Assimilation of ground-based GPS data into a limited area model

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Abstract

Two years of near-real time data from a dense global positioning system (GPS) network in Germany have been monitored at the German Weather Service (DWD). Numerical experiments assimilating vertically integrated water vapour observations or precipitable water (PW) from ground-based GPS stations into the operational limited area forecast model of DWD have been carried out. The impact of the assimilation of the GPS data is large in the first 6 hours of the forecast, and negligible in the forecast range after 24 hours. Upper-air verifications against radiosondes show that GPS PW improves the 12 hour forecast of humidity, up to 10% at some levels. A qualitative comparison with radar and synoptic observations indicates that GPS PW has a mixed impact in the forecast of precipitation. In a quantitative precipitation verification over a region provided with a dense rain gauge network, the experiment assimilating GPS data scores better than the control one without these data. However, the forecast started from the 12 UTC analysis of the GPS experiment produces systematically more rainfall than that started from the control experiment. This can be related to a positive bias of the GPS PW during daytime and it needs further investigations.

1. Introduction

Detailed short-range numerical weather prediction (NWP) requires observational information of good quality and with high spatial/temporal resolution. Due to various limitations, important quantities such as tropospheric water vapour are often inadequately covered by conventional observations from radiosondes or by meteorological satellite systems. The Global Positioning System (GPS) is developing into a powerful source of humidity information for fine-scale regional models.

A ground-based GPS station measures the delay that the radio signal from the GPS satellite suffers as it propagates through the atmosphere. When several satellites can be seen from the station, the delays are combined or "mapped" into a zenith total delay (ZTD) (Niell, 1996). The largest part of ZTD is the "dry" delay (90%) due to the dry air gases, the remaining delay or "wet" delay depends on moisture content of the atmosphere and is therefore highly variable. Precipitable Water (PW) can be derived from the ZTD using an approximate formula which requires the knowledge of the pressure and temperature at the GPS station (Bevis et al., 1994). GPS PW estimates are accurate at millimetre level and look very promising for usage in NWP models. They can be derived with high frequency and from a dense network, and are not affected by rain or clouds (all weather measurements). The disadvantage of having only one piece of information along the vertical can be alleviated with the aid of the data assimilation techniques used in NWP. Previous studies have demonstrated the feasibility of assimilating PW observations via nudging (Kuo et al, 1993) and via four-dimensional assimilation (Kuo et al, 1996; De Pondeca and Zou, 2001). They found that PW can improve the quality of the humidity analysis and also the short-range forecasts of precipitation in cases of intense rainfall.

For the GPS Atmosphere Sounding Project (GASP) of the Helmholtz Society, the GeoForschungsZentrum (GFZ), Potsdam, has started activities in 1999 establishing a GPS ground network at some synoptic sites of the German Weather Service (DWD). This network has been extended progressively, including stations of the Land Survey Agencies of Germany, and it consists at present of more than 100 sites. Since May 2000, GFZ has produced hourly estimates of PW using predicted orbits (Gendt et al., 2001). The whole data processing is running in near-real time, taking less than two hours from data acquisition to the delivery of the final product. This means that the data can be made available for operational short-range forecast with strict cut-off time.

DWD has been exploiting the usage of the GPS data from GFZ into its limited area model, namely the Local Model (LM), operational since December 1999. LM is a non-hydrostatic forecast model for central and western Europe, with a spatial grid resolution of approximately 7 km and 35 layers in the vertical (Steppeler et al., 2002). DWD has developed the new model with special emphasis on the hydrological cycle. Quantitative precipitation forecasts of LM are used for example to support operational flood prediction by hydrological models, and they are regularly monitored with a dense observations synop network (Damrath et al., 2000). The analysis of LM is produced with a continuous assimilation cycle nudging the model variables towards observations (Newton relaxation). The observations currently used are from surface stations, radiosondes, and, since June 2001, from aircrafts. Thus, humidity information is provided by synops (only at lowest model level) and by radiosondes. GPS PW data could be particularly beneficial to the LM moisture analysis because they fill the spatial/temporal gaps in the radiosonde network and they are complementary to aircraft wind and temperature measurements. Moreover, the nudging technique can fully exploit the high time resolution of the GPS data.

This paper contains a brief overview of the GFZ GPS quality, as determined by the monitoring at DWD (section 2), a description of how PW nudging has been implemented into LM (section 3), and the results of assimilation experiments using the new data (section 4).

2. Monitoring

Near-real time GPS data processed by GFZ have been received and monitored at DWD since May 2000. Hourly PW measurements from 85 GPS stations in Germany and surrounding countries (Fig. 1) have been compared with the output of LM analysis fields. The height difference between the location of the GPS

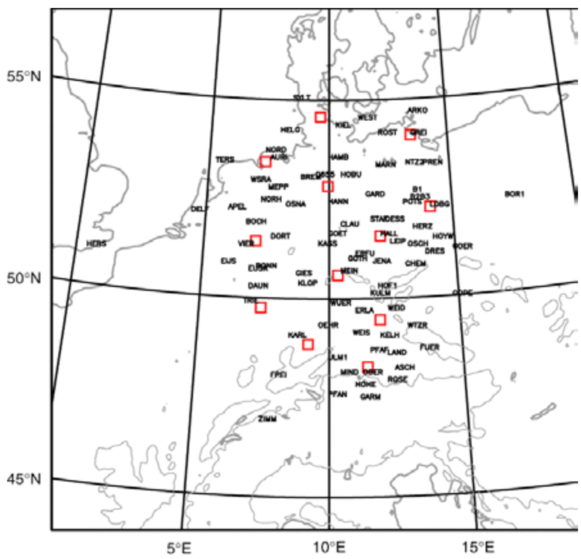

Figure1: The GPS stations processed at GFZ and monitored at DWD (status as April 2001). German radiosonde stations (squares) are also shown for reference.

antenna and the model orography has been taken in account for the sites above the model orography (the integration starts at the model level just below the antenna), whilst for the stations below the orography the integration starts from the lowest model level. In order to monitor all the data received, the model pressure and temperature interpolated to the station location have been used as input for the algorithm applied to derive PW from the ZTD (Bevis et al. 1994).

The data from 23 stations which were available from the very beginning have been used to produce the results shown in Figure 2. During the whole 2000 GPS PW is systematically lower than LM PW, later at the beginning of year 2001 it becomes higher. A similar jump in the mean difference is also seen in the comparison of data from the GPS station LDBG versus the nearby radiosonde situated at the Meteorological Observatorium, Lindenberg (Fig. 3). The reason is very likely related with a problem with the GFZ software running in 2000. Since the introduction of a new processing software on February 2000, the bias of GPS is positive against both model and radiosonde, for some periods in the order of 1 mm. Some studies confirm this wet bias of GPS, for example one year comparison at Cagliari, Italy, against radiosonde and microwave radiometer (Basili et al., 2001), but others (Emardson et al. 1998; Köpken, 2001) demonstrated an overall small dry bias of GPS data with respect to radiosondes and models. The GPS processing methods, the NWP models used for the comparison, and the site location, are all possible factors influencing systematic differences. GPS data produced with the same method over a longer period are required to know the actual bias of the data and to be able to correct them during the assimilation.

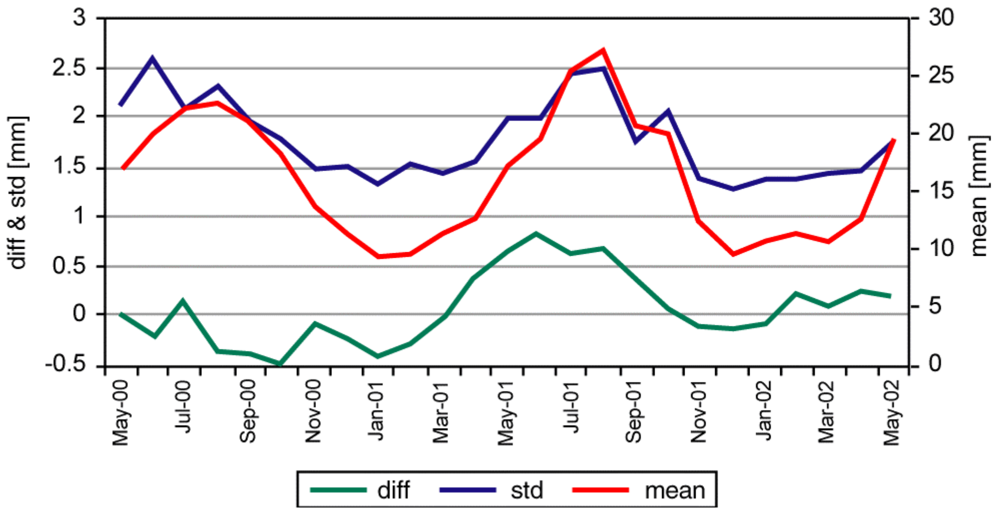

Figure 2: Monthly statistics of GPS PW minus LM PW (operational assimilation fields) over 23 stations, from May 2000 to May 2002: mean difference GPS PW minus LM PW (diff), standard deviation of the difference (std) and mean GPS PW (mean).

If data from 2000 are not considered, it is clear from Fig. 2 that the systematic difference between GPS and LM varies with season: during summer GPS indicates a higher humidity content in the atmosphere than LM, in winter almost the same or sometimes a smaller one. This variability reflects the seasonal changes in PW and it is mostly due to a disagreement between GPS and LM in the diurnal cycle of humidity. Fig. 4 shows the hourly mean of PW from GPS, LM analysis (LM1AN) and LM forecast started from 18 UTC (LM1MO) for 23 stations for a summer period (May-August 2001) and a winter period (October 2001-January 2002). Note that the difference between local time and UTC is about +1 h. In summer, whilst GPS observes an increase of PW by more than 1 mm from 6 UTC to 16 UTC, LM1AN describes a decrease of humidity from midnight to midday in the order of 1 mm. Around 12 UTC the analysis is 1.5 mm below the GPS mean value. The diurnal cycle of forecasted PW has a smaller amplitude than the analysis one, in particular it does not exhibit low humidity content between 10 UTC and 14 UTC. In winter there is no large diurnal variation in the GPS PW, and therefore there is a better agreement between observations and model. This humidity daily cycle of GPS agrees well with that obtained with very frequent measurements taken by a microwave radiometer during a whole year (Güldner and Spänkuch, 1999). The radiometer indicates also an increase of PW in the order of 1 mm during the morning in the summer season and much less variability during winter. A possible explanation for the low PW values of the model in the summer daytime. could be the difficulty in representing the diurnal cycle of convection (e.g. a too early onset of convective activity in the morning which dries out the model later on). Moreover, the analysis humidity decrease from night to day must reflect a similar decrease in the radiosonde data used by the analysis. For example the mean PW from radiosonde station Lindenberg for the period May-August 2001 is 22.4 mm at 00UTC and 21.4 at 12 UTC (1 mm difference in PW can be seen to correspond approximately to a 2% difference in relative humidity at all levels). This day-night difference in the radiosonde has been related to instrument errors at high humidity depending on solar elevation and cloud cover (John Nash, UK MetOffice, personal communication). Therefore the disagreement between GPS and LM is likely due to difficulties in modelling the humidity daily cycle and to the poor time resolution of the conventional observations.

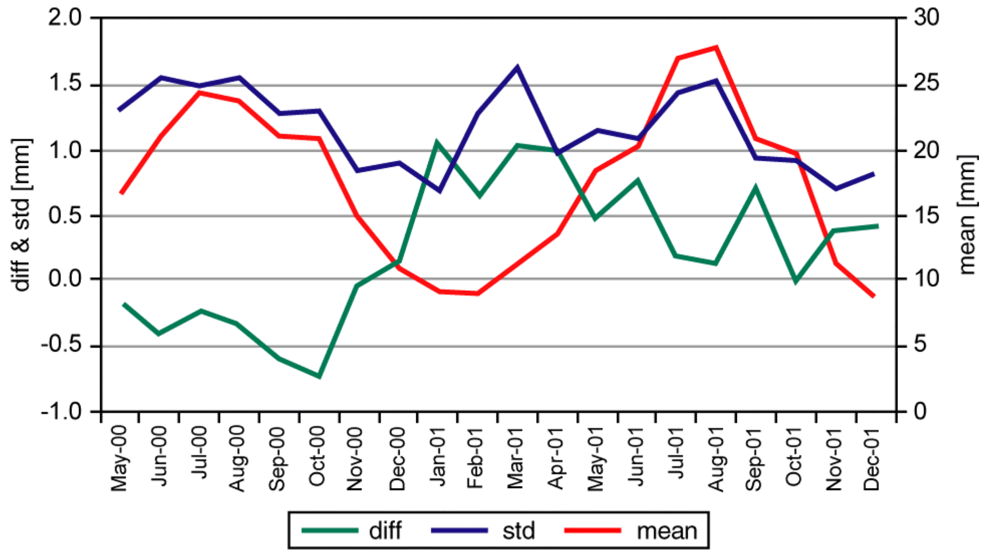

Figure 3: Monthly statistic of GPS PW (station LDBG) minus co-located radiosonde PW Lindenberg from May 2000 to December 2001: mean difference GPS PW minus radiosonde PW (diff), standard deviation of the difference (std) and mean GPS PW (mean).

A change applied to the GPS processing at GFZ on May 2002, i.e. reduction of the satellite elevation cut-off angle from 15 to 7 degree and gradient corrections used in the ZTD computations, has slightly reduced the moist bias of GPS. A comparison between results obtained with the old and new software for the month August 2001 has shown a reduction in the order of 0.2 mm but the difference in the daily cycle has remained. Changes made to the operational LM system during the comparison with GPS were also checked but were found to have negligible impact on the upper-air moisture analysis.

The standard deviation of the difference GPS minus LM is in the order of 2 mm, and ist variability reflects the seasonal change of PW, from a minimum value of 1.3 mm in winter to a maximum of 2.5 mm in summer. But taking the ratio of std to mean PW as a measurement of the relative error, it is actually true the contrary, relative errors are large for low mean PW (up to 16%) and small for high mean PW (9%). This means that the usage of GPS PW data in typical cold and dry winter conditions must be carefully considered. Both comparisons against LM and radiosonde, hint to an improvement of GPS data quality in terms of std from beginning of 2001, i.e. when GFZ introduced the new processing software.

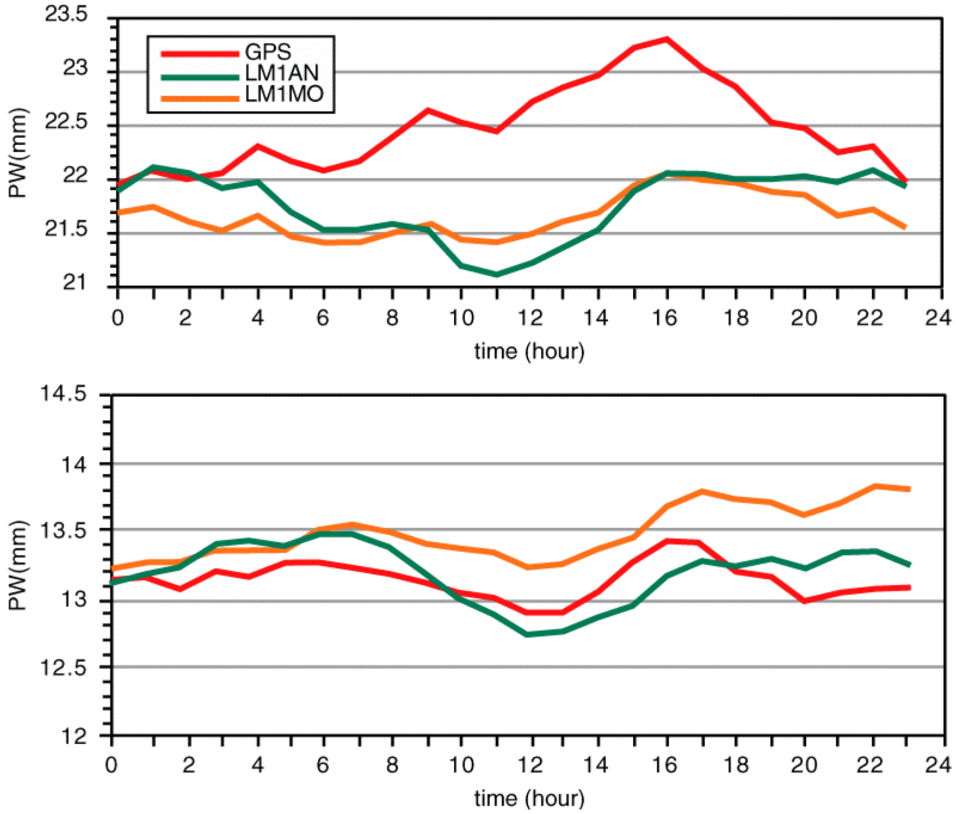

Figure 4: PW hourly average over 23 stations for the period May-August 2001 (above) and October 2001–January 2002 (below): GPS data (red), operational assimilation fields (green), 6-30 hour forecast from the 18 UTC operational forecast run (orange).

Finally, it must be mentioned that monitoring at each single site was also performed and helped in spotting some problems with the GPS data. For example missing information on antenna changes and data handling (conversions to 'Null'-antenna) had initially produced excessive path delays and biases in PW. At present almost all stations have a very similar quality in respect to LM.

3. Nudging of PW

The assimilation scheme of LM is based on nudging towards observations. This scheme can take full advantage of high frequent observations such as the GPS ones. A relaxation term is introduced in the prognostic equation so that, assuming a single observation, the tendency of the prognostic variable y(x,t) is given by:

The first term F denotes the dynamical and physical model. The second term consists of the observation increment (i.e. the difference between the observation yobs and the corresponding model value y(xobs,t)) multiplied by a weight G which depends on the constant nudging coefficient and the spatial and temporal distance between the observation and the time-space model grid point (for more details see Schraff, 1996). In the present operational implementation, the LM uses data from surface and aerological reports (no remote sensing data) and computes the observation increments once every 6 advection time steps of 40 seconds.

The nudging of GPS PW has been implemented following Kuo et al. (1993). A "pseudo- observed" profile of specific humidity qvobs is obtained scaling iteratively the model humidity profile qvmod with the ratio of observed to model PW, i.e. at each single model level k and for one iteration:

Model pressure and temperature interpolated at the GPS station height are used to derive PW from ZPD for all station types, as already described in the monitoring section. The mismatch between GPS sensors height and model orography for the GFZ GPS network it is generally not so large. Few exceptions are station JENA which is 80 m below the lowest model level, and few stations close to the Alps, e.g. station GARM which is 280 m above lowest model level. Since no systematic correlations were found between the height differences and the PW errors, the approximation of pressure and temperature at the GPS station with the model derived ones seems acceptable.

The retrieved profile of specific humidity is then nudged into the model. A vertical quality weight function W(k) proportional to the specific humidity at saturation and to the thickness of the level k, is introduced in the G term for GPS. Thus the GPS humidity profile is given larger weight at those levels which can contribute more to the integrated value PW, normally between 700 hPa and 800 hpa, and less at other levels. In order to avoid modifications of the humidity field at upper levels that contribute very little to the GPS measurement, the retrieved GPS profile is neglected above 500 hPa.

During the nudging process, the GPS derived profiles are treated like radiosonde profiles, except that they have a horizontal radius of influence of approximately 70 km instead 120 km, which appears to be adequate for the dense GPS network. A threshold quality control has been also introduced for GPS observations, but it was found to reject very few observations.

4. Assimilation experiments

An impact study using GPS data in LM has been conducted for a 10 day period in August 2001 (16-25 August). During the first four days of the period an intense south-west circulation produced unstable and storming weather conditions over Central Europe, afterwards, a Scandinavian high pressure system brought more stable weather conditions. This period was selected because of the poor performance of the operational LM forecast, especially with respect to precipitation. Two assimilation experiments have been run, a control (CNT), same as the routine LM, and a GPS, including half-hourly GPS data from 76 stations in Germany and surrounding countries. Unfortunately, at the time of the experiments, no data from French stations were available. 24 hour forecasts started from the assimilation fields of 00 UTC and 12 UTC of each experiment and were verified against GPS itself, radiosonde observations, and synoptic and radar precipitation observations.

Figure 5 shows a verification of the experiment forecasts started at 00 UTC against GPS observations. The rms error of the difference observed minus forecast PW for the forecasts of CNT and GPS are averaged over 9 cases and plotted as function of the forecast range. At forecast step T+0 (analysis) the fit of GPS to the observations is approximately 1 mm against the value of 2.5 mm of CNT. This confirms that the GPS observation have been successfully assimilated. In the forecast range up to T+12 the error of the GPS experiment remains smaller than that of the CNT, but after T+12 the rms of the two runs are almost the same, i.e. the impact of the GPS data has become negligible.

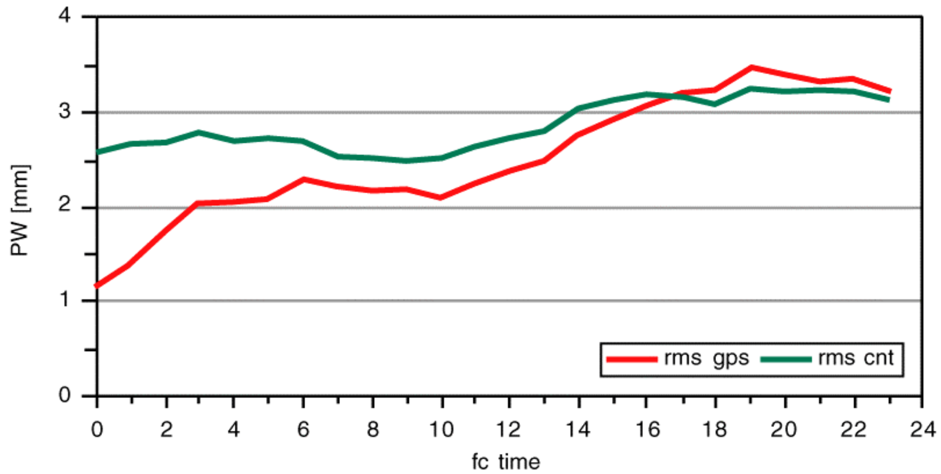

Figure 5: PW root mean square error (rms) computed against the GPS observations of the 24 hour forecast started at 00 UTC as function of forecast hour: rms of the GPS forecast (red), rms of the CNT forecast (green). Mean over 9 cases, from 17 to 25 August

The upper-air verifications against radiosondes data, demonstrate a clear positive impact of the GPS PW data (Fig 6). The relative humidity, temperature and wind rms errors of the 12 hour forecast of the GPS experiment are smaller than those of the CNT experiment at all levels. The most marked improvement is in the relative humidity between 800 hPa and 600 hPa, with an error reduction of the order of 10%. The same verification but for the 24 hour range gave very similar results for GPS and CNT, confirming the neutral impact of GPS data later on in the forecast.

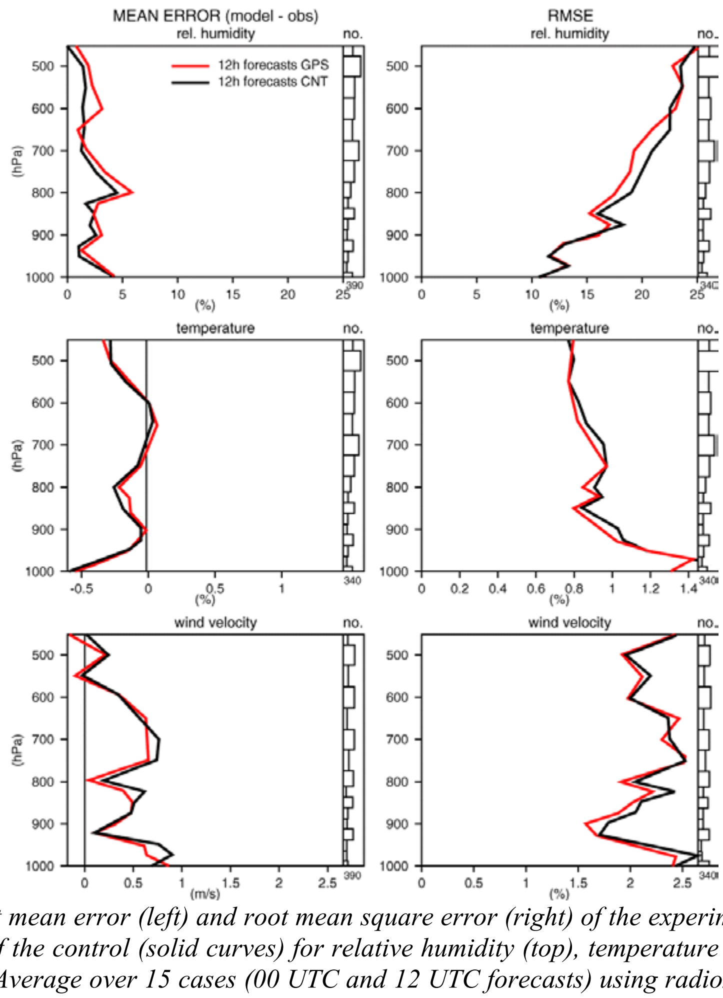

Figure 6: Forecast mean error (left) and root mean square error (right) of the experiment with GPS data (red curves) and of the control (solid curves) for relative humidity (top), temperature (middle), and wind velocity (bottom). Average over 15 cases (00 UTC and 12 UTC forecasts) using radiosondes in Germany and surrounding countries.

A subjective evaluation of 6-and 12-hour precipitation patterns from the LM assimilation and forecasts against analysis derived from SYNOP observations and against radar images suggests that GPS has a mixed impact on precipitation. For example, the GPS 0-6 forecast started from the 12 UTC of 18 August enhances the erroneous excessive rainfall of CNT all over central Germany (Fig. 7). In general, the 12 UTC forecast of the GPS experiment generates more rain than the corresponding CNT forecast. This can be related to the positive bias of the GPS PW with respect to LM during daytime, which has been seen in the monitoring results. In another case, the 0-6 forecast started from the 00 UTC of 21 August, the GPS data correctly reduce the rain of CNT over the south-west and eastwards of Germany (Fig. 8).

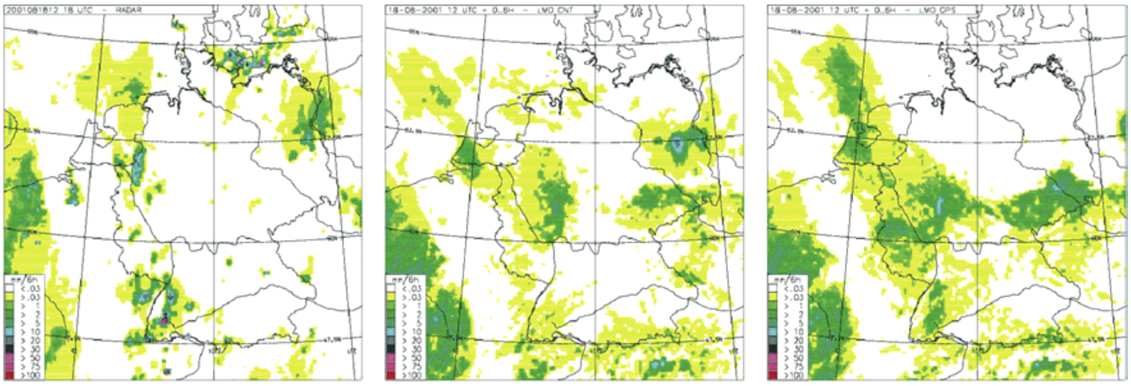

Figure 7: Accumulated precipitation from 12 to 18 UTC on 18 August 2001 as observed by radar observation (left), and from the 0-6 hour 12 UTC forecast of the control run (centre) and of the GPS experiment (right)

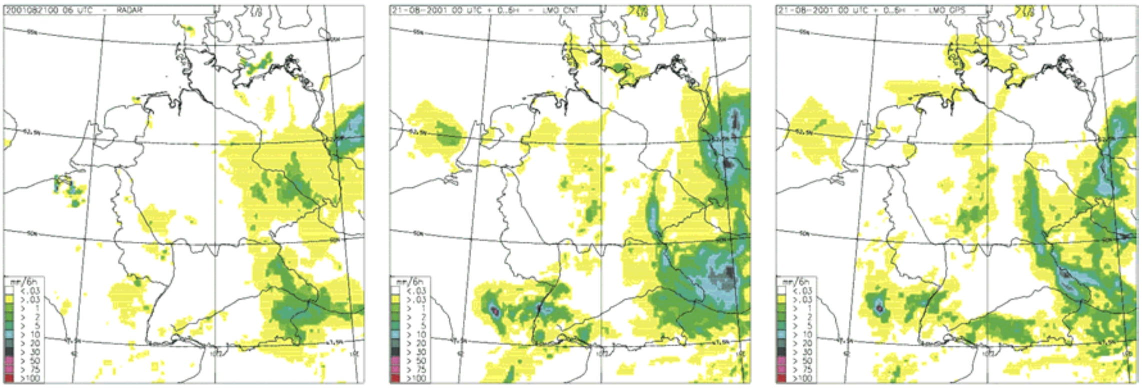

Figure 8: As Fig.7 but from 0 to 6 UTC on 21 August (left) and from 0-6 hour 00 UTC forecast (centre and right).

A quantitative evaluation of precipitation forecast for the federal state Baden-Württemberg in the south-west of Germany has been also performed (Fig. 9). The analysis based on hourly measurements from more than 100 ombrometers spread over this area is particularly suitable to validate short-range forecasts. (The very dense rain gauge network of Germany delivers only 24 hour precipitation amounts). Unfortunately the GFZ GPS network used for the assimilation experiment is not optimal for Baden-Württemberg, with only two stations, FREI and KARL, located in the region and no stations westwards over France (upwind during the experiment). However, the verification shows a small positive impact of GPS data, especially in the 0-6 hour forecast started at 00 UTC (two forecasts are clearly improved). The impact in the forecast range T+6 to T+18 is on average neutral, the only difference being in two forecasts started from 12 UTC, when the GPS experiment produces more rain than CNT.

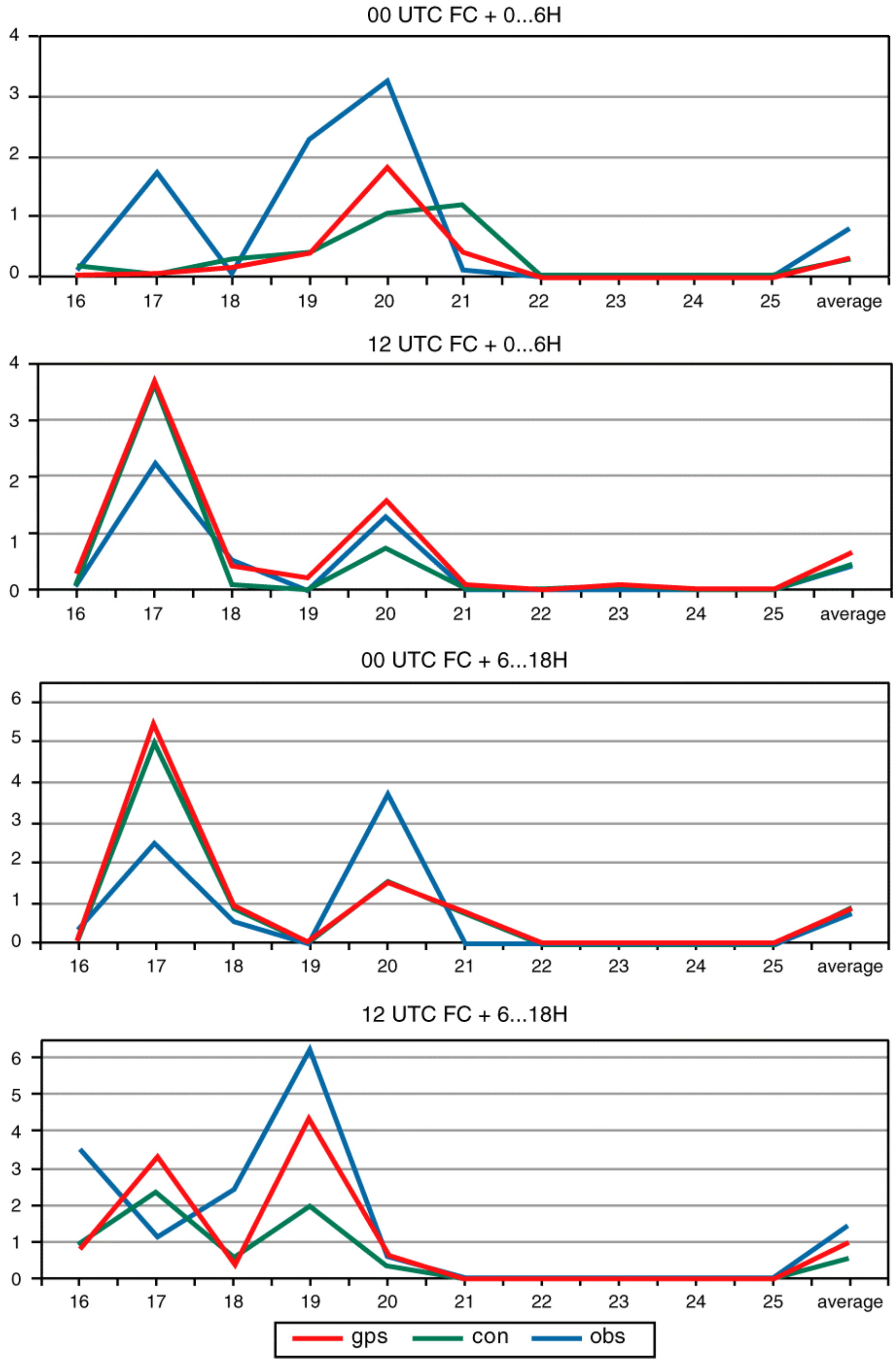

Figure 9: Precipitation verification for Baden-Württemberg: mean precipitation for the area observed (blue), forecasted by the GPS experiment (red), and by the control experiment (green).

5. Conclusions

The results of monitoring the GPS data processed by GFZ indicate that their quality is acceptable for data assimilation purposes. An interesting finding is that sequences of hourly GPS data reveal a diurnal cycle not correctly captured by the model. Assimilation experiments have shown that the model PW is relaxed towards the GPS PW successfully during the assimilation period and that the impact of the data is positive in the first forecast hours and neutral afterwards. The impact on the precipitation forecast is, however, mixed. The GPS experiment tends to produce excessive rainfall during daytime, a problem which has been related to the higher moisture content of the data versus LM. Further work has to be dedicated to the tuning of the PW nudging, in particular to improve the overall impact of GPS on precipitation. A new impact study will be performed during summer 2002, including a bias correction, aimed to reduce the excessive precipitation amount, and the use of 3 dimensional cloud information to improve the vertical distribution of the single integrated value provided by GPS. The new experiments could also profit from a more expanded GPS network, e.g. since May 2002 data from French stations are also available.

Acknowledgments. This study was carried out under the grant of the German Federal Ministry of Education and Research (BMBF) No. 01SF9922/2.

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