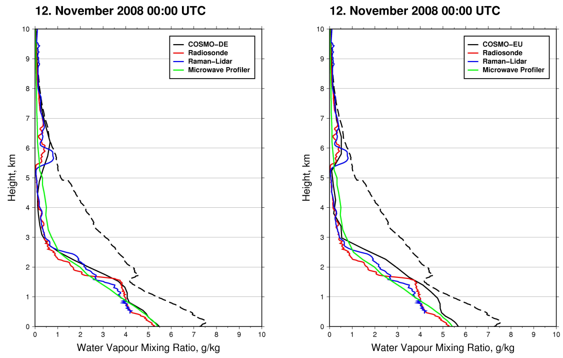

Figure 6: Comparison of COSMO-DE (left) and COSMO-EU (right) water vapour mixing ratio profiles with observation - dashed line indicates the saturation based on radiosonde measurements

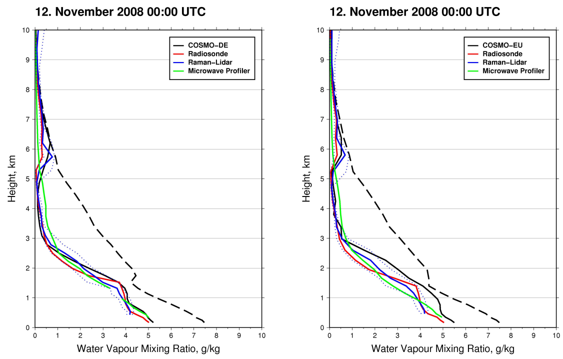

Figure 7: Comparison of COSMO-DE (left) and COSMO-EU (right) water vapour mixing ratio profiles with averaged profiles

and the reference Raman-lidar measurement (Figure 2). In both cases the cloud layer, indicated by an increase in water vapour mixing ratio, is resolved.

3. RESULTS

Figure 6 compares the water vapour profiles predicted by COSMO-DE and COSMO-EU for 12 November 2008, 00:00 UTC, with the radiosonde, microwave-profiler and Raman-lidar measurements at the same time. The dashed line is the saturation water vapour mixing ratio for the observed radiosonde temperatures. In the case of COSMO-DE, all profiles agree within a limited uncertainty, whereas the COSMO-EU model overestimates the water vapour slightly. To improve the comparison, the observations were averaged over the individual layers of the models and integrated over 60 minutes (Figure 7). In Figure 7, the dotted lines indicate the variability of the Raman-lidar observations of each layer. In this case, the agreement between the predicted COSMO-DE and the observed water vapour mixing ratio profiles is excellent. The COSMO-EU profile is of lower accuracy. Compared to the observations, the predicted mixing ratios are too high in the boundary layer.

To analyze the differences between predicted and observed water vapour profiles on a monthly basis, all available midnight observations in November 2008 were

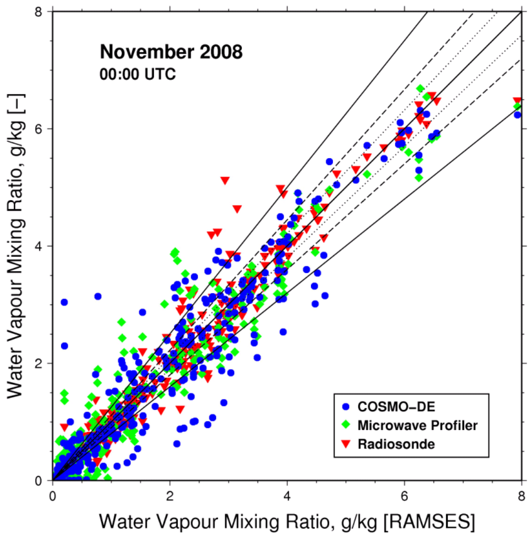

Figure 8: Comparison of water vapour mixing ratio for November 2008 (COSMO-DE versus observation)

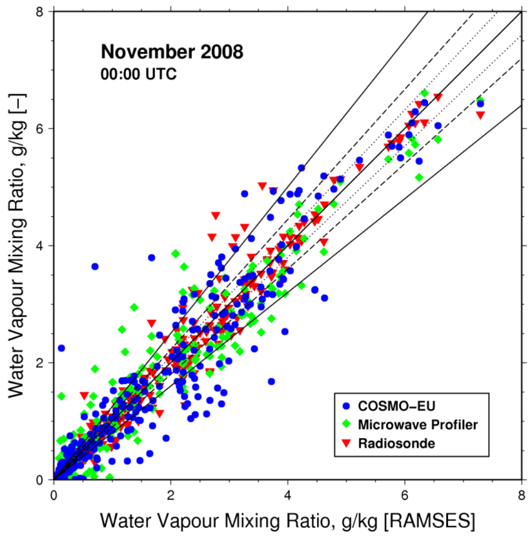

Figure 9: Comparison of water vapour mixing ratio for November 2008 (COSMO-EU versus observation)

taken into account. The results are displayed in Figures 8 and 9. In both figures a deviation of 5% from the averaged reference Raman-lidar measurement is plotted as dotted lines, a 10% deviation as dashed lines and a 20% deviation as solid lines. For high water vapour mixing ratios (larger than 4 g/kg), the differences can reach up to 10%. In the case of low water vapour mixing ratios, larger differences can be found (up to 2 g/kg). The differences are largest for the modeled water vapour and smallest for the radiosonde data. The scatter of the microwave observation indicates that its accuracy to measure water vapour is less than the accuracy of the radiosonde measurement, but better than the model accuracies. Therefore, the microwave profiles are still a good reference, especially in the boundary layer up to a height of approximately 3-4 km.

4. SUMMARY AND OUTLOOK

In this study, measurements of the Raman lidar RAMSES are used as the reference to evaluate other remote observations, and especially the routine DWD water vapour forecasts. Various conclusions can be drawn. First, it is shown that the general patterns are modeled fairly well. Second, the water vapour variability suggests that there is scope for further model improvement. Third, for November 2008 the detailed comparison shows agreement within 10% ($\sim$<0.5 g/kg) for high water vapour and within 20% to 25% ($\sim$<2.0 g/kg) for lower water vapour content. Furthermore, the comparisons suggest that Raman-lidar measurements are potentially useful in characterizing the small-scale (subgrid) variability.

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