# Developments at DWD:<br>Integrated water vapour (IWV) from ground-based GPS

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## 1 Introduction

Detailed analysis used for very short-range numerical weather prediction (NWP) requires observational information of good quality and with high spatial and temporal resolution. Sampling tropospheric humidity by radiosondes or by meteorological satellite systems is often not sufficient for this purpose.

The delay of radio signals from several GPS satellites to a GPS receiver at the ground can be processed to derive the integrated water vapour (IWV) in the atmospheric column above the station with good accuracy, provided that the pressure and temperature at the GPS station are also known (Bevis et al., 1994). In 2001 and 2002, DWD has tested the assimilation of hourly or half-hourly data from some 100 GPS Stations in Germany processed by the GeoForschungsZentrum Potsdam (GFZ, see Reigber et al., 2002; Gendt et al., 2004) into the then operational configuration of the COSMO model (formerly Lokal Modell LM) which had a mesh width of 7 km (Tomassini, 2003; Tomassini and Schraff, 2002).

Since then, GFZ has further increased the number of stations and enhanced the data frequency to one every 15 minutes. In the current contribution, the assimilation of these GPS data is tested for the first time with the convection-permitting configuration COSMO-DE.

## 2 Nudging of integrated water vapour and experimental set-up

The data assimilation scheme of the COSMO-Model is based on nudging towards observations (see Schraff and Hess, 2003). This technique can make full use of high-frequent data such as the GPS data considered here. However, the observation increments have to be expressed (nearly) in terms of the model state variables. Since specific humidity rather than IWV is the state variable for water vapour, the observational information on IWV has to be conveyed into information on specific humidity. For this purpose, a 'pseudo-observed' profile of specific humidity is retrieved by scaling iteratively the model humidity profile with the ratio of observed to modelled IWV. (The iteration may be necessary to avoid over-saturation, and the IWV ratio takes into account the (mostly very small) differences between station height and model orography.)

The retrieved humidity profile can then be nudged in a similar way as a radiosonde humidity profile. However, an additional quality weight $\leq 1$ and proportional to the specific humidity at saturation and to the thickness of the model layer is assigned to the humidity retrieval at each model level. In this way, the GPS humidity profile is given larger weight at those levels which can give a larger contribution to the integrated value IWV, normally between 700 hPa and 800 hpa, and less at other levels. Furthermore, the horizontal radius of influence is reduced from about 120 km valid for radiosondes to about 50 km, which appears to be adequate for the dense GPS network.

169 GPS stations, most of them in Germany, have been selected for assimilation after a monitoring period. Generally, the GPS-derived IWV has been found to verify well with the humidity from the Vaisala Radiosondes RS92, except for the well-known 12-UTC (midday) dry bias of the RS92 version that was widely used in summer 2007. The assimilation period from 1 to 13 June 2007 was characterised by weakly anticyclonic air-mass convection. 21-hour forecasts were started daily at 0, 6, 12, and 18 UTC from the assimilation cycle with the COSMO-DE configuration, i.e. using a mesh width of 2.8 km . 3 experiments are compared:

- CNT: operational set-up, including latent heat nudging for the assimilation of radar-derived surface precipitation rate
- GPS: like CNT, but with additional assimilation of the GPS-derived IWV data
- NoRSq: like CNT, but without nudging of radiosonde humidity

Note that in NoRSq, the humidity runs nearly freely in the inner model domain since the direct influence of the only used humidity observations, that is from surface mesonet stations, is limited to the lowest model layer which has a thickness of 20 m only. Some additional influence from radiosonde humidity comes through the lateral boundaries.

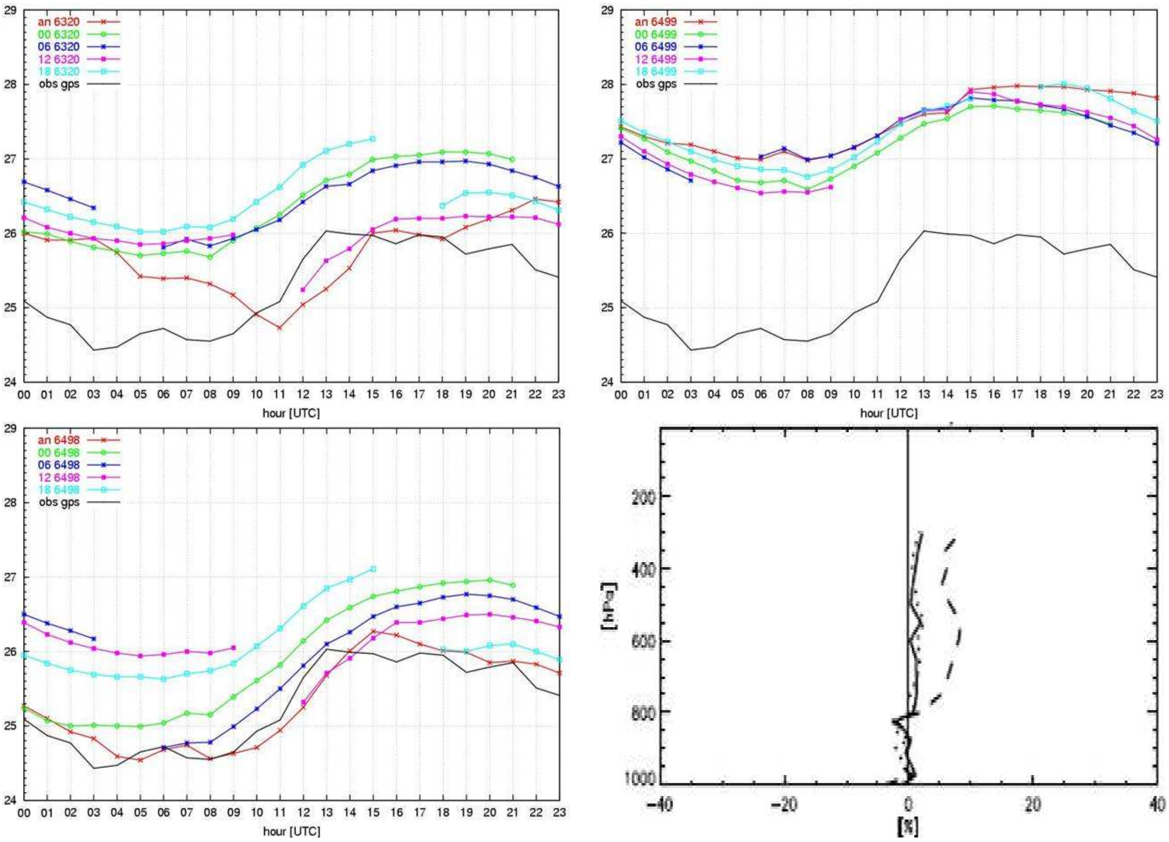


Figure 1: Integrated water vapour IWV in kg $m^{-2}$ averaged over the 169 GPS observation locations as a function of daytime (UTC) for the period of 1 - 13 June 2007. Black line: GPS observations; red: COSMO-DE assimilation cycle; green: 00-UTC forecast runs; blue: 06-UTC forecast runs; purple: 12-UTC forecast runs; cyan: 18-UTC forecast runs. Upper left panel: CNT; upper right: NoRSq (i.e. without use of radiosonde humidity data); lower left: GPS experiment. Lower right panel: Vertical profile of bias (model - radiosonde observations) of relative humidity for the same period. Solid: CNT; dashed: NoRSq; dotted: GPS.

## 3 Case Study

Since experiment NoRSq is only very weakly affected by humidity observations, its mean IWV content should reflect well the model climate of the water cycle. The 'model climate' shall denote here simply the mean model state reached after running the model freely for a long time without any influence from observations. It is the model-internal equilibrium which depends on all the (physical and numerical) processes simulated by the model. Figure 1 shows that while the daily variation of IWV in NoRSq matches the GPS observations well, the mean IWV is overestimated both in the assimilation cycle and in all forecasts by about 2 $\mathrm{kg\,m^{-2}}$. Thus, the model has to build up too large an amount of moisture in the atmosphere until evaporation and precipitation become equilibrated. It appears that the processes which decrease the moisture content, typically by precipitation, are not effective enough in COSMO-DE. It is interesting to note that the excess of moisture in the model climate takes place above rather than within the planetary boundary layer (see lower right panel of Figure 1).

With the assimilation of the radiosonde humidity data in CNT, the bias in IWV is at least halved in the assimilation cycle. It even becomes negative at noon and in the early afternoon as a result of the above-mentioned dry bias of the Vaisala RS92 sondes used in 2007. The remaining bias of 1 $\mathrm{kg\,m^{-2}}$ at 0 UTC indicates that the assimilation of the radiosonde data is not effective enough to completely eliminate the model's wet bias in the whole region covered by the GPS stations although there is nearly no wet bias against the radiosondes themselves

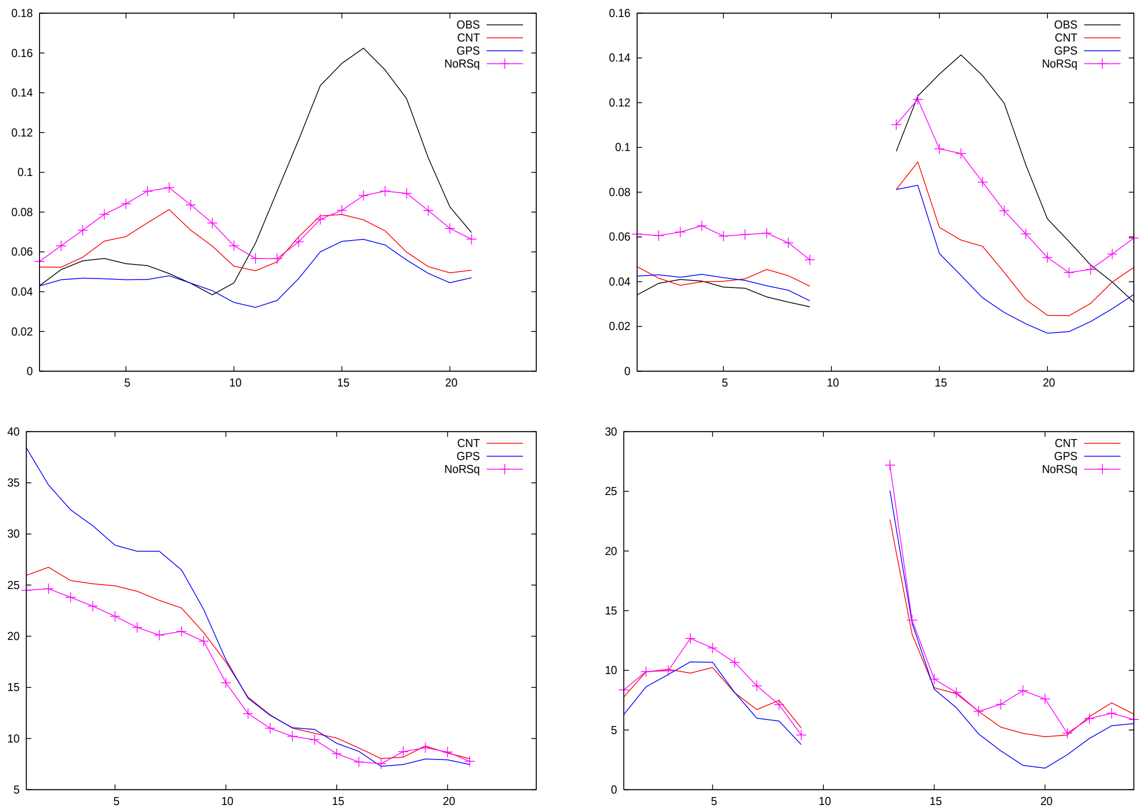


Figure 2: Upper left panel: hourly precipitation amounts greater than 0.1 mm/h from COSMO-DE 00-UTC forecast runs averaged over the radar domain as a function of daytime (UTC) for the period of 31 May to 13 June 2007. Lower left: as upper left, but Equitable Threat Score (ETS) of hourly precipitation against radar data for a threshold of 0.1 mm/h. Right panels: as left panels, but for 12-UTC forecast runs and a threshold of 1.0 mm/h. Black solid line: radar-derived precipitation; red solid: CNT; blue solid: GPS; purple crosses: NoRSq.

(see lower right panel of Figure 1 for relative humidity – the temperature bias (not shown) is also close to zero). In agreement with the assimilation cycle, the 12-UTC forecast runs start with a dry bias but moisten rapidly towards the model's wet-biased internal equilibrium. The other forecasts start already with a wet bias which increases moderately during the forecasts but remains smaller than in NoRSq.

With the assmilation of GPS-derived IWV, the bias against the GPS data disappears during the assimilation cycle and at the beginning of the forecasts. In all the forecasts of experiment GPS, a wet bias then develops and increases towards the model climate, attaining similar values as in CNT.

The model bias in atmospheric water vapour is closely related to biases in surface precipitation (see Figure 2). In comparison to the radar-derived precipitation which has a very pronounced peak in the afternoon, NoRSq strongly overestimates both weak and strong precipitation in the night and early morning and strongly underestimates it throughout the afternoon. The assimilation of radiosonde humidity in CNT reduces precipitation in the 0-UTC forecast runs moderately. In the 12-UTC forecast runs, however, the reduction is large throughout the forecast period and eliminates the positive bias at night. When the GPS data are additionally assimilated, the positive bias in the night and morning is eliminated and close to zero both for 0- and 12-UTC runs. On the other hand, the negative bias in the afternoon is further enhanced.

In terms of equitable threat scores (ETS) against radar-derived precipitation (lower panels of Figure 2), the assimilation of the GPS data has a large positive impact in the first 9 hours of the 0-UTC runs for low thresholds (which reflect areas of precipitation). In contrast, there is a clear negative impact on the 12-UTC runs during the late afternoon, particularly for strong precipitation (e.g. 1.0 mm/h threshold). The ETS score is a quality measure and should indicate mainly how well the patterns match. However, it is not independent from the bias. Past experience with many experiments has shown that it correlates positively with the frequency bias (FBI) not only for FBI values less than 1 (negative bias) but up to values of about 2. This suggests that the use of the GPS data has indeed improved the geographical location of precipitation in the 0-UTC forecast runs while it is unclear whether and to what extent the decrease of the ETS in the 12-UTC runs is an effect of the enhanced negative bias.

## 4 Concluding Remarks

This study illustrates that the GPS data are very useful for verification of the daily cycle of humidity in the model. It is revealed that the model-internal equilibrium (or 'model climate') of COSMO-DE has a strong overall positive water vapour bias in summer. With the assimilation of GPS-derived IWV, this bias is greatly reduced in the assimilation and early in the forecast. Also, the mean precipitation amounts are reduced throughout the forecast range. Since the diurnal cycle of convection is far too weak in the model, both positive and negative impacts on biases and verification scores result. Maybe apart from the consistent benefit in the 0-UTC forecast runs during the first 9 hours, the impact of the GPS data appears to be dominated by effects of model biases. For instance, this is likely true for the enhanced tendency to suppress strong precipitation in the afternoon.

The above experiments have been performed with a model version that was operational at DWD before September 2008. Then, DWD operationally introduced a modification in the subgrid-scale cloud scheme and a reduction of the upper limit for the turbulent mixing length (Seifert et al., 2008). Tests have shown, that the new version of COSMO-DE reduces the underestimation of the diurnal cycle of convective precipitation and also improves the bias and ETS of the 0-UTC runs during the first about 9 hours. It is expected that this will influence the impact of the GPS data. Therefore, similar experiments and evaluations as done in this study should be repeated with the new model version to assess the impact of nudging GPS data into a convection-permitting model when the biases are not so large. Further experiments should also be done for winter periods, including low stratus cases.

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