Assimilation of COST 716 Near Real Time GPS data in the nonhydrostatic limited area model used at MeteoSwiss

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Abstract

Application of the GPS derived water vapour into Numerical Weather Prediction (NWP) models is one of the focuses of the COST Action 716. For this purpose the GPS data covering Europe have been collected within the Near - Real Time (NRT) demonstration project and provided for Observing System Experiments (OSE). For the experiments presented in this manuscript the operational NWP system of MeteoSwiss is used. The limited area nonhydrostatic aLpine Model (aLMo) of MeteoSwiss covers most of western Europe, has a horizontal resolution of 7 km, 45 layers in the vertical, and use a data assimilation scheme based on the Newtonian relaxation (nudging) method. In total 17 days analyses and two 30 hours daily forecasts have been computed, with 100 GPS sites assimilated for three selected periods in autumn 2001, winter and summer 2002.

The NRT data quality has been compared with the Post - Processed data. Agreement within 3 mm level Zenith Total Delay bias and 8 mm standard deviation was found, corresponding to an Integrated Water Vapour (IWV) bias below 0.5 kg/m^2. Most of the NRT data over aLMo domain are available within prescribed 1 h 45 time window. In the nudging process the NRT data are successfully used by the model to correct the IWV deficiencies present in the reference analysis; stronger forcing with a shorter time scale could be however recommended. Comparing the GPS derived IWV with radiosonde observations, a dry radiosonde bias has been found over northern Italy.

The GPS IWV impact on aLMo is large in June 2002, moderate in September 2001 and minor in January 2002 Observing System Experiment (OSE). January OSE is inconclusive due to inconsistent use of the humidity correction scheme. In June OSE a substantial IWV impact is seen up to the end of the forecast. Over Switzerland the dry bias in the reference analysis has been successfully corrected and the 2m temperature and dew point have been slightly improved

over the whole aLMo domain. The subjective verification of precipitation against radar data in autumn 2001 and summer 2002 gives mixed results. In the forecast the impact is limited to the first six hours and to strong precipitation events. A missing precipitation pattern has been recovered via GPS assimilation in June 20 2002 forecast. A negative impact on precipitation analysis on June 23 has been observed.

The future operational use of GPS will depend on data availability; european GPS networks belong mainly to the geodetic community. A further increase of GPS network density in southern Europe is welcome. The GPS derived gradient and Slant Path estimates could possibly improve efficiency of IWV assimilation via the nudging technique.

1. Introduction

The last decade brought in operational Numerical Weather Prediction (NWP) a new generation of nonhydrostatic meso - γ scale models. They run with a horizontal resolution below 10 km (mesh size) and are aimed to better resolve storm - scale phenomena, complex topography and to provide reliable short range forecast up to 2 or 3 days.

For the needs of high resolution NWP models a further extension of the existing Meteorological Observing System will be necessary. In particular, Bettems (2002) reported that additional information about local structures in the humidity field will be needed. Some promising candidates are the weather radar and lidar networks. In the last decade it was expected that satellite - borne instruments like Special Sensor Microwave/Imager (SSM/I) and Advanced Microwave Sounding Unit (AMSU) would deliver water vapour information with the high temporal and spatial resolution needed for the NWP models. However, the satellite retrievals are often limited to the ocean regions and the footprint of about 50 km is too coarse for high - resolution mesoscale models; due to the frequency employed the satellite instruments are also disturbed by rain. MODIS, the Moderate Resolution Imaging Spectroradiometer, has a spatial resolution of 1 km but a poor temporal resolution, i.e. daily averaged water vapour products. Another source of water vapour information are the ground - based networks of Global Positioning System (GPS) receivers, currently operated for geophysical purposes. With improvements of the GPS accuracy, i.e. improved mapping functions and antenna phase centre models (Haase et al., 2002), it is possible to obtain reliable information of the atmospheric signal delay in the zenith direction (ZTD). In 1992 Mike Bevis (Bevis et al., 1992) proposed to use the ground-based GPS for retrieving the water vapour content of the atmosphere. In the following years several publications investigated the accuracy of GPS in comparison with the conventional sources of water vapour information like ,radiosondes and water vapour radiometers, and in comparison with unconventional ones like sunphotometer, sunspectrometer and VLBI (Very Long Baseline Interferometer). The findings, as summarised in Haase et al. (2002), confirm the accuracy of GPS derived Integrated Water Vapour (IWV) in the range of 1 kg/m^2, i.e. the same level of accuracy as the conventional observations.

The validation of mesoscale NWP models using GPS is presented in Cucurull et al. (2000), Kopken (2001), Haase et al. (2002), Tomassini et al. (2002) and Guerova et al. (2003). Tomassini et al. (2002) studied the diurnal IWV cycle from GPS and LM over Germany in summer 2000. They found a systematic IWV underestimation, higher than 1 kg/m^2, in the model analysis for the hours between 06 and 18 UTC. The HIRLAM model has been validated for the western Mediterranean area (Haase et al., 2002). An IWV bias of 0.5 kg/m^2 and standard deviation of 3 kg/m^2 is reported as well as a latitude dependence of the standard deviation. The validation studies agree that a dense GPS network provides a valuable additional information for NWP models.

Assimilation experiments with GPS IWV are reported in several publications: Kuo et al. (1996), Guo et al. (2000), Smith et al. (2000), De Pondeca and Zou (2001), Vedel et al. (2002), Falvey and Beavan (2002), Tomassini et al. (2002), Gutman et al. (2003) and Nakamura et al. (2003). The GPS impact is mainly evaluated by analysing the model precipitation skills. The results point towards an overall neutral impact when assimilating GPS. However, during active weather phases the GPS is reported to have a positive influence on the location of the front boundaries, and a continuous improvement of precipitation forecast skills has been obtained in a five year assimilation period in the USA (Gutman et al., 2003). Falvey and Beavan (2002) and Tomassini et al. (2002) use a nudging scheme, which makes their results of particular interest for the study presented here. Falvey and Beavan (2002) report that continuous GPS assimilation improved the upwind total rainfall to 1 % significance level only. They also discuss one case where the humidity profile adjustment deteriorated the precipitation structure; the reason was the proportional moisture removal from all model levels based on the GPS observation. In Tomassini et al. (2002) a mixed impact on precipitation analysis is reported for a severe weather case.

In Europe the work on possible application of ground - based GPS in operational meteorology was started with the MAGIC project. An extensive overview about MAGIC is given in Haase et al. (2002). In 1999 the COST Action 716 ”Exploitation of ground based GPS for climate and numerical weather prediction application” followed (Elgered, 2001). The Swiss contribution to COST 716 was established as a collaboration between three Institutes namely, the Swiss Federal Office of Topography (Swisstopo), the Federal Office of Meteorology and Climatology (MeteoSwiss) and the Institute of Applied Physics at the University of Bern (Brockmann et al. 2002). The first goal in evaluating the potential of GPS for meteorological purposes, was the verification of the operational NWP models against GPS data from the Automated GPS Network of Switzerland (AGNES), reported in Guerova et al. (2003a). The second goal, evaluating the impact of GPS data in the NWP system of MeteoSwiss, was initiated in 2001. A first GPS assimilation experiment was calculated for two weeks of September 2001. The precipitation verification over Switzerland shows improvements of the scores as well as an improved diurnal precipitation cycle. In addition we found out that the typical horizontal scale for spreading of the observation increments was too large, particularly in presence of strong water vapour gradients; to avoid this problem the corresponding model parameter was modified. The results obtained in this first experiment (Guerova et al., 2003b) have been considered encouraging, and three new Observing System Experiments (OSE) have been calculated in 2002.

This manuscript reports the results of those three OSEs. In section 2 the mesoscale model of MeteoSwiss is described. The COST 716 Near - Real Time (NRT) demonstration project is outlined in section 3. Section 4 reports the OSE set - up. The results are discussed in section 5 and summarised in section 6.

2. The operational NWP system at MeteoSwiss

a. The aLpine Model - on overview

Since April 2001 a nonhydrostatic mesoscale model named aLpine Model (aLMo) is used for operational NWP at MeteoSwiss. ALMo is the Swiss configuration of the COSMO (COnsortium for Small-Scale MOdelling) limited area model (Doms et al. 2001) developed by the National Weather Services of Switzerland, Italy, Poland and Greece under the lead of the National Weather Service of Germany (DWD). The Swiss implementation of the model has a horizontal resolution of about 7 km, and the domain extends from 35.11 N -9.33 E to 57.03 N 23.42 E (figure 1), covering most of western Europe. A terrain following vertical coordinate system is used, with 45 vertical layers and about 100 m vertical resolution in the lowest 2 km of the atmosphere (Bettems, 2002), and a top level at 20 hPa. A filtered orography was introduced to produce more realistic precipitation fields. Lateral boundary conditions are assimilated following Davies (1976). The aLMo prognostic variables are: horizontal and vertical Cartesian wind components, temperature, perturbation pressure, specific humidity and cloud water content.

The aLMo parameterization schemes take into account a variety of physical processes like: grid-scale clouds and precipitation, subgrid-scale clouds, moist convection, radiation, vertical diffusion, boundary layer and soil processes. The subgrid-scale cloudiness is a combination of cloudiness due to convective processes and cloudiness described as an empirical function depending on relative humidity and height. The grid scale clouds are described via cloud water saturation adjustment. For precipitation formation a Kessler type bulk parameterization scheme is used, and four categories of water substances are considered, namely: water vapour, cloud water, rain and snow. The aLMo hydrological cycle and microphysical processes are presented in figure 2. As seen from figure 2 the cloud ice phase is neglected, assuming a fast transformation from cloud water to snow. A cloud ice scheme has been developed (Doms, 2002) but was not yet tested at the time of the experiments.

b. The data assimilation scheme

The aLMo data assimilation is based on Newtonian relaxation (or nudging) scheme (Schraff, 1997); the model's prognostic variables are relaxed towards prescribed value within a fixed time window. In aLMo the relaxation is performed towards direct observations. For example, the prognostic equation for the specific humidity - q and for a single observation has the following form:

$$\frac{\partial}{\partial t}q(t) = Q(q, u, v, ...t) + G_q.W_q.[q_{obs} - q_{mod}], \tag{1}$$

where Q denotes the model physics and dynamics, q_{obs} and q_{mod} are the observed and the model specific humidity, $G_q = 6.10^{-4}s^{-1}$ is the coefficient defining the relaxation scale and W_q consists of spatial and temporal weights and of a quality factor. The second term in equation (1) is the nudging term and the part $[q_{obs} - q_{mod}]$ is called the observation increment. For the horizontal spreading of the observation increments an autoregressive weight function is used:

$$W_q(x) = (1 + x/s)e^{-x/s}, \tag{2}$$

where x is the distance between the model grid point and the observation and s is a correlation scale factor. The temporal weight function $W_q(t)$ equals one at the observation time and decreases linearly to zero at 1.5 hours before and 0.5 hours after the observation time, i.e. a 2 hour asymmetric saw tooth shaped time window is used. The observation density is also taken into account to set the value of W_q. The observation increments are computed once every 6 time steps i.e. once every 240s.

In the nudging scheme a direct assimilation of GPS derived IWV is not possible as no prognostic variable of this type is available in the model equations. Thus, an indirect assimilation procedure based on Kuo et al. (1993) has been developed at DWD (Tomassini et al., 2002). This procedure is briefly summarised here. First, the Zenith Total Delay (ZTD) from GPS is converted into IWV following Bevis et al. (1992) using the model temperature and surface pressure. Second, IWV ratio between the observation and the model is calculated. Third, using this ratio the model specific humidity profile is scaled from surface to the 500 hPa level. Specific humidity is set to saturation at any level where the specific humidity exceeds its saturation value due to the scaling. The humidity increments are spread laterally using a correlation scale factor of 35 km (s in equation 2). Only GPS stations with a difference between station height and model orography larger than -100 m have been assimilated. For GPS stations above the model orography, the model level closest to the GPS height has been used as initial level in the profile scaling. This condition about the height of the station is particularly important for the Alpine areas in Switzerland, France, Austria and Italy. Due to this condition about 20 GPS stations have not been assimilated, eight of them from the Swiss GPS network.

3. GPS Near - Real Time Demonstration Project

The Near - Real Time (NRT) demonstration experiment started in May 2001 as a main activity in Working Group 2 of the COST Action 716 (COST-716, 2002). The objective of this experiment was to develop a dense NRT GPS network covering Europe and providing ZTD estimates suited for operational NWP, i.e. with data delivery within 1 h 45 min after the observation time. Seven regional processing centres are contributing to the NRT project, delivering hourly ZTD files from about 250 stations in a predefined COST format (COST-716, 2001a) to the ftp server of the UK Met Office. An extensive overview about the NRT project is available in Van der Marel et al. (2003).

The assimilation experiments reported in this manuscript used data from about 100 GPS stations, processed by three processing centres; LPT (Swisstopo, Wabern, Switzerland), GOP (Geodetic Observatory Pecny, Czech Republic) and GFZ (GeoForschungsZentrum, Potsdam, Germany). The selection of processing centres is based on optimal domain coverage, data quality and availability. For the period May 2001 - December 2002 the three centres delivered more then 90 % of the data within the selected time window of 1 h 45 min (Van der Marel et al., 2003). The data provided by LPT and GOP have been processed using the Bernese Normal Equation Stacking Software with a time window of 7 and 12 hours, respectively, 30 s sampling rate and elevation cut-off angle of 10°. The GFZ data have been processed with Precise Point Positioning Software - (EPOS) with data sampling of 120 s and elevation cut-off 7°. Hourly observations are reported by LPT and GOP, at H + 30’, and two observations per hour are reported by GFZ, at H + 15’ and H + 45’. As seen in figure 1 the overall GPS coverage over Switzerland and north of Switzerland is pretty good, but is poor in the southern part of the aLMo domain.

4. The Observing System Experiment Design

All assimilation experiments reported here have been performed by nesting aLMo in the ECMWF global model, the boundary conditions being obtained from the main ECMWF 4D - VAR assimilation cycle with a 6 hour update frequency. All standard meteorological observations are assimilated (SYNOP, BUOY, TEMP, aircraft wind and temperature), but no satellite data are used. Two daily 30 hour forecasts starting at 00 and 12 UTC have been calculated without (reference experiment) and with GPS data assimilation (GPS experiment). Initial conditions for these forecasts were obtained from the corresponding aLMo assimilation cycle. In the forecast runs the observations are still assimilated during the first two hours.

Three weather regimes have been selected for these OSE, namely: an advective period in September 2001, a winter low stratus case in January 2002 and a summer convection period in June 2002. During the five days period from 9 to 13 September 2001 the weather was driven by a cyclone located over the Baltic Sea and a cold front moving slowly eastward, passing over Switzerland on September 9 and initiating cyclogenesis in the the Gulf of Genoa in the night of September 10. The five days period between 10 and 14 of January 2002 is characterised by low stratus over the Swiss Plateau and Southern Bavaria, induced by an anticyclone with weak pressure gradients located over Hungary - a typical winter situation. The third experiment, from the 18 to the 24 of June 2002, was a very active period with intense precipitation events and front passages. One should note, that the French GPS stations have only been available for this June OSE.

5. Experimental results

A comprehensive verification of the three Observing System Experiments has been performed. The vertical structure and the near - surface parameters have been verified for the entire model domain. The precipitation and cloud cover observations were collected for the western and central part of the domain. The diurnal IWV cycle and ZTD are studied over Switzerland.

a. Upper-air and near-surface verification

The vertical structure of the model atmosphere has been verified against 28 radiosonde stations (TEMP) regularly distributed over aLMo domain, using the operational package of MeteoSwiss. Bias and standard deviation (std) for temperature, relative humidity, wind direction, wind speed and the geopotential are calculated for the forecast times: +00, +06, +12, +18, +24 and +30h. The temperature, wind and geopotential (bias and std) do not significantly differ between the reference and GPS forecast. In figure 3, the bias and standard deviation (aLMo - TEMP) of the relative humidity are plotted for forecast times at +00h and +06h, for the 17 days period. A small increase of the bias of the order of 3 to 4 % is observed in the GPS experiment for the layers above 800 hPa; the assimilation of GPS data resulted in a global increase of the model humidity content. This is specially pronounced over northern Italy (Milan and Udine radiosondes) where the positive humidity bias reaches 10 - 12 % in June 2002 OSE. This bias is not limited only to the first +06h forecast, but is also present up to +30h forecast. This is a sign of a systematic underestimation in the radiosonde humidity profiles. Studies in Japan (Ohtani and Naito, 2000) and western Mediterranean (Haase et al., 2002) report a dry radiosonde bias in mid day observations.

Near-surface parameters have been verified against about 1000 surface stations from the SYNOP network; the pressure (PS), dry bulb temperature (T_2M) and dew point temperature (TD_2M) at 2m have been considered. Table 1 summarises the bias and the std of the reference and the GPS analyses for the three OSE periods. Overall T_2M and TD_2M biases are moderately improved in September and June OSEs and degraded in January OSE; impact of GPS on the standard deviation shows the same trend, but with a much smaller magnitude. Note that in the September OSE the bias of all parameters is reduced in comparison with the June and January OSEs. The reason is an overall good skill of the model for this September period, which is further confirmed by the precipitation verification.

In the September OSE, the improvement of the 2m temperature bias and of the dew point temperature bias is 7 % and 13 %, respectively. In the January OSE, assimilating GPS degrade model performance, with a 7 % degradation of TD_2M and a 17 % degradation for T_2M. We believe the reason for this negative impact is related to the absence of the cloud ice scheme and the associated adjustments of the TEMP humidity in the assimilation cycle, which will be further commented in section 5.b. The surface verification of the June OSE presents a positive impact of the GPS data on the model performance. The dew point temperature bias is improved by about 0.1 K, or about 14 %, and the 2m dry bulb temperature is improved by about 25 %. This is a positive signal in favour of GPS observations.

b. PRECIPITATION AND CLOUD COVER VERIFICATION

To provide an overview of the GPS impact on the model humidity field, the IWV differences (GPS minus reference) are plotted in figure 4 for the September 10, 2001, January 14, 2002 and June 20, 2002 cases. In the September 2001 case (figure 4a) a moderate impact is observed when assimilating

GPS, with an average difference at analysis time of $\pm$ 20 % for an average IWV amount of 20 kg/m^2. This impact has completely vanished in the +12h forecast. Most of IWV modifications are over northern Italy and over the Gulf of Genoa (see Guerova et al., 2003b for a full analysis of this period). As seen in figure 4b, the IWV differences for the January case are small. The average IWV difference between the GPS and the reference experiment is in the range of $\pm$ 10 % for an average IWV amount of 10 kg/m^2. Unlike the other two experiments, the June 2002 period is of prime interest in terms of GPS impact on the model humidity field. During this period (figure 4c) the GPS assimilation resulted in significant modifications of the aLMo IWV field over the entire model domain, with an average impact of $\pm$ 30 % at analysis time for an average IWV amount of 32 kg/m^2. Moreover, both the 00 and 12 UTC forecasts exhibit substantial IWV differences, in order of $\pm$ 20 %, up to the end of the forecast (+30h). Note that the plots presented in figure 4 are 00 UTC analysis, which means that the radiosondes humidity profiles have also been available at this time; in this respect the GPS contribution in June OSE is substantial. This is possibly a consequence of the GPS network density and high temporal availability which allows better representation of water vapour structure during periods of active weather.

To further investigate the GPS impact on the model skills, the precipitation data have been examined. The radar composite covering Germany, France, Belgium and Netherlands has been available through M. Tomassini (DWD). Additionally, the Swiss radar composite and the surface precipitation from the ANETZ network are used. ANETZ is the Swiss automatic surface stations network. To get better evaluation of timing and structure of precipitation patterns, the six hour instead of 24 hour accumulated precipitation is used.

For the September 10, 2001 case, a weak impact on the precipitation field is seen in the first six forecast hours. Figure 5 shows the precipitation plots from the reference and GPS forecast. Due to lack of radar data for this date the verification is done against the ANETZ data. The observations give a slight advantage for the GPS forecast (figure 5b) in terms of reduction of precipitation intensity and better correspondence for precipitation free regions. Note, that the predicted maximum precipitation is 34 $mm/6h$ in the GPS experiment and 37 $mm/6h$ in the reference experiment, significantly overestimating the measured value of 6.2 $mm/6h$. In this respect the GPS data seem to have a potential to push the model towards more realistic forecast, but they are not able to compensate for the model deficiencies probably responsible for this massive overestimation. This case is one of the few cases during the September OSE where some differences in the precipitation patterns could be recognised over the entire aLMo domain. In addition the daily precipitation statistic for Switzerland does not show significant differences between the forecasts with and without GPS. This weak impact could be related to the lack of upwind GPS sites in this experiment (French stations are only assimilated in the June 2002 experiment).

During the June 2002 OSE period, intense precipitation events (above $20mm/6h$) are reported on the 20 - 21 and 23 - 24 June. Two interesting cases can be singled out: one with a positive impact on the forecast and one with negative impact on the analysis. The first case is the 00 UTC forecast on 20 June 2002 and is presented in figure 6. The intense precipitation event seen in the GPS experiment (upper left corner of figure 6b) is not observed in the reference experiment (figure 6a). In comparison the radar data (figure 6c) shows intense precipitation over the Jura mountain i.e. Northwest of Switzerland. From figure 4c, one can see that a moisture deficiency of up to 8 kg/m^2 was present at 00 UTC west of Switzerland in the reference run (the intense orange patch). The predominant south - westerly flow in the hours between 00 and 06 UTC advected this additional moisture towards Switzerland, which resulted in the reported precipitation improvement. In this case the GPS data provide important information at the right time and place and improve the forecast.

The second case, this time with a negative impact on the aLMo analysis, has been seen in the night of 23 - 24 June in the hours between 18 and 06 UTC. The model precipitation from the reference and GPS analyses are plotted in figure 7a and 7b and the radar data are in figure 7c. The GPS assimilation resulted in a substantial increase of large - scale precipitation amount in southern Switzerland with a maximum higher than 200 $mm/6h$, tripling the reference value. Over southern Switzerland the radar data is certainly in better agreement with the reference than with the GPS experiment. The explanation of this case could be traced to the too fast advection of humidity structures towards Switzerland in aLMo, by the predominant south-westerly air flow, provoking a continuous feeding of the model with water vapour through assimilation of the Italian GPS site Torino. A detailed study of the IWV amount on 23 and 24 June 2002 indicates a peak value of 55 kg/m^2 in northern Italy and 45 kg/m^2 in Switzerland (figure 9a), an extremely high water vapour content rarely observed at these latitudes. The specific humidity profiles from Torino show that moisture was substantially increased in the lower 2 to 2.5 km in the model GPS analysis.

A summary of the findings from the qualitative intercomparison between aLMo precipitation and the radar data gives an impact limited to the early forecast hours (up to +6h), which is consistent with the findings reported by Gutman et al. (2003).

In the January OSE the focus was on forecast of low stratus cloud cover. Table 2 shows the total cloud cover as analysed and predicted by aLMo with and without GPS, and the corresponding observations from the ANETZ network. The cloud cover is measured in octa from: clear sky condition - 0 octa to complete cloud cover - 8 octas. The model tends to overestimate clear sky conditions and underestimates the fully overcast situations; this is a known deficiency of aLMo, which fails to correctly simulate stratus situations over the Swiss Plateau. Assimilation of the GPS data strengthen this tendency, in both the analysis and the forecast. Visual comparisons with the METEOSAT cloud cover confirms that assimilating GPS retrieved water vapour has a negative impact on the analysis of the low level stratus over the Swiss Plateau and southern Germany. A possible explanation for this negative impact is the absence of prognostic cloud ice scheme and the use of raw GPS derived IWV (Ch. Schraff, personal communication). At temperature below $0°C$ clouds usually form and exist at saturation over ice; however, in absence of cloud ice scheme, the clouds can only form at saturation over water, i.e. at higher values of specific humidity. So, to get the correct cloud amount, the observed humidity should be increased; this adjustment is taken into account for radiosonde observations but not for the GPS observations. For a winter period this adjustment is important and it should have been introduced in the January OSE.

c. Diurnal IWV cycle and ZTD verification for Switzerland

The diurnal cycle of water vapour is an important part of the model verification. The diurnal IWV cycle for nine Swiss GPS stations at altitude below 800 m is plotted in figure 8 for the analysis and the forecast. The plot 8a presents the June 2002 OSE reference and GPS analyses (black and red lines), and the IWV extracted from the Near - Real Time (blue line) and the Post - Processed (PP) GPS data (green line). The reference analysis tends to underestimate the water vapour in the atmosphere when compared with both NRT and PP GPS observations. The bias (aLMo reference / NRT) is in order of -0.64 kg/m^2. On the other side the GPS analysis is overestimating the IWV and the bias is 0.34 kg/m^2. The standard deviation has been reduced from 0.87 kg/m^2 in reference to 0.48 kg/m^2 in the GPS experiment. A visual investigation of the GPS analysis and the NRT observation show satisfactory agreement, except for the early morning hours; however, one should note that NRT observations were missing in the early morning of June 24. A day by day evaluation of the diurnal cycle shows substantial differences between the reference and GPS analysis. On June 21, 22 and 24 the reference model bias, compared to the NRT data, is -2.0, -3.8 and -2.5 kg/m^2 respectively, i.e. the model underestimates substantially the water vapour content. On the other side on June 18 and 19 the reference model bias is positive 2.6 and 1.5 kg/m^2. The figure 8a is rather difficult to interpret as it covers only one week with rapid changes in the atmospheric conditions. The diurnal cycle of the 00 UTC forecast (figure 8b) shows a clear underestimation of the water vapour in aLMo in the second part of the day; a slight correction of this error is observed when starting from the gps analysis.

In order to investigate the efficiency of the assimilation scheme and the accuracy of the NRT GPS data, the IWV and ZTD for the GPS sites Payerne (PAYE) are plotted in figure 9. In the panel, one sees that the IWV differences between the reference and GPS experiment are up to 7 - 8 kg/m^2 and that most of the large errors are corrected. However, it is also seen that the assimilation of GPS does not always drive the model to the observed value: for example at 07 UTC on June 18 the difference between model and observation remains in the range of 3 kg/m^2 and the minimum of IWV is reached with a three hours delay. A possible explanation is the scale of the nudging term employed in aLMo, which is not optimal for the fast temporal variations of the water vapour; the nudging coefficient (G) used here corresponds to a time scale of about 90 min.

In figure 9a and 9b one notes the strong discrepancy between the NRT and PP GPS at midday of June 20. A sharp peak of 35 kg/m^2 is seen in the PP data, which is not well pronounced in the NRT one. This peak has been verified against independent measurements from a sunphotometer, which supports the rapid jump and drop seen in the PP data; this peak is in fact associated with the passage of a cold front. Thus it is to be concluded that NRT processing tends to smooth out the rapid variations of ZTD. This can be explained with the Near - Real Time processing strategy, which incorporates past observations in a 7 hour window to compute the actual ZTD value (processing time window described in section 3). Except for this single observation, a surprisingly good agreement between the two processing schemes is observed. Table 3 displays the bias of the Near - Real Time solution compared with the PP solution for nine Swiss sites, which is in the range 0.4 to 3.7 mm. The averaged ZTD bias is 2.3 mm and the std is in the 8 mm range. This is in agreement with the work reported in Haase et al. (2002) about intercomparison of the MAGIC data set. A ZTD bias of 3 mm corresponds to a IWV bias lower than 0.5 kg/m^2. This result is certainly very encouraging for NWP, as the period under consideration is characterised by rapid changes in atmospheric conditions.

6. Conclusions

With the development of high-resolution mesoscale models rose the need of reliable water vapour information with high temporal and spatial resolution. One such source of information are the ground - based networks of Global Positioning System (GPS) receivers. The focus of the European COST Action 716 was to evaluate the applicability of GPS in operational Numerical Weather Prediction (NWP) through data validation and assimilation experiments. The GPS impact on the operational NWP system of MeteoSwiss, the aLpine Model (aLMo), is reported in this manuscript.

The GPS data from more than 200 European sites have been provided within the Near - Real Time (NRT) demonstration project of COST 716. The quality of NRT data have been validated with the Post Processed (PP) data from Switzerland. It can be concluded that the two data sets have similar quality with few cases of smoothing observed in the NRT data during active weather events. The IWV bias of the NRT data compared with the PP data is less than 0.5 kg/m^2. The data from three COST Processing Centres, namely LPT, GFZ and GOP, are delivered within 1h 45 min observation window in more than 90 % of the cases. The three Centres provide data for 95 % of the GPS sites available in aLMo domain.

Through assimilation experiments with aLMo it was found that the nudging scheme is well able to correct the IWV deficiencies observed in the reference model. A stronger forcing with a shorter time scale could even improve this behaviour in presence of fast meteorological events. The reconstruction of humidity profile is one of the weakest elements of the process; combining GPS with other humidity information or using Slant Path GPS observations could be envisaged to improve this weakness. Comparing radiosonde with GPS, a dry radiosonde bias has been found over Northern Italy. This is consistent with the studies of Ohtani and Naito (2000) and Haase et al. (2002) and seems to be a deficiency in the radiosonde observation during day time.

The impact of GPS assimilation on the aLMo IWV field in winter OSE was weaker than the impact on June and September OSEs. Moreover due to inconsistent usage of humidity correction scheme the results from winter OSE are inconclusive. The strongest GPS impact was obtained in June 2002 OSE, and is visible up to the end of the forecast (+30h). For this period the aLMo reference analysis exhibits a dry bias over Switzerland which is well corrected by assimilating GPS; 2m temperature and dew point temperature analysis have also been improved over the whole domain. However, the impact on the precipitation analysis and forecast is mixed. A missing structure is recovered in the precipitation forecast on June 20 2002. A negative impact on precipitation analysis reported on June 23 is possibly due to model weakness in a special weather situation over northern Italy. The impact on precipitation forecast is limited to the first 6 hours and to intense precipitation events. In our preliminary September 2001 OSE (Guerova et al., 2003b) one case of positive impact on the cloudiness is reported and the precipitation daily cycle of the assimilation cycle was improved.

The use of GPS in NWP has a foreseeable long-term future due to the importance of humidity information for high resolution mesoscale models and the good spatial coverage and temporal availability of these data. The future potential of GPS will be further extended with the new European project - GALILEO (the European Satellite Navigation System) in operational service from 2008. The GPS derived water vapour gradients could help improving the spatial spreading of humidity in active weather regimes and in regions with strong water vapour inhomogeneity. One further improvement could be the retrieval of GPS humidity profiles (tomography), with the limiting factor being the accurate Slant Path estimates. The operational use of GPS in NWP models depends also on future data availability; GPS networks belong mainly to the geodetic community and are not incorporated in the WMO Meteorological Observing System.

Acknowledgement. This work is supported by the Swiss Federal Office of Education and Science under Grant C97.0027. We acknowledge F. Schubiger, M. Arpagaus, P. Kaufmann and A. Rosa from MeteoSwiss for providing verification data. We are grateful to the Swiss Centre for Scientific Computing for resources and support; observing system experiments require indeed a lot of computing power!

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Table captions

Table 1: Near-surface verification of September, January and June OSEs with the SYNOP data. Bias and std of pressure (PS), dry bulb temperature (T 2M) and dew point temperature (TD 2M) at 2m are listed for the reference and GPS analyses. GPS assimilation resulted in improvements of the 2m temperature and dew point temperature in September and June OSEs.

Table 2: January OSE, aLMo /ANETZ total cloud cover amount in octas for the analysis (analysis time 00 to 24 UTC) and forecast (forecast hours 0 to +30). ALMo tends to overestimate the clear sky and underestimate the overcasted situations. GPS assimilation strengthens this tendency.

Table 3: Comparison of Near - Real Time and Post - Processed solutions. ZTD bias and std for nine Swiss GPS sites for the period 18 to 24 June 2002. Note that the bias is better than 3 mm and the std is in the 8 mm range.

Figure captions

Figure 1: ALMo domain and the location of the European GPS sites (red dots) used in our experiments. The colour scale presents the orography and the thin red line the country boundaries.

Figure 2: Hydrological cycle and microphysical processes implemented in aLMo. Four types of hygrometeors are considered namely: water vapour, cloud water, rain and snow. Note that no ice phase was implemented.

Figure 3: Upper - air verification (aLMo minus TEMP) of relative humidity bias (left) and std (right) for September, January and June OSEs. The blue dashed line presents the GPS forecast and the red line the reference forecast at:

a. +00h and b. +06h. A minor bias increase at +06h is obtained when assimilating GPS, but std is slightly improved.

Figure 5: Accumulated six precipitation forecast on 10 September 2001 00 UTC to 06 UTC over Switzerland: a. reference forecast and b. GPS forecast. The contour line defines the Swiss boundary and the main rivers and lakes. Note the differences in the precipitation patterns in the GPS and the reference experiment over the Jura mountain.

Figure 6: Six hour accumulated precipitation 00 to 06 UTC on 20 June 2002 from: a. reference forecast, b. GPS forecast and c. radar observation. The forecasted intense precipitation over Jura region (i.e. north-western Switzerland) in the GPS experiment is confirmed in the radar plot.

Figure 7: Six hour accumulated precipitation 18 to 24 UTC on 23 June 2002 from: a. reference analysis, b. GPS analysis and c. radar observation. Assimilation of the GPS site Torino resulted in significant overestimation of precipitation over southern Switzerland.

Figure 8: June OSE diurnal IWV cycle for nine Swiss GPS sites below 800 msl.

a. The reference analysis - black line , the GPS analysis - red line, Post - Processed GPS green line and NRT GPS - blue line are shown.

b. same as a. but for the 00 UTC forecast.

Note, the underestimation of the water vapour in the late afternoon hours in the reference and GPS forecast.

Figure 9: IWV and ZTD for station Payerne in June OSE.

a. IWV amount in kg/m^2 from the NRT (blue line) and Post - Processed (green line) GPS data and the aLMo reference (black line) and GPS (red line) analysis.

b. ZTD in m at station Payerne from NRT (blue dots) and the Post - Processed (green dots) data. The bias NRT/PP data for station Payerne is 1.8 mm.

Table 1: aLMo minus SYNOP in September, January and June OSEs.

	Sept. ref	Sept. GPS	Jan. ref	Jan. GPS	June ref	June GPS
PS bias [Pa]	-146.2	-146.9	-153.0	-153.1	-152.3	-152.9
PS std [Pa]	2563.0	2563.0	2710.0	2710.0	2423.0	2423.0
TD 2M bias [K]	-0.68	-0.60	-0.78	-0.84	-0.82	-0.72
TD 2M std [K]	2.29	2.26	2.96	2.94	2.73	2.69
T 2M bias [K]	0.15	0.14	-0.32	-0.39	0.27	0.21
T 2M std [K]	2.29	2.26	2.47	2.49	2.55	2.52

Table 2: January 2002 OSE aLMo versus ANETZ cloud cover.

CLC [octa]	0	1	2	3	4	5	6	7	8	TOTAL
ANETZ :	367	78	52	61	30	21	26	40	346	1021
aLMo ref. analysis :	445	106	38	24	23	16	23	33	313	1021
aLMo GPS analysis :	440	115	57	34	22	25	28	41	259	1021
ANETZ :	465	92	57	66	34	27	32	50	444	1267
aLMo ref. forecast :	640	146	58	41	36	33	38	43	232	1267
aLMo GPS forecast :	674	128	60	49	44	26	36	42	208	1267

Table 3: ZTD (Near - Real Time minus Post - Processed) bias and std in m for the period 18 -24 June 2002.

GPS site:	ZTD $[m]$	
	BIAS NRT/PP	STD NRT/PP
EPFL (Lausane)	0.0028	0.0076
ETHZ (Zurich)	0.0030	0.0081
FHBB (Basel)	0.0004	0.0075
GENE (Geneva)	0.0037	0.0072
LUZE (Luzern)	0.0026	0.0088
NEUC (Neuchatel)	0.0020	0.0087
PAYE (Payerne)	0.0018	0.0078
STGA (St. Gallen)	0.0025	0.0079
UZNA (Uznach)	0.0020	0.0086

Figure 1

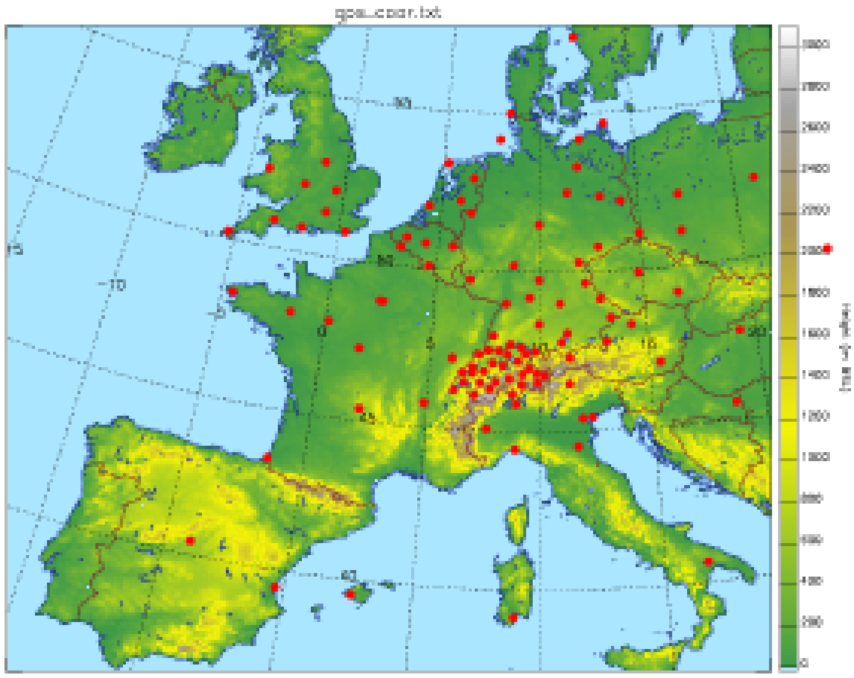


Figure 2

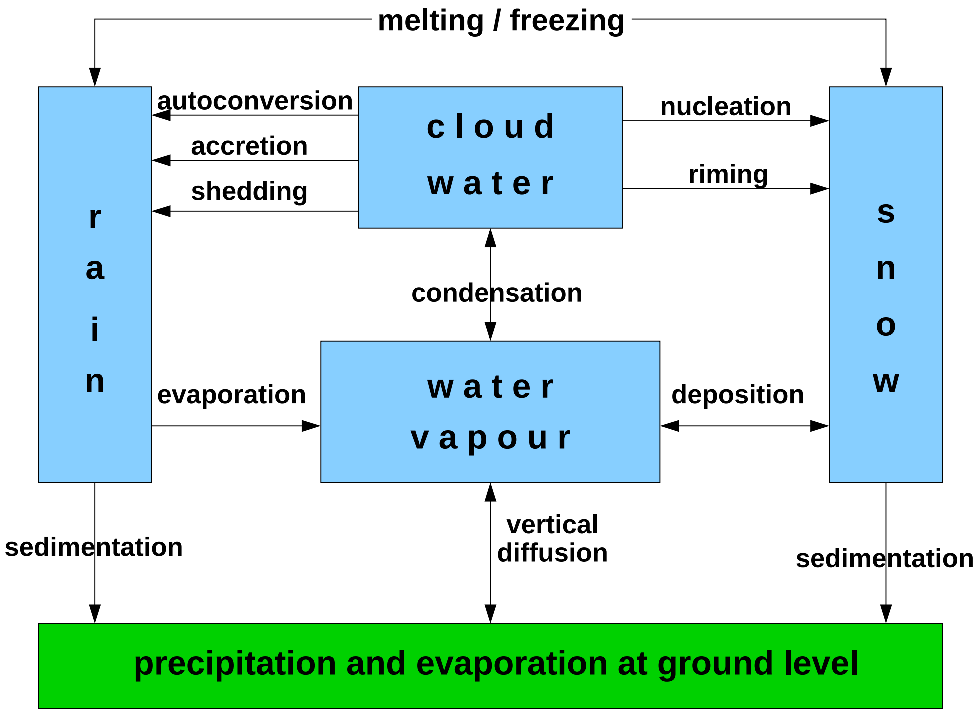

melting / freezing
autoconversion
accretion
shedding
cloud water
nucleation
riming
rain
snow
condensation
evaporation
water vapour
deposition
sedimentation
vertical diffusion
sedimentation
precipitation and evaporation at ground level

Figure 3a

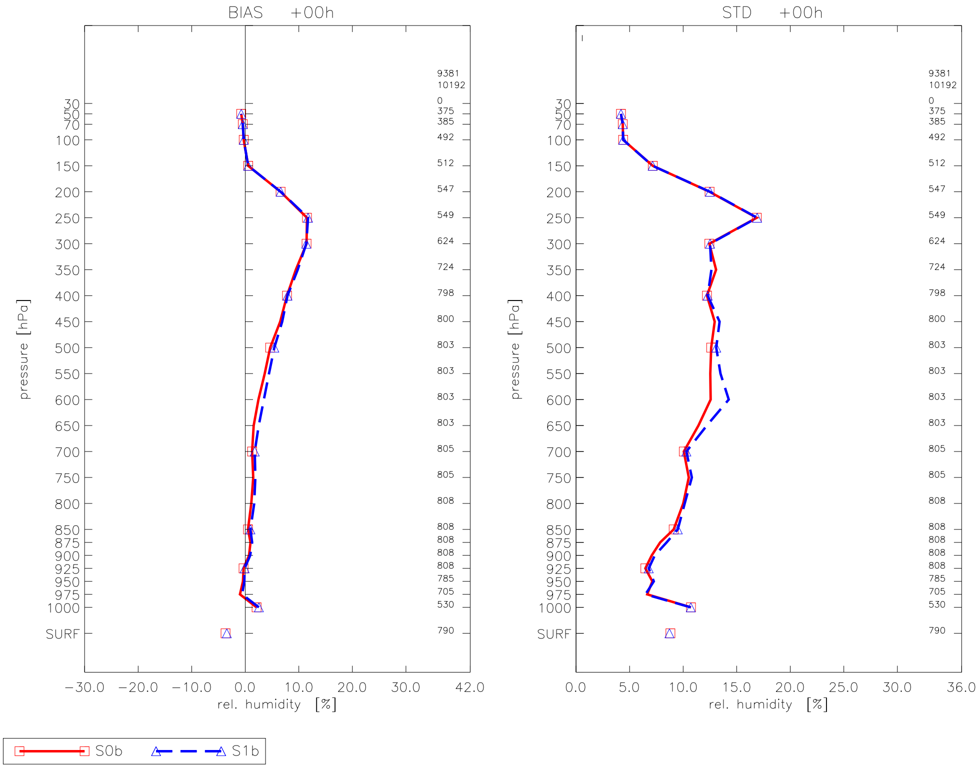


Figure 3b

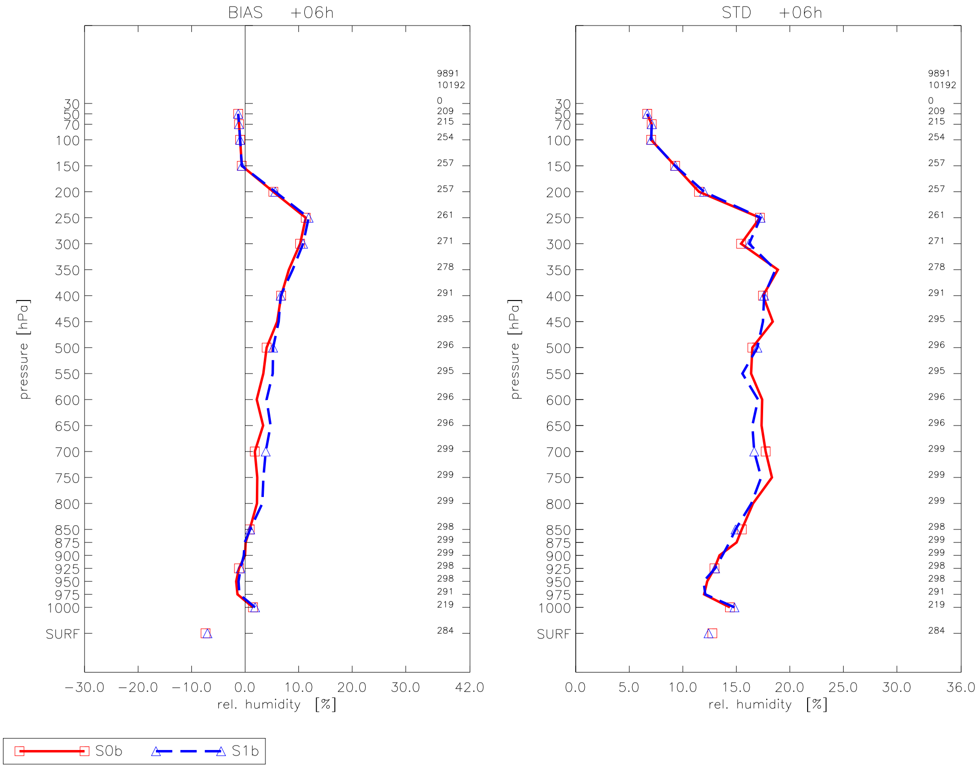
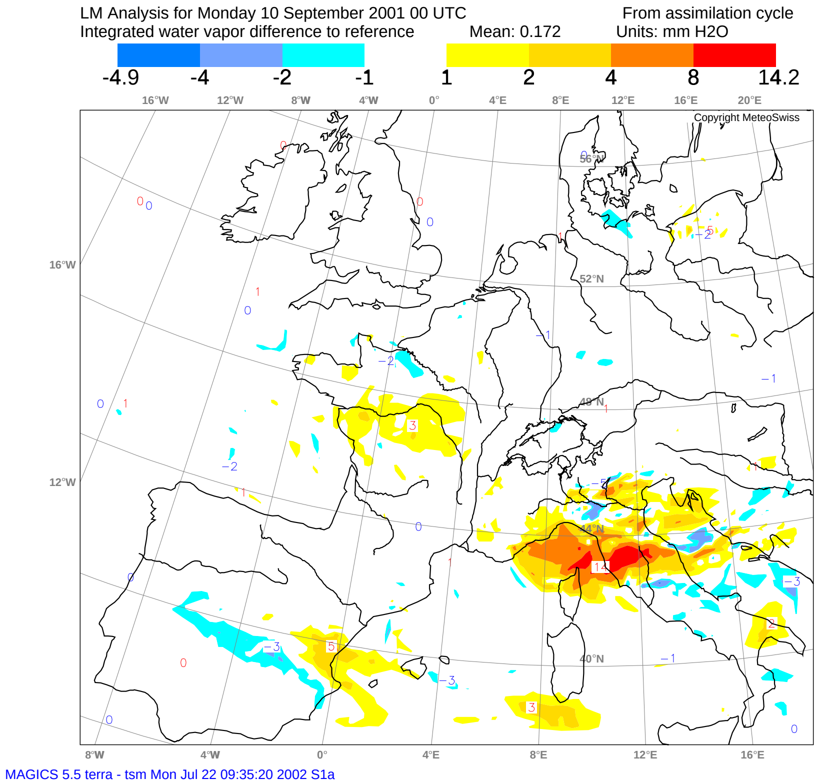
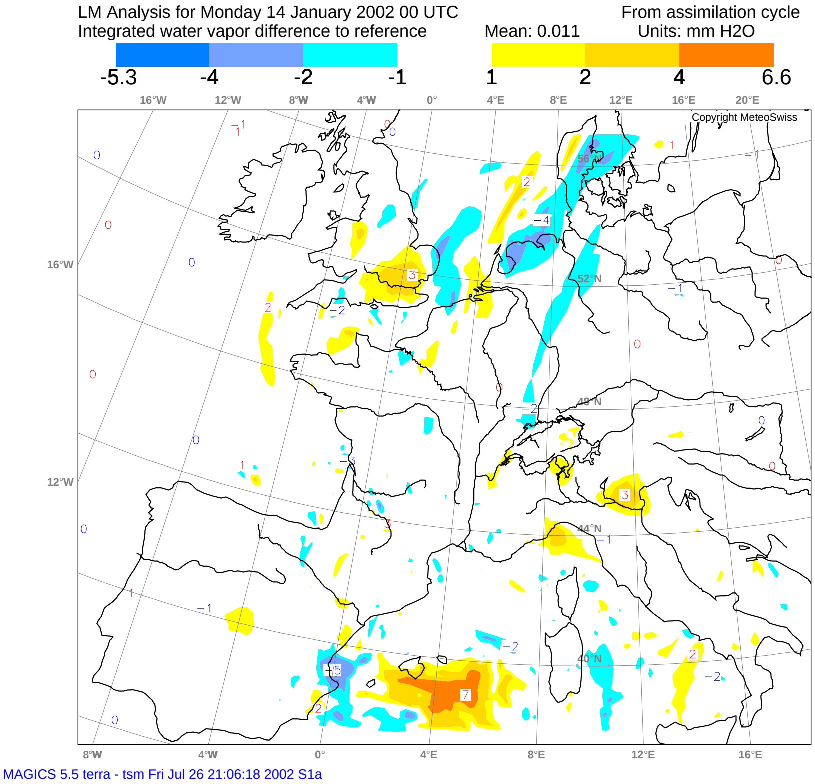


Figure 4a



LM Analysis for Monday 10 September 2001 00 UTC
Integrated water vapor difference to reference
Mean: 0.172
From assimilation cycle
Units: mm H2O
-4.9 -4 -2 -1 1 2 4 8 14.2
Copyright MeteoSwiss
MAGICS 5.5 terra - tsm Mon Jul 22 09:35:20 2002 S1a

Figure 4b



LM Analysis for Monday 14 January 2002 00 UTC
Integrated water vapor difference to reference
Mean: 0.011
From assimilation cycle
Units: mm H2O
-5.3
-4
-2
-1
1
2
4
6.6
Copyright MeteoSwiss
MAGICS 5.5 terra - tsm Fri Jul 26 21:06:18 2002 S1a

Figure 4c

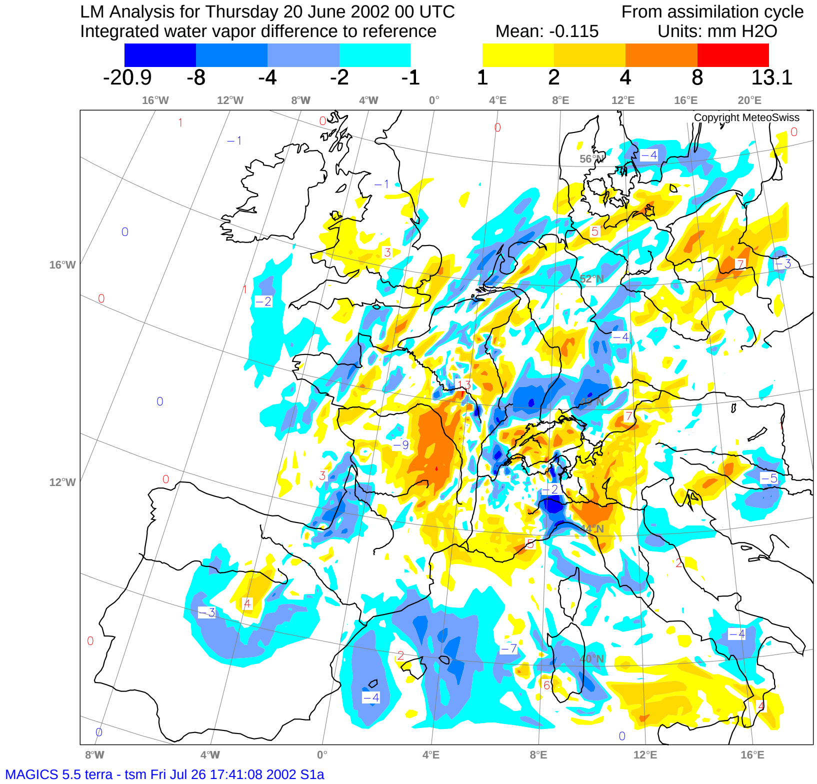

LM Analysis for Thursday 20 June 2002 00 UTC
Integrated water vapor difference to reference
Mean: -0.115
From assimilation cycle
Units: mm H2O
-20.9 -8 -4 -2 -1 1 2 4 8 13.1
Copyright MeteoSwiss
MAGICS 5.5 terra - tsm Fri Jul 26 17:41:08 2002 S1a

Figure 5a

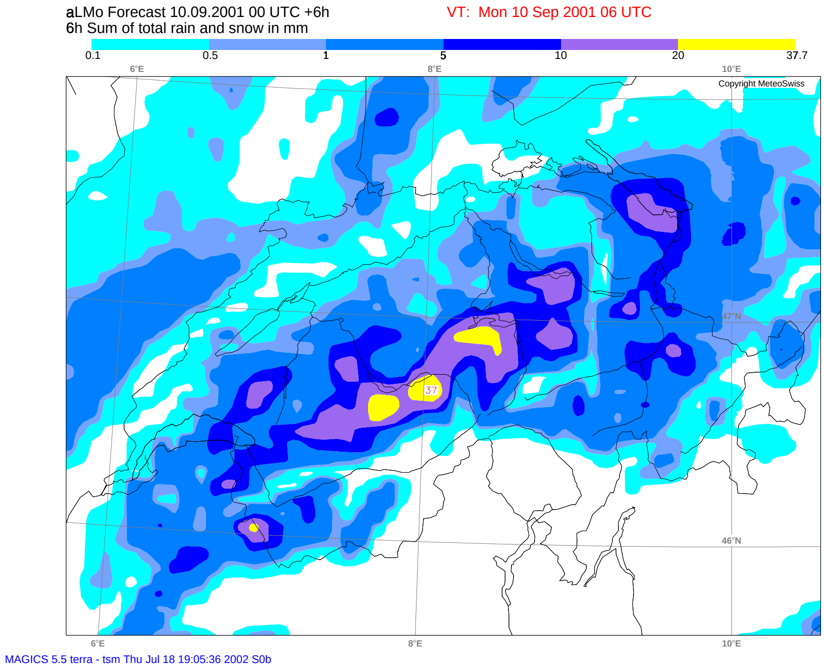

aLMo Forecast 10.09.2001 00 UTC +6h
6h Sum of total rain and snow in mm
VT: Mon 10 Sep 2001 06 UTC
0.1
0.5
1
5
10
20
37.7
6°E
8°E
10°E
Copyright MeteoSwiss
47°N
46°N
37
MAGICS 5.5 terra - tsm Thu Jul 18 19:05:36 2002 S0b

Figure 5b

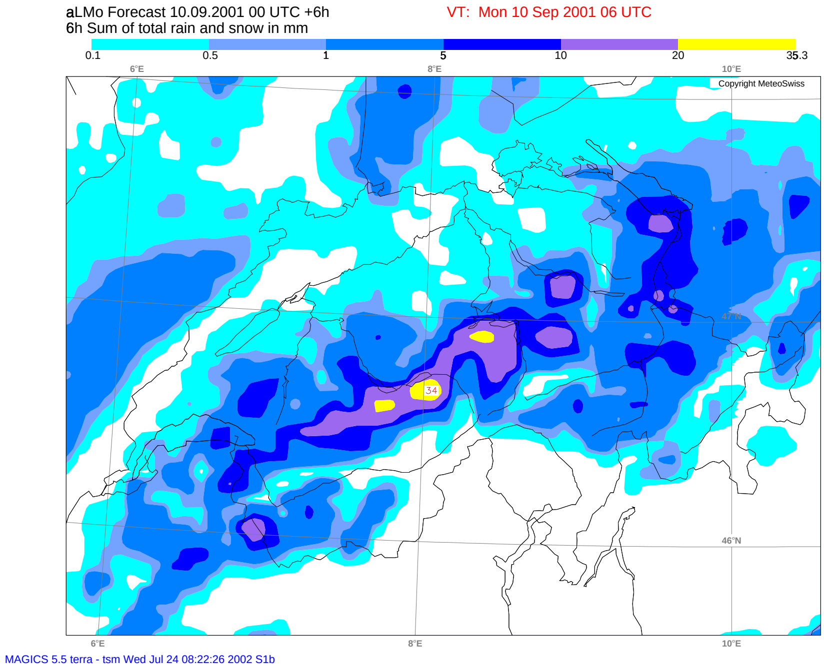

aLMo Forecast 10.09.2001 00 UTC +6h
6h Sum of total rain and snow in mm
VT: Mon 10 Sep 2001 06 UTC
0.1
0.5
1
5
10
20
35.3
6°E
8°E
10°E
Copyright MeteoSwiss
46°N
34
MAGICS 5.5 terra - tsm Wed Jul 24 08:22:26 2002 S1b

Figure 6a

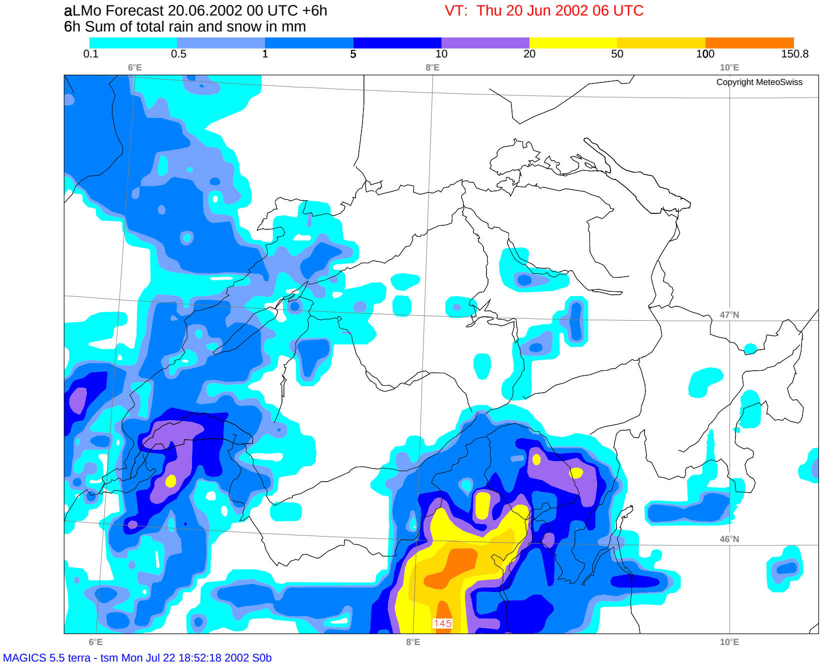
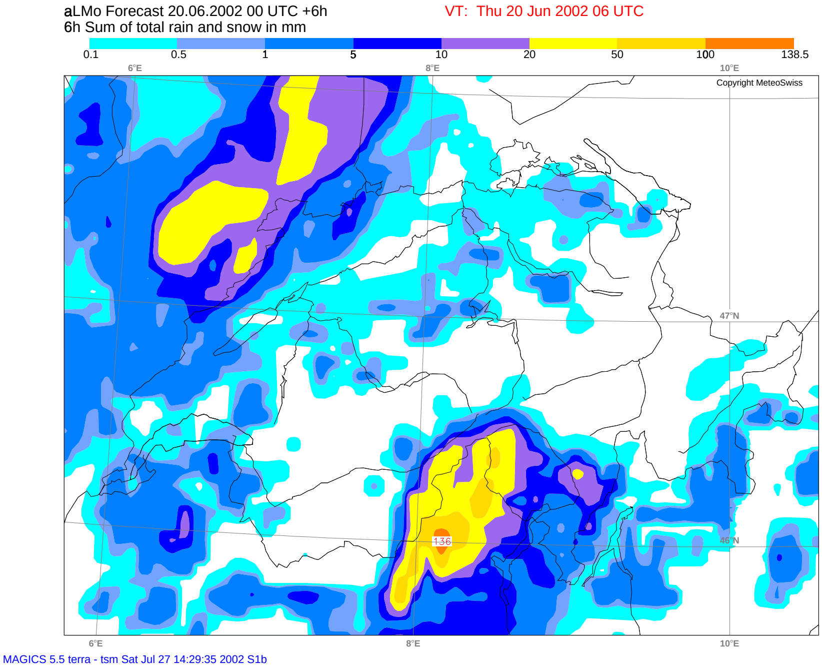
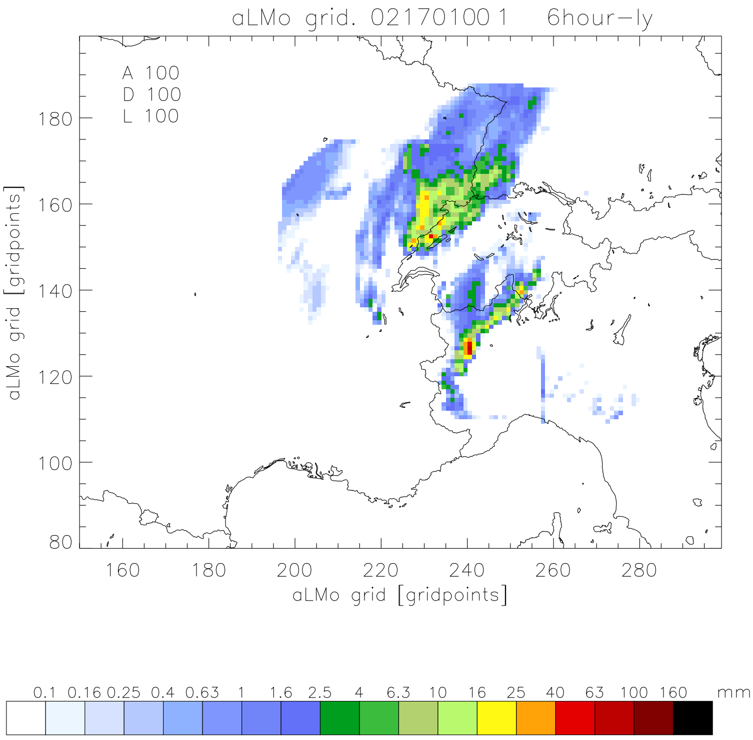

aLMo Forecast 20.06.2002 00 UTC +6h
6h Sum of total rain and snow in mm
VT: Thu 20 Jun 2002 06 UTC
0.1
0.5
1
5
10
20
50
100
150.8
6°E
8°E
10°E
Copyright MeteoSwiss
47°N
46°N
145
MAGICS 5.5 terra - tsm Mon Jul 22 18:52:18 2002 S0b

Figure 6b



aLMo Forecast 20.06.2002 00 UTC +6h
6h Sum of total rain and snow in mm
VT: Thu 20 Jun 2002 06 UTC
0.1 0.5 1 5 10 20 50 100 138.5
6°E 8°E 10°E
47°N
46°N
136
Copyright MeteoSwiss
MAGICS 5.5 terra - tsm Sat Jul 27 14:29:35 2002 S1b

Figure 6c



aLMo grid. 02170100 1   6hour-ly
A 100
D 100
L 100
180
160
140
120
100
80
aLMo grid [gridpoints]
160
180
200
220
240
260
280
aLMo grid [gridpoints]
mm
0.1
0.16
0.25
0.4
0.63
1
1.6
2.5
4
6.3
10
16
25
40
63
100
160
mm

Figure 7a

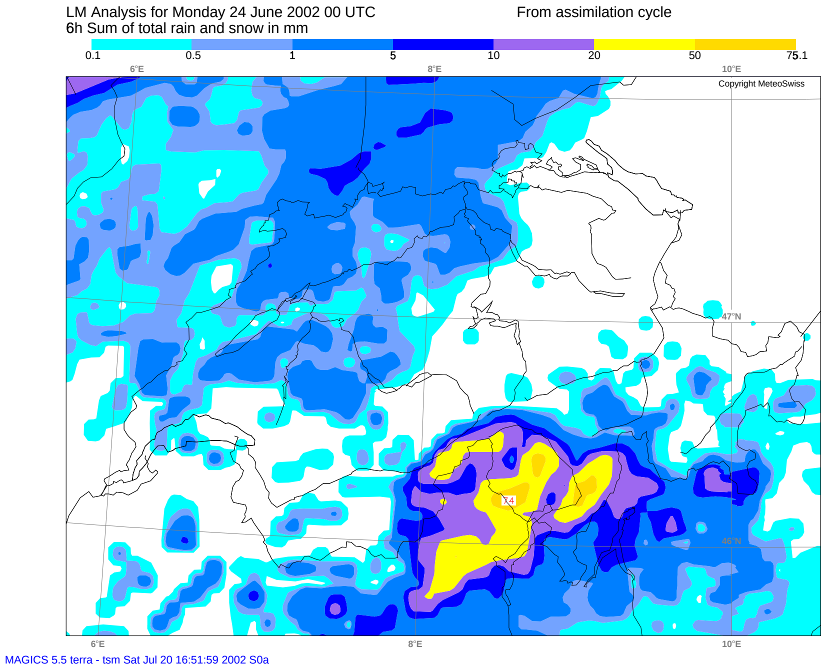

LM Analysis for Monday 24 June 2002 00 UTC
6h Sum of total rain and snow in mm
From assimilation cycle
0.1
0.5
1
5
10
20
50
75.1
6°E
8°E
10°E
47°N
46°N
Copyright MeteoSwiss
MAGICS 5.5 terra - tsm Sat Jul 20 16:51:59 2002 S0a

Figure 7b

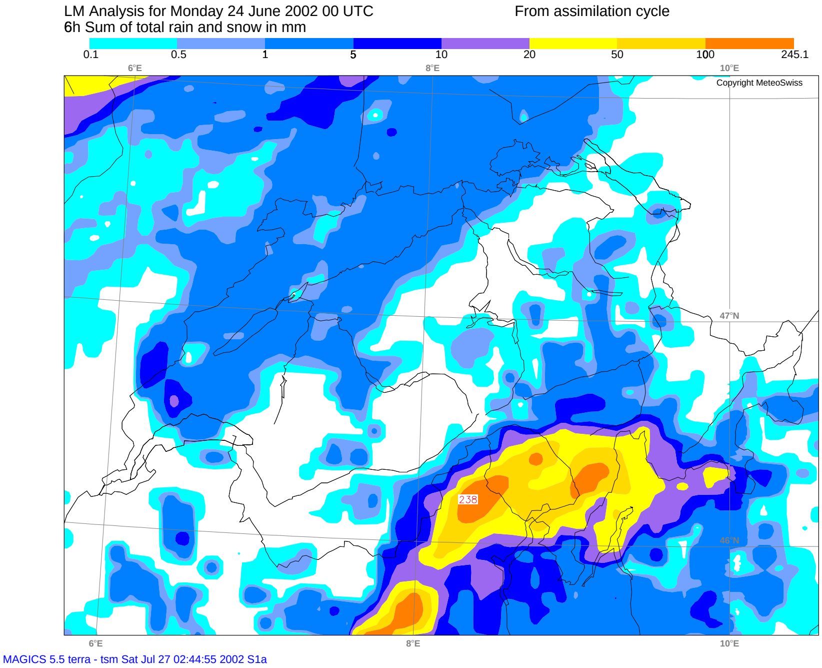

LM Analysis for Monday 24 June 2002 00 UTC
6h Sum of total rain and snow in mm
From assimilation cycle
0.1
0.5
1
5
10
20
50
100
245.1
6°E
8°E
10°E
47°N
46°N
Copyright MeteoSwiss
235
MAGICS 5.5 terra - tsm Sat Jul 27 02:44:55 2002 S1a

Figure 7c

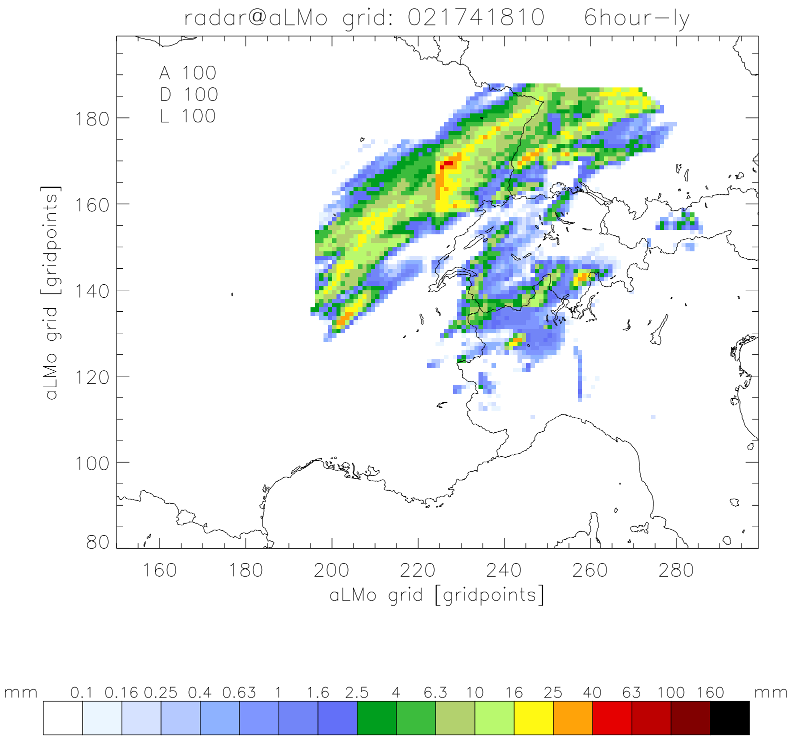
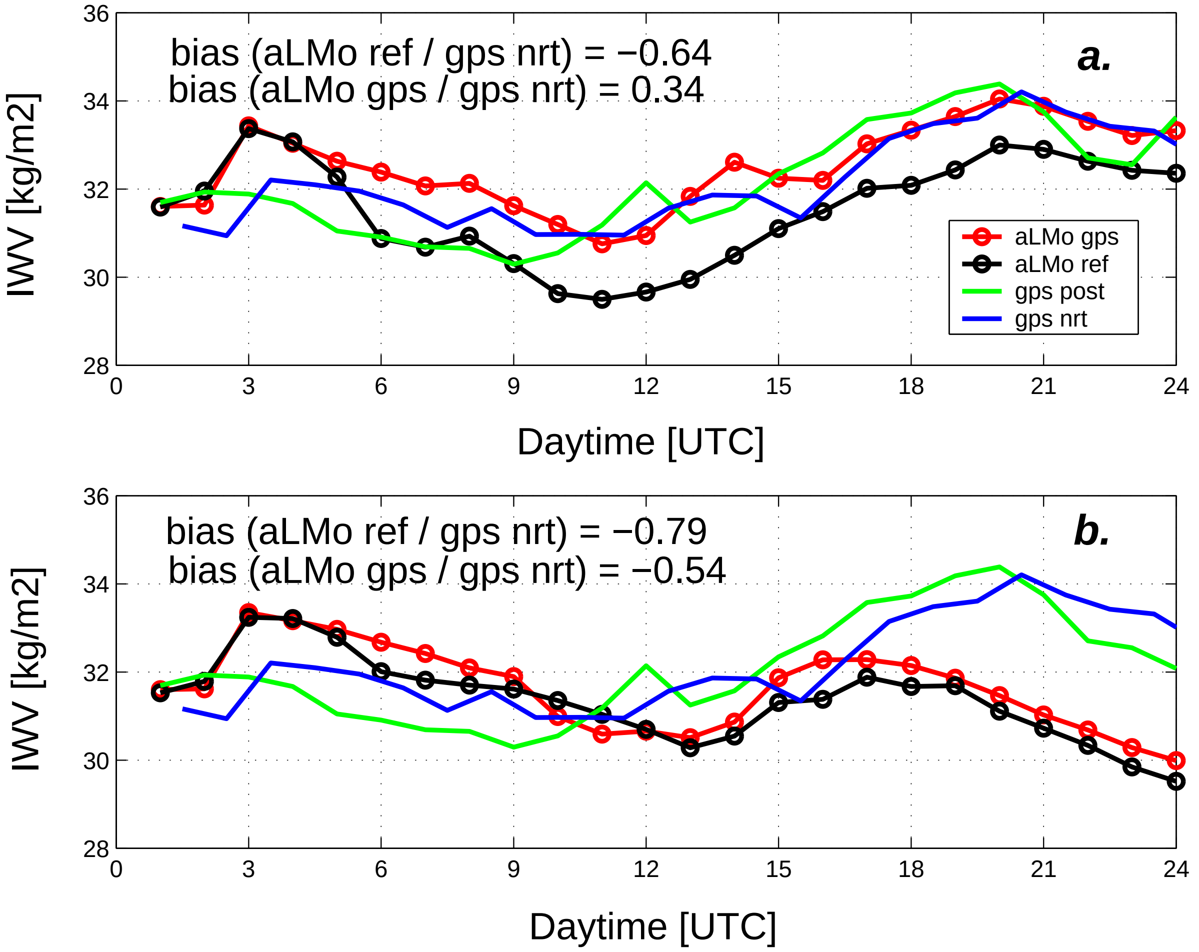
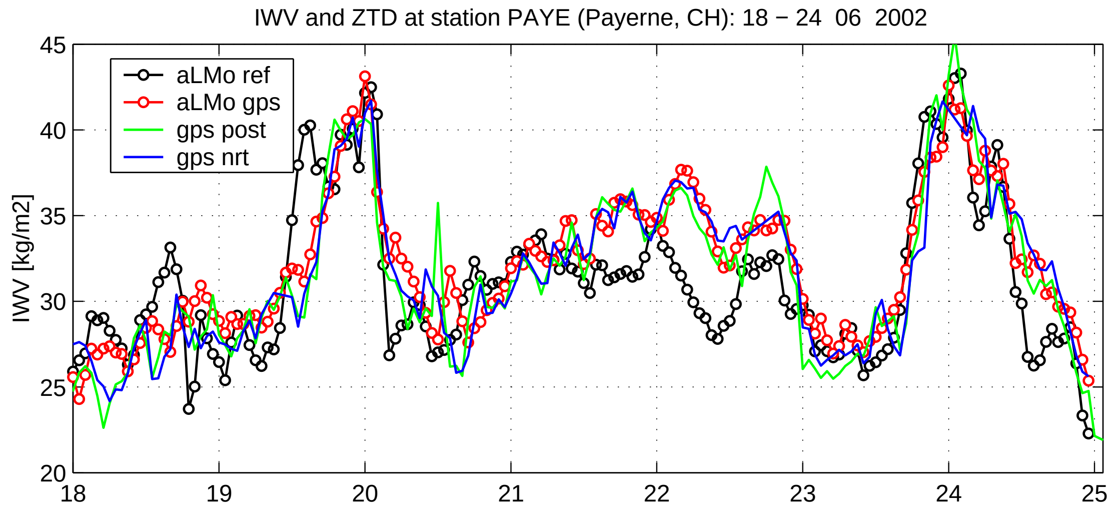

radar@aLMo grid: 021741810 6hour-ly
A 100
D 100
L 100
aLMo grid [gridpoints]
aLMo grid [gridpoints]
mm 0.1 0.16 0.25 0.4 0.63 1 1.6 2.5 4 6.3 10 16 25 40 63 100 160 mm

Figure 8ab

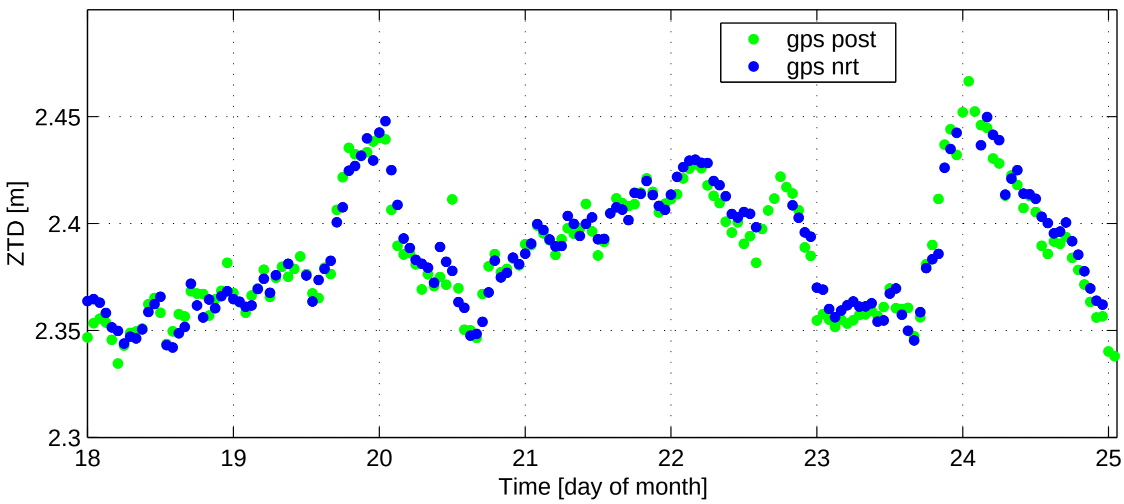


bias (aLMo ref / gps nrt) = −0.64
bias (aLMo gps / gps nrt) = 0.34
a.
aLMo gps
aLMo ref
gps post
gps nrt
IWV [kg/m2]
Daytime [UTC]
bias (aLMo ref / gps nrt) = −0.79
bias (aLMo gps / gps nrt) = −0.54
b.
IWV [kg/m2]
Daytime [UTC]

Figure 9ab



IWV and ZTD at station PAYE (Payerne, CH): 18 − 24 06 2002
IWV [kg/m2]
aLMo ref
aLMo gps
gps post
gps nrt
45
40
35
30
25
20
18
19
20
21
22
23
24
25



ZTD [m]
gps post
gps nrt
2.45
2.4
2.35
2.3
18
19
20
21
22
23
24
25
Time [day of month]