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Impact of GPS zenith delay assimilation on convective-scale prediction of Mediterranean heavy rainfall

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[1] The numerical weather prediction forecast skill of heavy precipitation events in the Mediterranean regions is currently limited, partly because of the paucity of water vapor observations assimilated today. An attempt to fill this observational gap is provided by Global Positioning System (GPS) ground station data over Europe that are now routinely processed into observations of Zenith Total Delay (ZTD), which is closely related to the tropospheric water vapor content. We evaluate here the impact of assimilating the GPS ZTD on the high-resolution (2.4-km) nonhydrostatic prediction of rainfall for the heavy precipitation event of 5–9 September 2005 over Southern France. First, we assimilate the GPS ZTD observations in the three-dimensional variational (3DVAR) data assimilation system of the 9.5-km horizontal resolution ALADIN/France hydrostatic model with parameterized convection. This one-month-long assimilation experiment includes the heavy rainfall period. Prior to the assimilation, a GPS ZTD observation preprocessing is carried out for quality control and bias correction. We find that the GPS ZTD observations impact mainly the representation of the humidity in the low to middle troposphere. We then conduct forecast trials with the Meso-NH model, which explicitly resolves the deep convection, using the analyses of the 3DVAR ALADIN/France assimilation experiments as initial and boundary conditions. Our results indicate a benefit of GPS ZTD data assimilation for improving the Meso-NH precipitation forecasts of the heavy rainfall event.

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1. Introduction

[2] Partly because of its high spatial and temporal variability, the moisture field is one of the less well described variables in initial conditions of numerical weather prediction systems. This is one of the major sources of uncertainties in short-range high-resolution forecasts of precipitation [Kuo *et al.*, 1996]. For instance, Ducrocq *et al.* [2002] have demonstrated the importance of initial humidity fields in improving forecasts on kilometer scale of heavy precipitation events. Thanks to coordinated efforts in the European Global Positioning System (GPS) geophysical community during the past few years, Zenith Total Delay (ZTD) data are now available in near real-time. The spatial resolution over Western Europe is about 100 km in average, and products are typically available every 15 minutes. The

GPS ZTD observation contains vertically integrated information of the atmospheric refractivity which is a function of pressure, temperature and water vapor pressure [Thayer, 1974]. This link with tropospheric humidity is quite appealing for the meteorological data assimilation community.

[3] Several studies have investigated the impact of ground-based GPS data assimilation on improving the analysis quality and forecast skill for different weather conditions. At first, methods were developed for assimilating Integrated Water Vapor (IWV) derived from GPS ZTD data and surface pressure and temperature data [Falvey and Beavan, 2002; Nakamura *et al.*, 2004; Koizumi and Sato, 2004; Guerova *et al.*, 2006; Smith *et al.*, 2007]. The hydrostatic component of the zenith delay can be estimated from surface pressure data and subtracted from ZTD to yield the so-called wet delay which is nearly proportional to the water vapor content of the atmospheric column, i.e., IWV. Now, variational data assimilation schemes that are widely used in meteorology allow using observations that are not state variables of the atmospheric model. Variational data assimilation relies on observation operators to compute the model equivalent observables from the model prognostic variables. Consequently, direct assimilation of zenith total delay observations is possible with these methods [De Ponte and Zou, 2001; Vedel and Huang, 2004; Peng and Zou, 2004; Poli *et al.*, 2007]. This enables to remove the errors due to the conversion of GPS ZTD into IWV [Brenot *et al.*, 2006]. Another advantage of assimilating GPS ZTD

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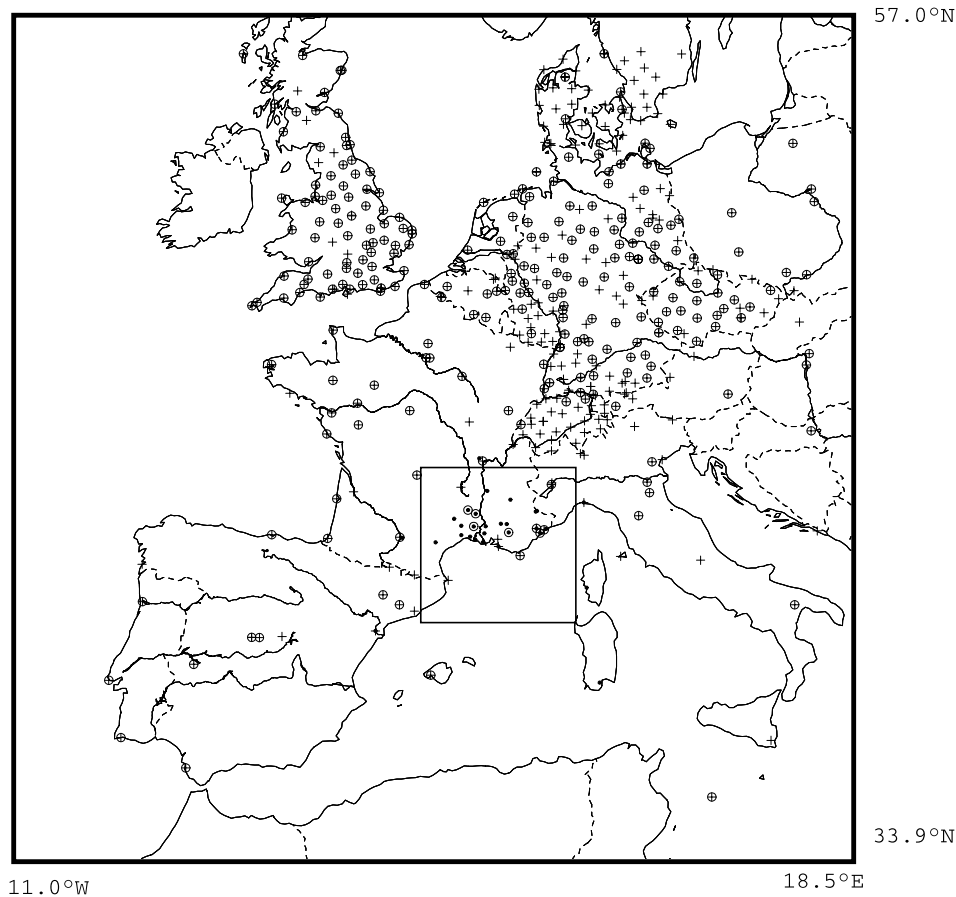


Figure 1. Location of the ground-based GPS stations from the operational E-GVAP (crosses) and dedicated OHM-CV (points) networks for September 2005, plotted over the ALADIN model domain. The stations selected for data assimilation are circled. The 2.4-km Meso-NH domain is delineated by the box.

instead of IWV is that ZTD contains information on surface pressure and temperature in the troposphere. The results of these previous studies on assimilation of ground-based GPS data show generally a positive impact on precipitation forecast, with amplitudes depending on the assimilation method and the density and size of the GPS network.

[4] Few studies have focused on mesoscale assimilation of GPS data and their impact on the short-range forecast of Mediterranean severe events. *Vedel et al.* [2004] showed a neutral impact over a two week time period in February 2002, except for a severe rainfall event for which a positive impact had been found. In that study, ZTD data from 58 ground-based GPS stations over Western Europe had been assimilated with the High-Resolution Limited Area Model (HIRLAM) numerical weather prediction three-dimensional variational (3DVAR) data assimilation system at 0.3° horizontal resolution. *Faccani et al.* [2005] evaluated the impact of assimilating data over a longer period of time (winter 2003 and summer 2004) and for a regional GPS network of 15 stations in the Basilicata region (Italy). They reported an improvement of the 9-km model forecast especially during the transition from winter to spring. At higher resolution (down to 6 km), *Cucurull et al.* [2004] have shown that the assimilation of ground-based GPS ZTD

data improved the forecast of a strong mesoscale Mediterranean storm.

[5] Our goal is to investigate the impact of GPS data assimilation on forecast at kilometer scale for which convection is not parameterized, as in the previously quoted studies, but explicitly resolved by the model. Previously, *Ducrocq et al.* [2002] and *Richard et al.* [2007] pointed out different responses to the same initial conditions between parameterized and explicitly resolved convection for the precipitation forecast.

[6] In the present study, we examine the impact of GPS ZTD data assimilation on the convective-scale prediction of a Mediterranean heavy precipitation event. We assimilate ground-based GPS ZTD data from an extensive network of 262 stations covering Western and Mediterranean European regions. The 3DVAR data assimilation is first carried out for the complete month of September 2005 at 9.5-km horizontal resolution with the ALADIN/France (Limited Area Dynamical Adaptation International Development) numerical weather prediction system. Then, the impact on the 2.4-km resolution forecast is examined for the heavy precipitation episode that occurred from 5 to 9 September 2005 over Southern France with the Mesoscale Nonhydrostatic (Meso-NH) numerical weather prediction system.

[7] The outline of the paper is as follows. Section 2 presents the data and methodology used in this study. Section 3 describes results of the assimilation experiments performed with the 3DVAR ALADIN system. Section 4 presents the case study of 5–9 September 2005 and discusses the impact of assimilating GPS ZTD data on the ALADIN/France and Meso-NH forecasts of that event. The conclusions follow in section 5.

2. Methodology

2.1. GPS ZTD Observations

[8] The present study uses two GPS ZTD data sets. The first data set was received in near real-time by Météo-France operational databases from the European GPS station network, via the Global Telecommunication System (GTS). The near-real-time collection, processing, and GTS dissemination of the ground-based GPS delay measurements into ZTD observations is performed through the EUMETNET GPS water vapor program (E-GVAP, <http://egvap.dmi.dk/>). These E-GVAP GPS ZTD data have been assimilated in operations by Météo-France's global model ARPEGE (Research Project on Small and Large Scales) four-dimensional variational (4DVAR) data assimilation system since September 2006 [Poli et al., 2007]. For the time period considered in this study (15 August–30 September 2005), data from about 449 stations all over Europe were available, processed by 11 GPS data centers. The sampling rate, between 5–60 minutes, depends on the processing strategy used by each center. Note that raw data from each GPS station can be processed into ZTD observations by several centers.

[9] We further include observations from a research network in order to increase the number of GPS ZTD observations in the region of the heavy precipitation event. This non-real-time 32-station network was deployed from 2002 to 2007 by the Mediterranean Cévennes-Vivarais Hydrometeorological Observatory (OHM-CV [Delrieu et al., 2005]) over the Northwestern Mediterranean region. The 15-minute GPS ZTD solutions are computed in post-processing mode. This allows us to use final IGS orbits and a sliding window strategy, keeping only tropospheric parameters from the middle 4-hour of 12-hour sessions calculated every 4 hours. Moreover, the station positions obtained from a preceding analysis over 24-hour sessions are only loosely constrained. More details of the analysis strategy can be found in the work of Brenot et al. [2006]. Figure 1 shows the locations of the stations from the combination of the two GPS networks. For the time period considered here, we have a total of 481 stations and 1036 computations of these stations resulting from the processing by several centers of some stations. Note that four of the OHM-CV stations were also postprocessed by some of the E-GVAP centers. Figure 1 shows that the spatial resolution of the network is far from being uniform, with fewer GPS ZTD observations in the Mediterranean area as compared to Northern Europe.

2.2. The 9.5-km ALADIN 3DVAR Assimilation System

[10] A comprehensive description of the ALADIN/France (hereafter called ALADIN for simplicity) 3DVAR data assimilation scheme used in the present study was given

by Fischer et al. [2005] and Montmerle et al. [2007]. The assimilation scheme is based on the incremental formulation originally introduced in the ARPEGE/Integrated Forecast System (IFS) system [Courtier et al., 1998]. The background-error covariance matrix is built up from an ensemble of ALADIN 6-hour forecasts whose initial and lateral boundary conditions are provided from an ensemble of perturbed assimilation cycles from the global ARPEGE model [Ștefănescu et al., 2006]. This method allows producing mesoscale structure functions to spread the observation content. For instance, the specific humidity horizontal error correlation lengths are about 70 km in the middle troposphere.

[11] The 3DVAR ALADIN data assimilation system has been running operationally at Météo-France since July 2005 to produce four daily analyses (at 00, 06, 12, and 18 UTC) and associated short-range forecasts with a 9.5-km horizontal resolution [Montmerle et al., 2007]. The ALADIN model is based on the hydrostatic equations. Its geographical domain is shown in Figure 1. The observations assimilated in the system as of September 2005 did not yet include GPS ZTD, but included those from radio-sounding, screen-level stations, wind profilers, buoys, ships and aircraft. Assimilated satellite data included horizontal winds from atmospheric motion vectors (AMVs) and the Quikscat scatterometer, Advanced Microwave Sounding Unit (AMSU)-A and -B radiances from the National Oceanic and Atmospheric Administration (NOAA)-15, -16, -17 satellites and the National Aeronautics and Space Administration (NASA) AQUA satellite, High-Resolution Infrared Sounder (HIRS) radiances from NOAA-17 and clear air SEVIRI radiances from the METEOSAT-8 satellite. All these observations are used by default in our assimilation experiments.

2.3. ZTD Assimilation Setup

[12] The observation operator for the assimilation of GPS ZTD observations is based on the vertical integration of the atmospheric radio refractivity (see Vedel et al. [2001] for a derivation of zenith delays from meteorological variables)

$$ZTD = 10^{-6} \int_{z_0}^{\infty} \left(k_1 \frac{p}{T_v} \right) dz + 10^{-6} \int_{z_0}^{\infty} \left(k'_2 \frac{e}{T} + k_3 \frac{e}{T^2} \right) dz \quad (1)$$

where p is the atmospheric pressure, T and T_v are the temperature and the virtual temperature respectively, and e is the partial pressure of water vapor. The refractivity coefficients follow Bevis et al. [1994]: $k_1 = 77.6 \text{ K hPa}^{-1}$, $k_2 = 70.4 \text{ K hPa}^{-1}$, $k_3 = 3.739 \cdot 10^5 \text{ K}^2 \text{ hPa}^{-1}$ and $k'_2 = k_2 - k_1 \cdot R_d \cdot R_w^{-1}$, where R_d and R_w are the ideal gas constants for dry air and water vapor.

[13] The vertical integration procedure in equation (1) is carried out by accumulating the contribution of refractivity to ZTD belonging to each model layer above the observation location, from the top of the model down to the GPS receiver height z_0 . Beforehand, the model temperature and specific humidity profiles are horizontally interpolated to the observation location using a linear interpolation from the four surrounding model grid points.

[14] Because the model orography is approximate, the receivers may be located above or below the model lowest

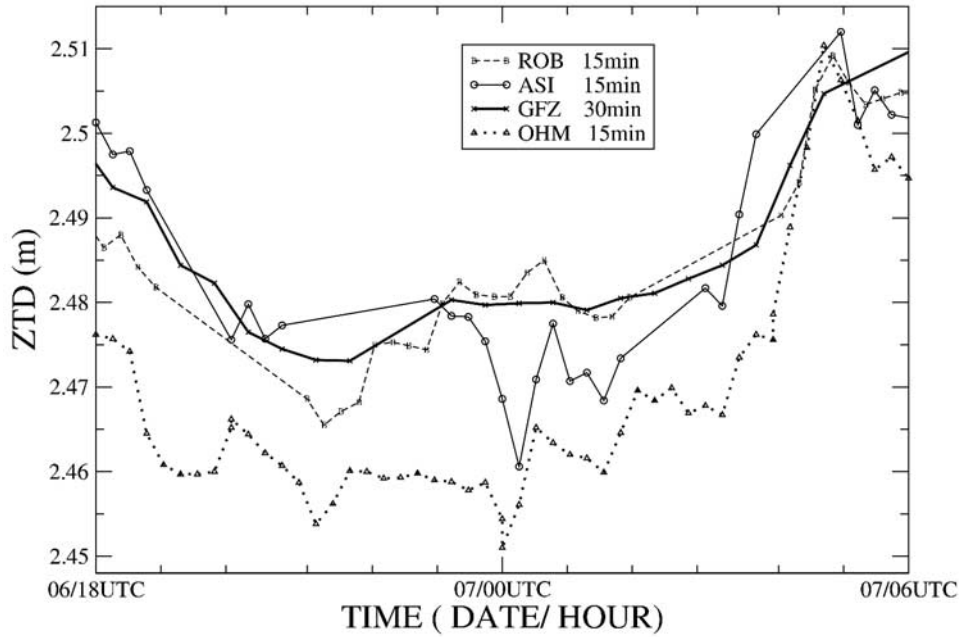


Figure 2. Time series of the GPS ZTD observations at the Genoa, Italy (GENO), station, as processed by ROB (Royal Observatory of Belgium), ASI (Agenzia Spaziale Italiana), GFZ (GeoForschungsZentrum), and the non-real-time OHM-CV postprocessing from 6 September 2005, 18 UTC to 7 September 2005, 06 UTC. The legend indicates the temporal resolution of the data for each processing center.

level. Consequently, when integrating equation (1) down to the precise receiver height, we interpolate or extrapolate model information to this height, using the same assumptions and algorithms as those used for the conventional observations in the IFS/ARPEGE/ALADIN data assimilation systems [Vasiljević *et al.*, 1992]. Specifically, if the GPS station altitude is below the altitude of the model ground surface, we assume a constant specific humidity and a constant temperature gradient and use the hydrostatic equation in order to estimate the model contribution down to the height of the GPS station. Otherwise, i.e., if the receiver is located above the model lowest level, the model values at the height of the station are determined by interpolation from the two adjacent levels and the integration stops at the GPS station height.

[15] We add also the contribution of the atmosphere located above the top of the model, applying Saastamoinen's [1972] formula at the top of the model

$$\Delta ZTD_{TOP} = 10^{-6} \frac{k_1 R_d p_{TOP}}{g_{TOP}} \quad (2)$$

where p_{TOP} is the pressure at the top of the model (in hPa), and the gravity acceleration at the top of the model g_{TOP} (in m s^{-2}) is given by $g_{TOP} = 9.784(1 - 0.00266 \cos 2\phi - 0.00028 \cdot 10^{-3} \cdot H)$ [Davis *et al.*, 1985], where ϕ is the latitude and H is the height at the top of the model (in m). This ZTD contribution outside the model vertical domain is estimated to be about 2.3 mm for Mediterranean regions with $p_{TOP} = 1$ hPa for the ALADIN model.

[16] In variational schemes, the minimization of the cost function involves the tangent linear models of the observa-

tion operators and their adjoint. The tangent linear model of the observation operator described above, as well as the adjoint of this tangent linear model, have been developed and validated using an ensemble of random perturbations around a standard atmosphere, following the same method as described by Poli *et al.* [2007].

[17] As stated earlier, one GPS station can be processed by several GPS processing centers, resulting in several ZTD time series for a given station. However, large discrepancies may occur between the different GPS ZTD solutions. For instance, Figure 2 displays the GPS ZTD observations as processed by four centers for the Genoa station (GENO) in Italy during the September 2005 heavy precipitation event. All centers do not process the data at the same time frequency (from 60 minutes for the BKG center to 15 minutes for the ROB and ASI centers). The occurrences of data gaps (i.e., missing data) are also different between centers. Differences on the order of 10 mm are not rare between center solutions for a given station, and reach in the example shown here about 30 mm on 7 September 00 UTC. These departures between centers are not uniform in time. The differences between the processing strategies (including different time resolutions and different sources for the ancillary information such as GPS satellite orbits for example) may contribute to these differences. For instance, one reason that can explain the differences between the OHM-CV postprocessed data and the other computations is that more precise satellite orbits are used to produce the OHM-CV solution. For data assimilation, we choose to retain only one solution per station for the whole period, because this guarantees a consistent data set for a given station. We select a priori the stations following the preprocessing

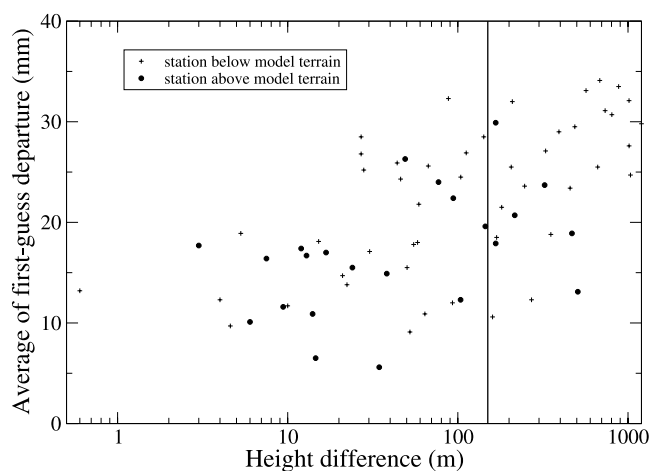


Figure 3. Average of the absolute value of the first-guess departure from 15 August to 30 September 2005 as a function of the height difference between station and model terrain for all the stations processed by the Swiss center Bundesamt für Landestopographie (LPT), mainly located in Switzerland. Stations above (below) the model terrain are plotted as bullets (crosses). The vertical solid line indicates the 150-m threshold above which stations are not selected for data assimilation.

developed by *Poli et al.* [2007] for a global data assimilation system, with some adaptations for the higher-resolution data assimilation system employed in the present study. The preprocessing selects a pair of station center if it passes the following checks.

[18] Step 1: The first-guess departures follow a Gaussian distribution, according to the Kolmogorov-Smirnov test with p values bigger than 0.05 (95% confidence). The first-guess departure is defined as the difference between the observed GPS ZTD and the model equivalent ZTD computed from the 6-hour ALADIN forecast which acts as the first guess in the assimilation cycle. The first-guess departures used for that preprocessing are computed from 15 August to 30 September 2005, for each available station-center combination.

[19] Step 2: The difference between the station height and the model terrain is less than 150 m. Even though the altitude difference is considered in the observation operator, large discrepancies can lead to an erroneous estimation of the model equivalent ZTD. For example, the boundary layer characteristics in a valley can differ significantly from those at higher altitudes. Figure 3 shows the mean of the first-guess departures between 15 August–30 September 2005, as a function of the height difference between the GPS station and the model surface. This plot considers only the stations located mainly over the Swiss mountainous regions. Stations below the model terrain are more frequent as they are located in valleys not described by the model resolution. The first-guess departures clearly increase with the difference between the station height and the model surface height. This justifies rejecting stations far from the model ground surface.

[20] Step 3: The time availability of the GPS ZTD data for a station-center pair during the whole period considered here is more than 40%.

[21] Step 4: If there are still several centers processing a given station, we retain either the processing center for which the standard deviation of the first-guess departure is the smallest or the processing center for which the first-guess departures are closest to a Gaussian distribution.

[22] A horizontal thinning is also applied to reduce the horizontal data density to the model horizontal resolution (minimum distance of 10 km between two selected stations). In the end, we retain 262 stations out of 481 stations.

[23] Moreover, for the assimilation, the observation has to meet the hypothesis of unbiased errors. To ensure that, the ZTD data are bias corrected before the assimilation following the method used by *Poli et al.* [2007]. The bias is calculated for each station-center pair from a 15-day average of observed GPS ZTD minus first-guess model equivalent ZTD between 15 and 31 August 2005. Then, it is removed from the GPS ZTD observation before assimilation, assuming a constant value in time. The average bias for all the stations is about 10 mm, up to 25 mm for some stations. We assume a GPS ZTD observation error standard deviation of the same order, i.e., 10 mm for all stations.

[24] Within the assimilation window which extends between ± 3 hours around the analysis time, only the GPS ZTD observation closest to the analysis time is selected. In practice over the whole month of September 2005, the selection of the closest observation in time means that the time difference between the analysis and the observation doesn't exceed 5 minutes for half of the observations and 15 minutes for 95% of the observations.

2.4. The 2.4-km Meso-NH Forecast System

[25] The impact on the convective-scale rainfall forecast is assessed with the research nonhydrostatic mesoscale model Meso-NH [*Lafore et al.*, 1998]. Meso-NH is run on two nested grids at 9.5-km and 2.4-km resolution respectively. Two-way nesting is performed in such a way that the coarser grid provides the lateral boundary conditions to the finer grid, while the variables of the coarser grid are relaxed toward the finer grid's values on the overlapping area. The coarser Meso-NH domain matches the ALADIN domain, excluding the eight outermost ALADIN grid points. The finer-scale Meso-NH domain is centered over the North-western Mediterranean. The 9.5-km 3DVAR ALADIN analyses are interpolated to the 9.5-km and 2.4-km Meso-NH domain to provide the Meso-NH initial conditions. The 6-hourly 3DVAR ALADIN analyses, linearly interpolated in time, provide also the lateral boundary conditions of the 9.5-km Meso-NH domain. Wave-radiation open boundary conditions are used, combining with a Davies type flow relaxation toward the 3DVAR ALADIN analyses on the six outermost Meso-NH grid points.

[26] The Meso-NH prognostic variables are the three components of the wind, the potential temperature, the turbulent kinetic energy and the mixing ratios of six water species (water vapor, cloud water, rainwater, primary ice, graupel, and snow). The water prognostic equations are governed by a bulk microphysical scheme [*Caniaux et al.*, 1994; *Pinty and Jabouille*, 1998]. For the coarser grid, the subgrid-scale convection is parameterized following *Bechtold et al.* [2001]. For the finer grid, no deep convection scheme is used. This model configuration has been already tested with success for simulation of Mediterranean

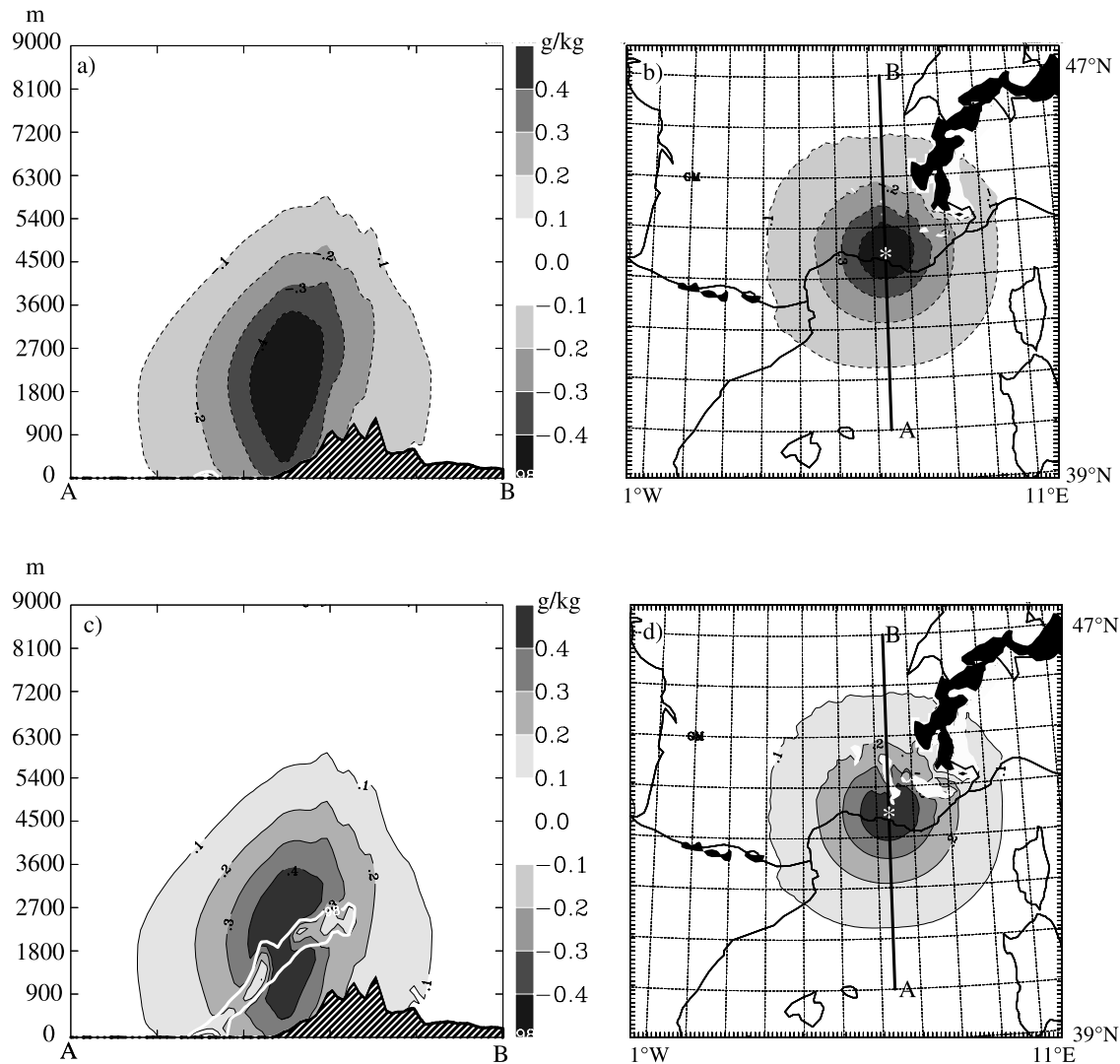


Figure 4. Analysis increment for specific humidity (in g/kg) induced by the assimilation of a single observation. Figures 4a and 4c show a vertical cross section along the AB axis represented in Figures 4b and 4d, which show the horizontal distribution at 2500-m altitude. For Figures 4a and 4b (Figures 4c and 4d), the single observation is located 50 m below (respectively, above) the model surface. The observation location is indicated by the white star in Figures 4b and 4d. Areas with relative humidity larger than 100% in the analysis are delineated by thick white lines in Figures 4a and 4c and by white areas in Figures 4b and 4d. Areas with model terrain above 2500-m altitude are indicated in black in Figures 4b and 4d.

intense rainfall events [Ducrocq et al., 2002; Nuissier et al., 2008].

3. Assimilation Experiments

3.1. Single Observation Analyses

[27] We first perform 3DVAR ALADIN analyses with only one GPS ZTD observation in order to document the

influence of this observation type on the model analyzed variables in the spatial domain. Twin single observation experiments are performed assuming the same observed ZTD value at the same horizontal location, but at station heights located 50 m above and below the model terrain. The value of observed ZTD in the two experiments is set to the first-guess model value assuming a station at the height of the model terrain (i.e., ZTD = 2.417 m). When the station

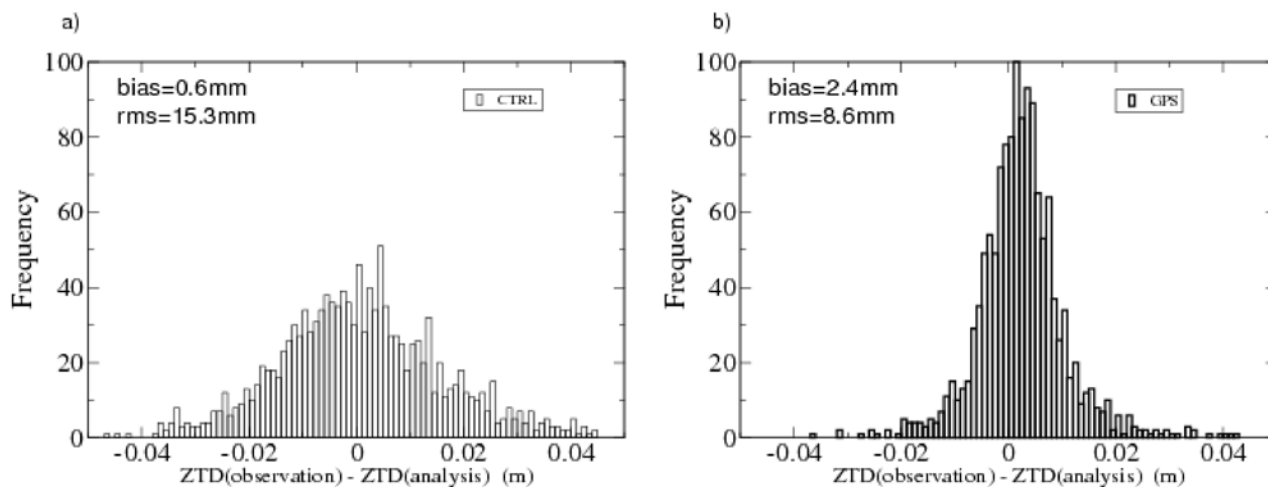


Figure 5. Histogram of the distribution of the differences between the observed ZTD and the analysis equivalent ZTD for all the GPS stations assimilated in the 00 UTC and 12 UTC analyses from 00 UTC, 5 September to 00 UTC, 9 September 2005 for (a) the CTRL assimilation cycle and (b) for the GPS assimilation cycle. The bias and the root mean square are indicated for both cycles (top left).

is below the model terrain, the observed ZTD is therefore smaller than the model equivalent ZTD at the height of the station. The ZTD first-guess departure is of -16.0 mm in that case. On the opposite, when the station is above the model ground surface, the observed ZTD is greater than the model equivalent ZTD, with a ZTD first-guess departure of $+16.1$ mm. The similarity of the magnitudes of the first-guess departures suggests a symmetric behavior of the observation operator in interpolating and extrapolating model information to the GPS station height. After assimilation, the departure of the ZTD observation from the analysis is reduced to -3.2 mm ($+3.4$ mm) for the experiment with the station located below (respectively, above) the model terrain. The main impact is found on the humidity field: the differences between analyses and first-guess (called analysis increments) are only marginal for temperature, pressure and wind. Figure 4 shows the analysis increment for the specific humidity for the two experiments. In the vertical domain, the influence of the observation is concentrated in the lower part of the atmosphere, with a maximum increment around 2–3-km altitude (Figures 4a and 4c). The horizontal extent of the increments, which is defined as the half width at half maximum, does not exceed 100 km around the observation location (Figures 4b and 4d). The twin experiments give almost symmetric increments, with a drying of the atmosphere when the observed ZTD is smaller than the first-guess value (Figures 4a and 4b) and a moistening otherwise (Figures 4c and 4d). Note that the humidity in the analysis is not allowed to exceed the saturation level, thus explaining why the increments are not completely symmetric between the twin experiments.

3.2. Assimilation Cycle Experiments

[28] Two sets of six-hourly forecast-analysis cycles are run from 1st to 30th of September 2005 with the 3DVAR assimilation system. The first cycle, hereafter called CTRL, includes the usual observations assimilated by the operational 3DVAR ALADIN. For the GPS cycle, we add the

GPS ZTD observations of the 262 station-center pairs. The Meso-NH model is not run in these experiments.

[29] Figure 5 shows that the analyses of the GPS assimilation cycle match the GPS ZTD observations better than the analyses of the CTRL assimilation cycle. However, the fit of the analyses and of the ALADIN 6-hour forecasts to the other assimilated observations remains mostly unchanged between the CTRL and the GPS cycle, except for the specific humidity observed by radio sounding. Figure 6 shows statistics for the whole month of September 2005, over the ALADIN domain, comparing GPS and CTRL 6-h forecasts with specific humidity observations from 64 radio-sounding sites. The radio-sounding observa-

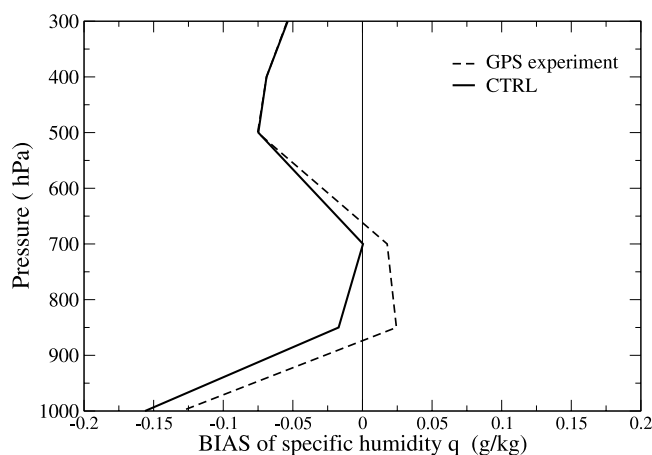


Figure 6. Specific humidity bias as a function of pressure level for the 6-hour ALADIN forecast against radio-sounding observations from 64 radio-sounding stations. Statistics are for the 1-month period from 1 to 30 September 2005 over the ALADIN domain. The dashed line (solid line) shows the 6-hour ALADIN forecast from the GPS (CTRL) assimilation cycle.

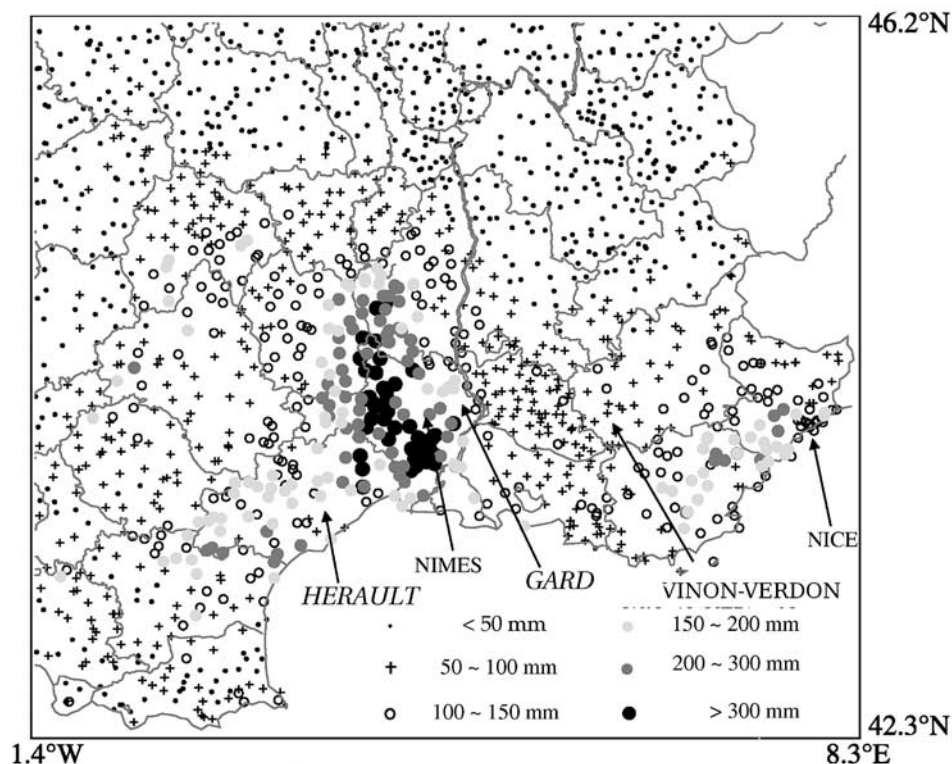


Figure 7. Map of the 4-day accumulated surface rainfall (in mm) from 5 September 2005, 06 UTC to 9 September 2005, 06 UTC over southeastern France from the Météo-France rain gauge network. The thin lines delineate the French administrative departments with the Herault and Gard departments indicated. Also indicated are the locations of the rain gauge stations of Nîmes, Vinon-Verdon, and Nice whose data are displayed in Figure 8.

tions have the drawbacks to be not independent data as they are used in the assimilation cycles and to suffer from dry and wet biases depending on the characteristics of the sondes [Cady-Peirera *et al.*, 2008; Suorti *et al.*, 2008], but they are the only type of observations readily available that allow us to assess the impact of assimilating GPS on the whole vertical profile of humidity in the area and time period of interest. In the lower troposphere, below the 850 hPa pressure level, both CTRL and GPS present an overall negative bias as compared to radio soundings, which suggests an underestimation of humidity in the lower troposphere by both cycling experiments. A smaller bias is found with the GPS experiment for levels below the 850 hPa level as well as above 700 hPa. Between these two pressure levels, the GPS 6-hour ALADIN forecast tends to be too humid. Note however that these differences are about one order of magnitude smaller than the standard deviation.

4. Case Study: 5–9 September 2005

4.1. Description of the Event

[30] Between 5 to 9 September 2005, several precipitating systems affected Southeastern France and Corsica. The accumulated rainfall during the total period was over 300 mm over a significant part of the region, reaching locally more than 500 mm near Nîmes (location indicated in Figure 7). Two main events may be distinguished in this precipitating period as shown by Figure 8a. During the night

of 5 to 6 September, heavy precipitation started in the East of the Hérault department and the West of the Gard department and continued in these areas during the following day. For this episode, the accumulated rainfall reached 320 mm near Nîmes (Gard department). Only weak precipitation was then observed on 7 September over the region. Then, in the morning of 8 September, convective precipitation coming from the Mediterranean Sea affected the Gard department again. The intensity of the precipitation strengthened during the afternoon. For this second heavy rain event, the accumulated rainfall reached about 220 mm near Nîmes.

[31] Figure 9 shows the upper-level large-scale situation associated with this precipitating event. A cold upper-level low-pressure center located over the near Atlantic generated a rapid cyclonic upper-level flow over Western France on 5 September 2005. On 7 September, the low-pressure system moved toward the South–East to reach Spain. At low levels (not shown), a low-pressure center over Eastern Spain and the Balearic Isles deepened and generated a low-level southerly flow over the Mediterranean. A frontal system with embedded convection over Southern France was responsible for the heavy precipitation during the first event. Then, from 7 to 9 September 2005, the cold upper-level low-pressure center moved slowly northward to be located over the Gulf of Lion and Catalonia on 8 September. A diffluent upper-level southerly flow prevailed over the region, associated with low-level moist and warm south-

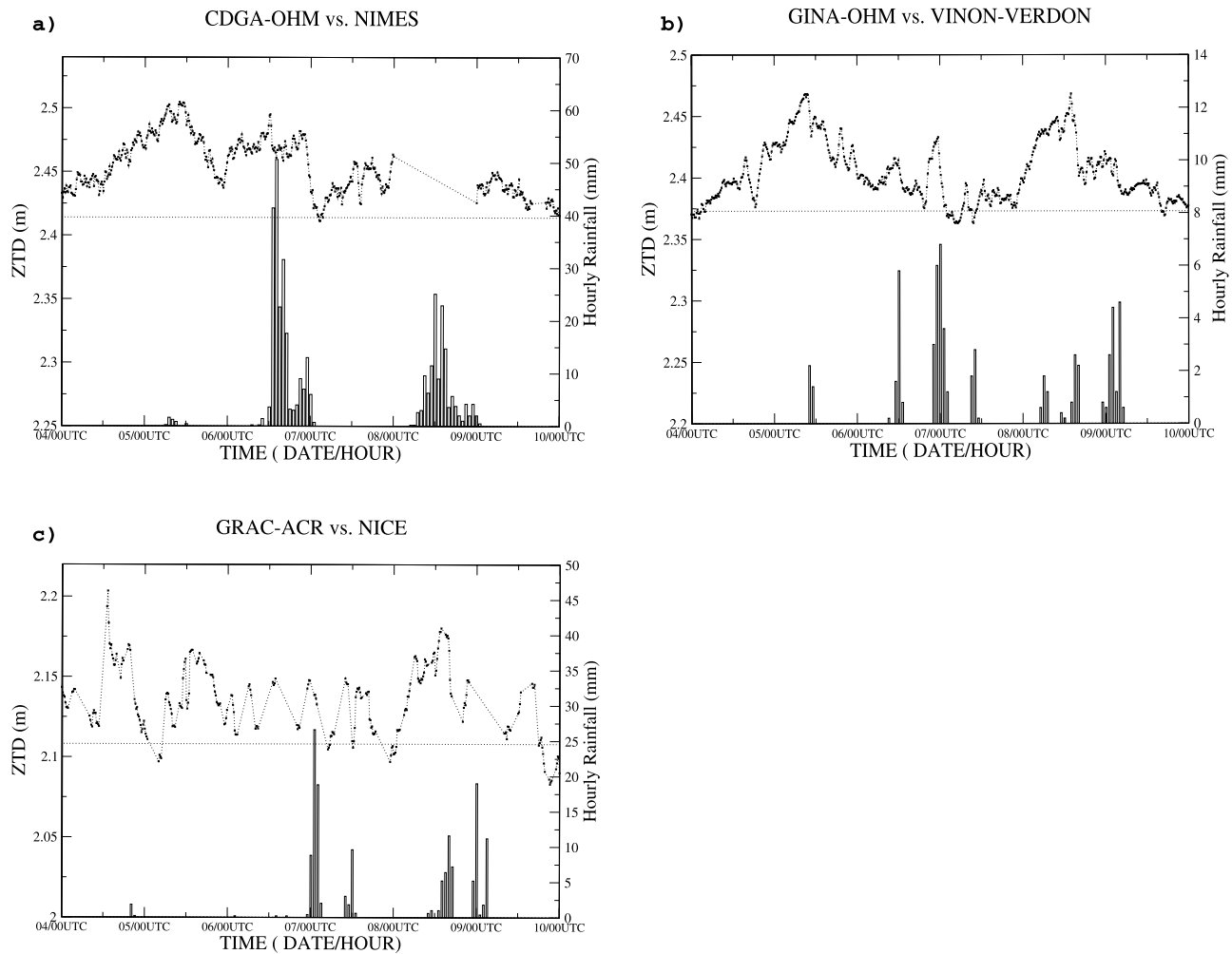


Figure 8. Hourly precipitation (vertical bars, in mm) at (a) Nîmes, (b) Vinon-Verdon, and (c) Nice rain gauge stations (see Figure 7 for the location) from 4 September 2005, 00 UTC to 10 September 2005, 00 UTC. The GPS ZTD (m) observations from nearby GPS stations are plotted as thick dots. The horizontal dashed line indicates the mean ZTD value for the time period 15 August 2005–30 September 2005.

easterly winds. This constituted a propitious environment for development of deep convection over the region. The upper-level low-center evolved into a secondary trough during the 9 September, with less propitious synoptic conditions for further convective development.

4.2. Impact of the GPS Assimilation on the 9.5-km ALADIN Analyses and Forecasts

[32] The GPS ZTD time series from selected stations in Southeastern France are displayed in Figure 8: the stations identified as CDGA, GINA, and GRAC are close to the rain gauge stations of Nîmes, Vinon-Verdon, and Nice, respectively (see Figure 7 for locations). These three stations report high ZTD values during the rainy period, larger than the average ZTD value found for the 15 August 2005 to 30 September 2005 period. High values of GPS ZTD reveal large tropospheric water vapor contents associated with the precipitating systems over the region. Note that the maximum values of GPS ZTD are often but not systematically associated with the hourly precipitation peaks.

[33] Figure 10 provides a representation of the modifications induced by the assimilation of GPS ZTD data on

parameters related to deep convection during the intense rainfall event. The IWV, the Convective Available Potential Energy (CAPE), and a vertical cross section of relative humidity issued from the GPS ALADIN analysis are displayed for 00 UTC, 6 September 2005. The differences between GPS and CTRL analyses for these parameters are also shown. Large values of IWV are associated with the rainy frontal system. The GPS assimilation cycle produces larger IWV within the rainy system as compared to the CTRL, but it also reduces moisture content eastward of the frontal system. The assimilation at 00 UTC, 6 September 2005, of GPS ZTD observations with high ZTD values partly explains the moistening of the analysis in the area of the frontal system, but is not the unique reason for the differences. Indeed, the first guess used to issue the GPS and CTRL analyses are also different, as they result from different 6-hourly assimilation cycles started 6 days prior to the event. Large values of CAPE are present over the Mediterranean Sea and feed the convection embedded within the southern tip of the frontal system. High CAPE values are also apparent at the leading edge of the frontal system over France. The GPS assimilation cycle tends to

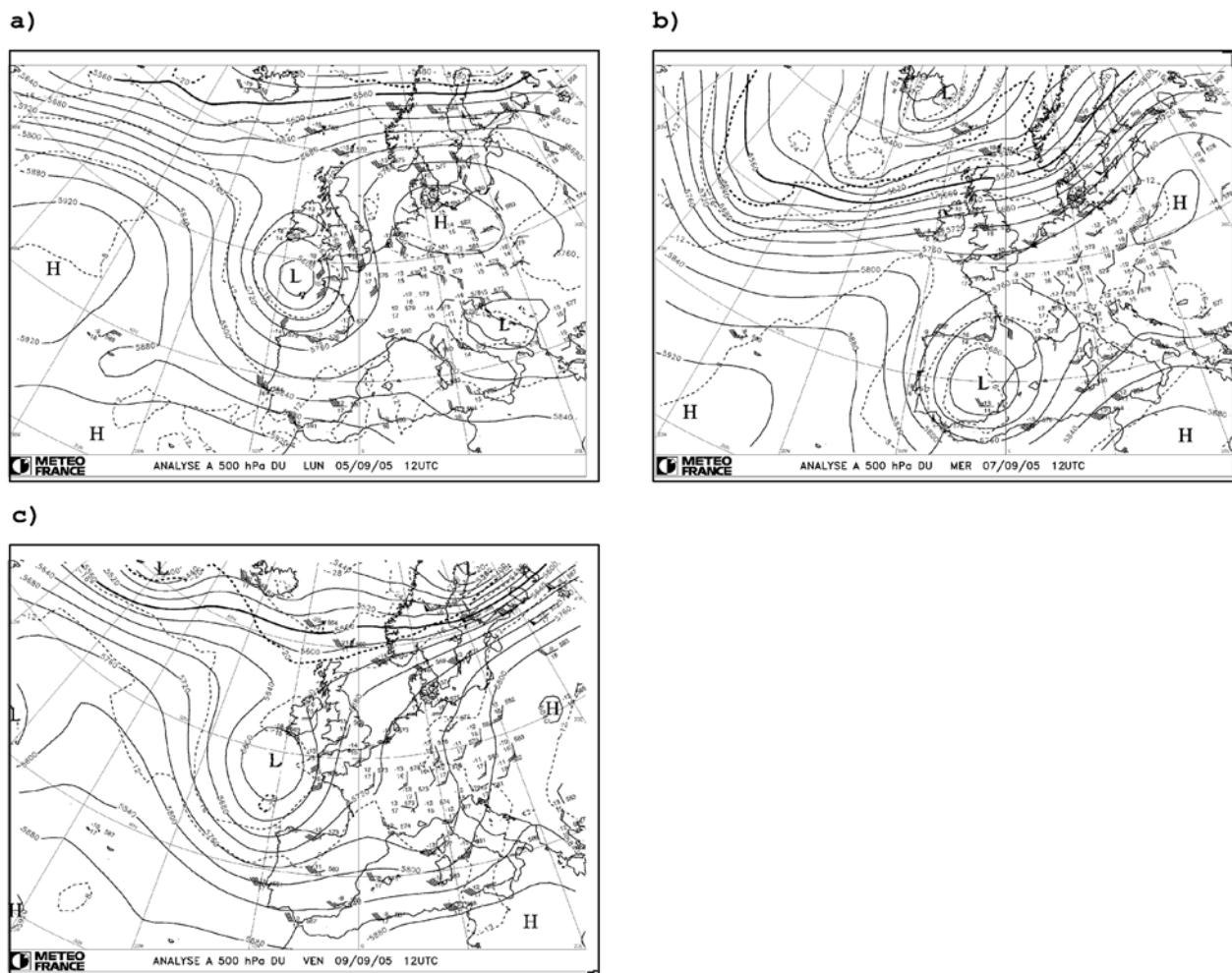


Figure 9. Maps of 500-hPa geopotential heights (solid lines) and temperatures (dashed lines) valid at 12 UTC on (a) 5 September 2005, (b) 7 September 2005, and (c) 9 September 2005.

enhance the CAPE at the leading edge compared to the CTRL. The vertical cross section of relative humidity shows an increase of tropospheric moisture associated with the frontal system in the GPS analysis.

4.3. Impact of the GPS Assimilation on the 2.4-km Meso-NH Forecasts

[34] In order to assess the impact of mesoscale assimilation of GPS ZTD observations on the convective-scale forecast of the 5–9 September 2005 heavy precipitation, we perform two sets of high-resolution simulations with the Meso-NH model. We use as initial and boundary conditions the GPS and CTRL 3DVAR ALADIN analyses, respectively. The two forecast trials are conducted every 12 hours from 00 UTC, 5 September to 00 UTC, 9 September 2005 with each run lasting 18 hours. Meso-NH simulations starting from analyses issued from the CTRL (GPS) ALADIN assimilation cycle are called hereafter MCTRL (respectively, MGPS). We focus here on the results of the 2.4-km horizontal resolution forecast runs.

[35] Using as initial conditions an analysis with GPS ZTD data assimilation does not drastically change the high-resolution forecast of the heavy rain episode. However, significant local differences are found. Figure 11 provides

an illustration of the Meso-NH runs issued from ALADIN analyses valid at 00 UTC, 6 September 2005. The MGPS run produces less frontal precipitation in the North of the domain. The bias computed for this time period confirms that MGPS presents a slightly better forecast than MCTRL.

[36] An objective verification is provided by Quantitative Precipitation Forecast (QPF) scores computed over the total rainy period for each 6-hour accumulated precipitation (i.e., 0–6 h, 6–12 h and 12–18 h forecast range) using rain gauge observations as a verification. Figure 12 shows the Equitable Threat Score (ETS), the Probability of Detection (POD) and the False Alarm Rate (FAR), for precipitation events with observed rainfall in excess of 0.1 mm, 0.5 mm, 1 mm, 5 mm, 10 mm, and 20 mm. The ETS can range from $-1/3$ to 1, with a perfect score of 1. From Figure 12, we can see that the ETS is generally better in both experiments for smaller thresholds than for larger thresholds, reflecting the fact that strong rainfall events are usually poorly predicted. The MGPS experiment shows an improved ETS forecast skill for all the thresholds as compared to the MCTRL experiment. The POD which can range from 0 to 1, with a perfect score of 1, is the rate of observed rain events that are correctly predicted. The FAR, which can also range from 0 to 1, but with a perfect score of 0, is the rate of predicted

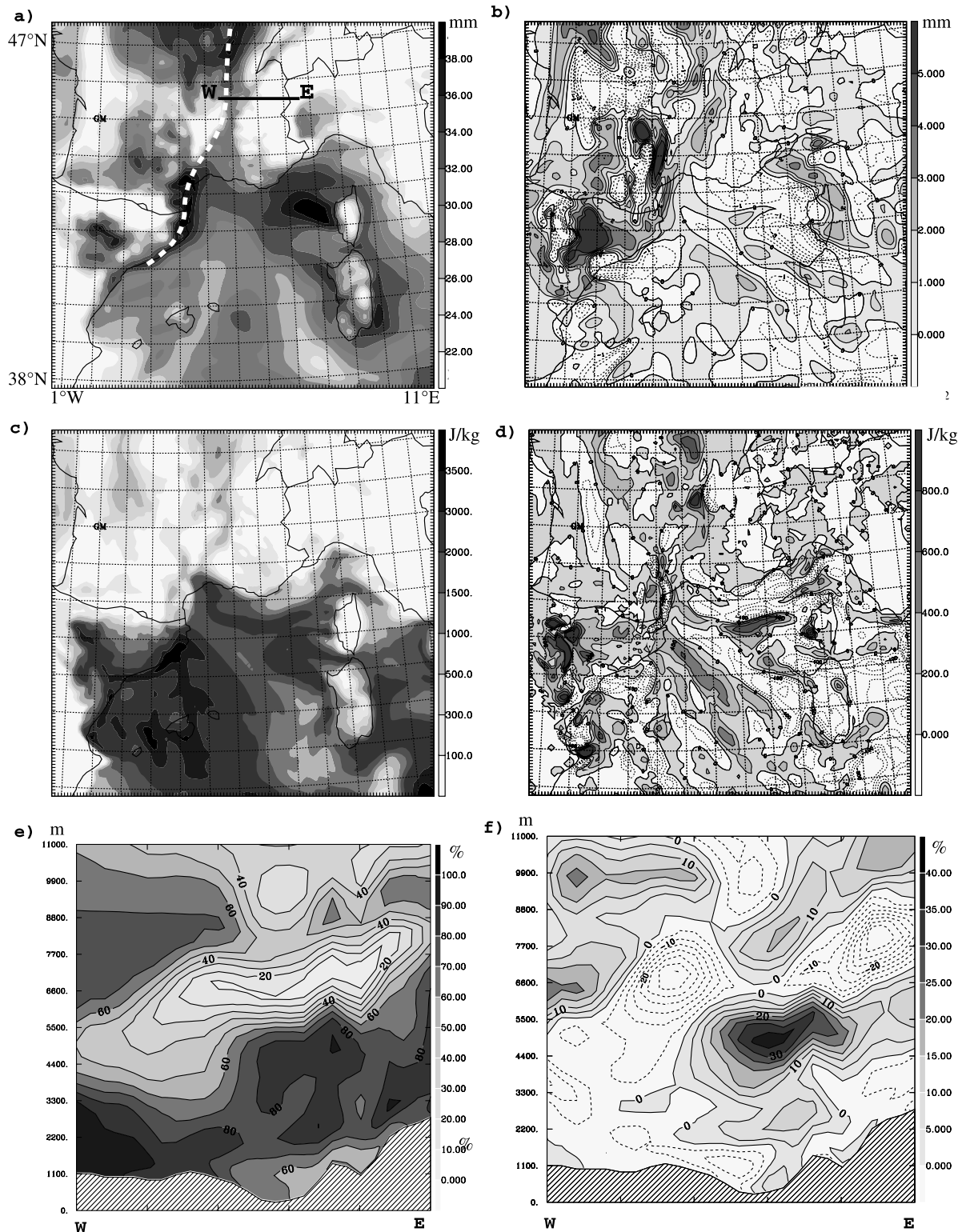


Figure 10. ALADIN analyses at 00 UTC, 6 September 2005: (a) Integrated Water Vapor (IWV, in mm) from GPS analysis; (b) IWV differences between GPS and CTRL analyses (positive values in shaded tones, negative values in dashed lines with 1-mm intervals); (c) CAPE (in J/kg) from GPS analysis; (d) CAPE differences between GPS and CTRL analyses (positive values in shaded tones, negative values in dashed lines with 200 J/kg intervals); (e) vertical cross section of relative humidity (%) from GPS analysis; (f) vertical cross section of relative humidity differences between GPS and CTRL analyses (positive values in shaded tones, negative values in dashed lines with 5% intervals). Figure 10a shows the location of the cross section axis (W–E black solid line) and the surface front (dashed white line).

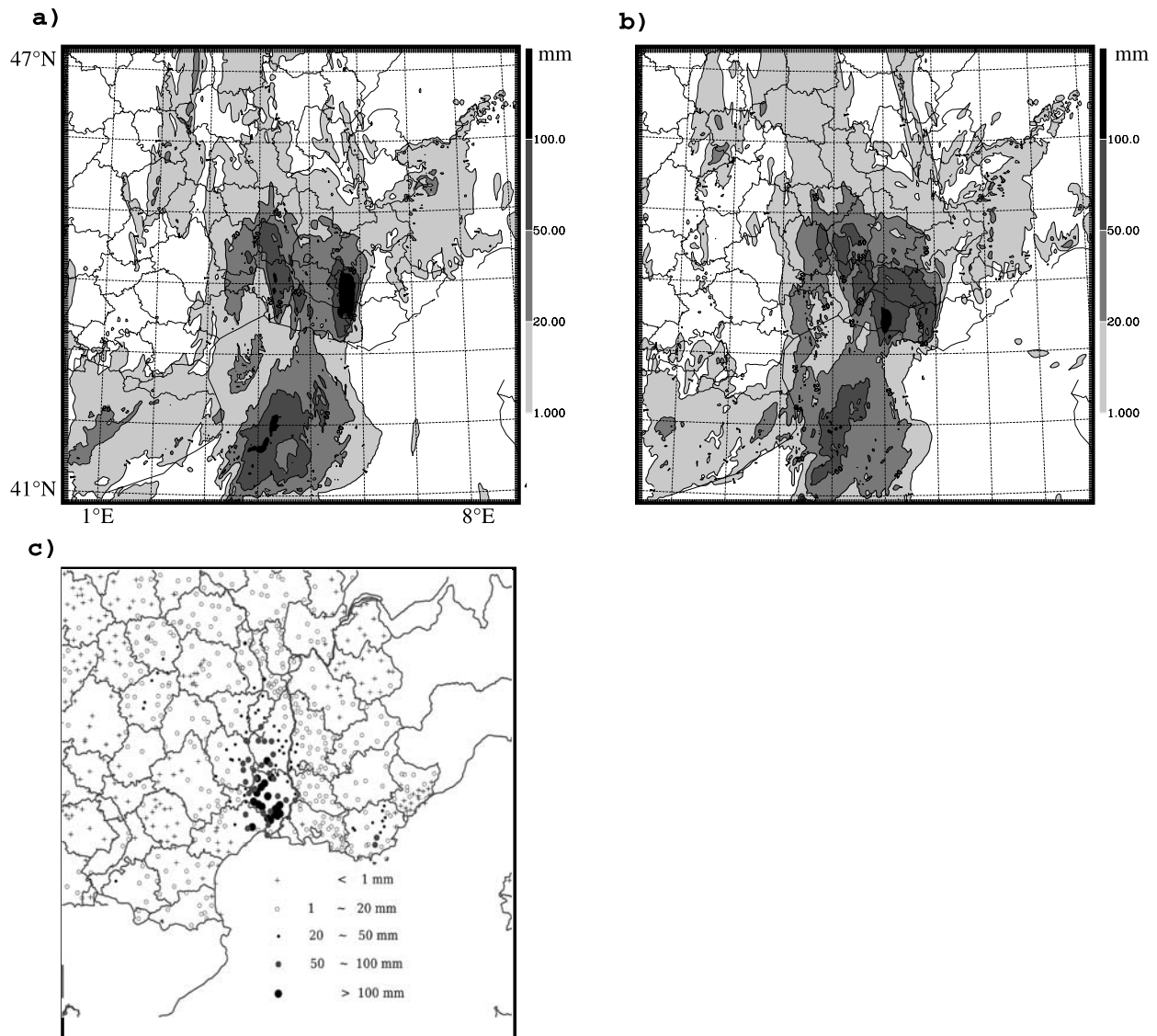


Figure 11. Maps of the 12-hour accumulated precipitation (in mm) from 03 UTC to 15 UTC, 6 September 2005 for (a) MGPS forecast run starting from the GPS analysis at 00 UTC, (b) MCTRL forecast run starting from the CTRL analysis at 00 UTC, and (c) rain gauge observations.

rain events that are not observed. The FAR and the POD scores should be examined in conjunction. Here, the POD and the FAR values are also better for MGPS than for MCTRL for all the thresholds. Overall, the addition of GPS ZTD data in the assimilation modifies the initial conditions so that the 6-hour accumulated precipitation forecast skill is then improved, as verified by comparison to rain gauge observations.

4.4. Discussion

[37] The one-month-long 3DVAR ALADIN assimilation experiment GPS remains very close to the CTRL experiment, except for the moisture field. This conclusion is reached on the basis of comparisons with GPS ZTD and radio-sounding humidity observations. Radio-sounding observations are not totally independent observations as they are used in the both assimilation cycles and can have also some dry or wet bias depending of the sonde character-

istics, but they constitute the only available reference for the humidity profile.

[38] On the basis of the objective and subjective verifications of the 2.4-km forecasts for the event of 5–9 September 2005, the MGPS forecast performs better than the MCTRL forecast as regards precipitation. It seems that the impact of adding GPS ZTD observations is to modify the moisture field transported northward from the Mediterranean Sea; the convective-scale forecast then makes use of that information to simulate precipitation that is more in line with the reality (as reported by rain gauge observations). In the light of these elements, it could be even more useful to assimilate GPS ZTD observations over the Mediterranean Sea (i.e., upstream of the precipitating systems). However, no such observations are available today.

[39] We add a word of caution to mention that different results could be obtained in different meteorological situations, as is always the case with atmospheric studies, and

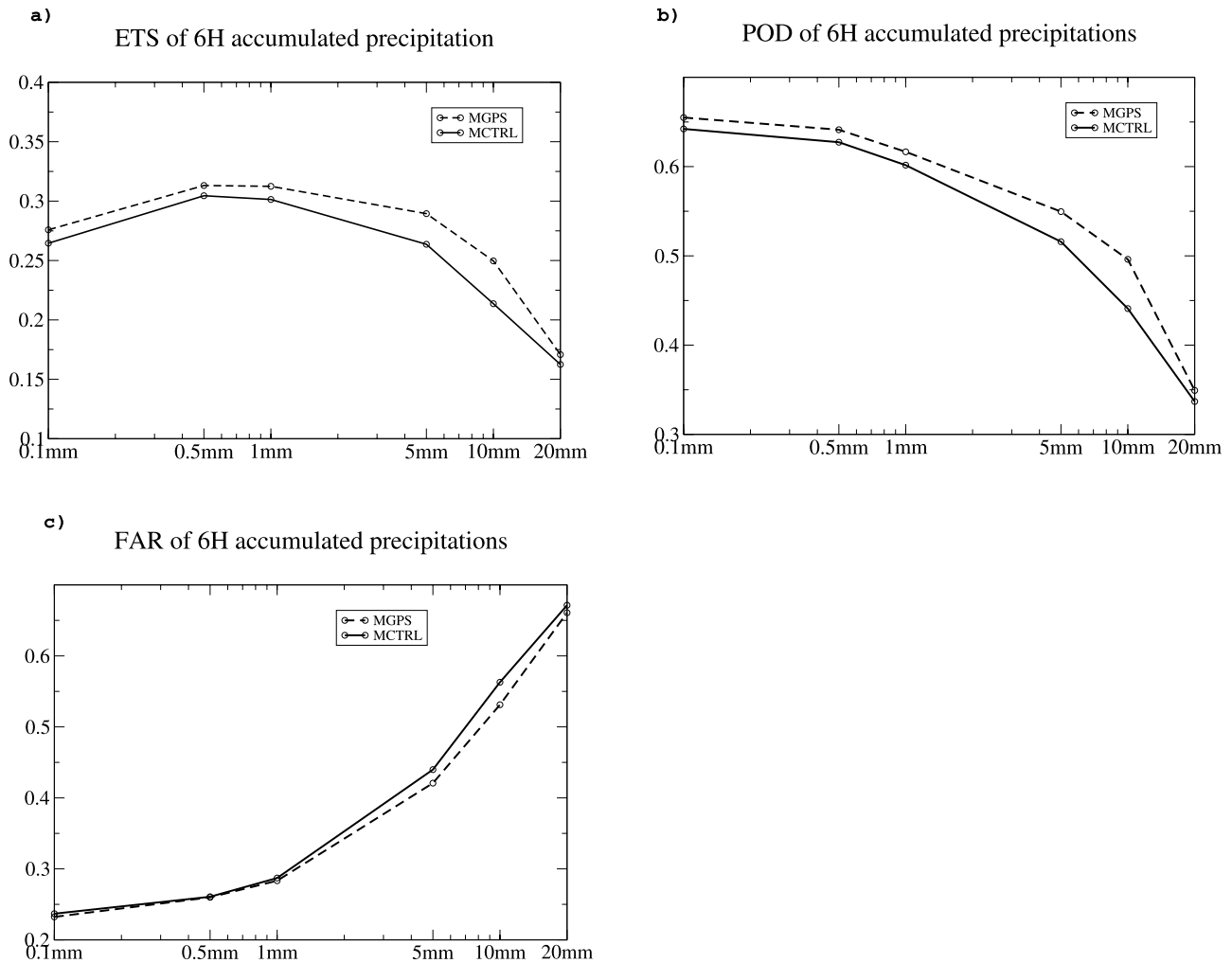


Figure 12. Quantitative scores against observations for the 6-hour accumulated precipitation for all the MGPS (dashed line) and MCTRL (solid line) forecast runs from 00 UTC, 5 September 2005 to 18 UTC, 9 September 2005: (a) Equitable Threat Score (ETS), (b) Probability of Detection (POD), and (c) False Alarm Rate (FAR) are displayed for the 0.1-, 1-, 10-, and 20-mm thresholds. The scores are computed for a geographical domain with latitudes between 46°N and 42°N and longitudes between 2°E and 8°E .

in particular with limited-area modeling studies. The representativeness of the present results could be assessed by investigating several events over the same domain, or by investigating different events at about the same time but over different domains. However, because of the inherent nature of limited-area modeling, both ventures are technically difficult to pursue as the experimental setup requires special preparation for each time period and geographical domain, and is furthermore CPU consuming. This limitation will be addressed when a next generation high-resolution assimilation and forecast model with explicit convection and efficient numerical schemes becomes available in operations. It will thus become easier to run it on different time periods.

5. Conclusions and Future Work

[40] We have investigated the impact of assimilating GPS ZTD data with a 3DVAR mesoscale data assimilation system. The single observation assimilation experiment

showed that the assimilation of GPS ZTD leads mainly to a modification of the moisture field in the mid-to-low troposphere within a radius of about 70 km around the GPS station location. The assimilation of a large number of GPS ZTD data (more than 250 stations over Western Europe, from the E-GVAP operational network and the OHM-CV research network) together with the other observations operationally assimilated by the 3DVAR ALADIN data assimilation system has been performed for the month of September 2005. The scores computed for the 6-hour first-guess fit to the observations for the whole month point out a slight positive impact for the low-level specific humidity, using radio soundings for validation.

[41] Then, the impact of the GPS ZTD assimilation on the convective-scale forecast of the 5–9 September 2005 Mediterranean heavy precipitation event has been assessed. The 3DVAR ALADIN analyses issued from the two assimilation cycles (with, and without GPS ZTD data assimilation) were used as initial conditions to issue high horizontal resolution (2.4 km) mesoscale nonhydrostatic forecasts with

the Meso-NH atmospheric model. For the whole rainy period, from 5 September to 9 September 2005, two 18-hour-duration Meso-NH runs were issued every day at 00 and 12 UTC. An overall slightly positive impact on the fine-scale precipitation forecast was found, both subjectively and objectively, by comparison with rain gauge observations over the area.

[42] Although this was not yet the case in 2005, the E-GVAP GPS ZTD data have been assimilated in the operational 3DVAR ALADIN system after September 2006. The present study, focused on September 2005, shows that a larger benefit is gained as regards the prediction of intense rain events when the analysis obtained after GPS ZTD assimilation is used by a convective-scale forecast model.

[43] On the basis of these encouraging results, future work will focus on the assimilation of GPS ZTD data directly into the convective-scale high-resolution model. The 2.5-km resolution 3DVAR assimilation and forecast system AROME (Applications of Research to Operations for Mesoscale) is planned to become operational at the end of 2008. It is expected that a finer-scale model will allow reducing the height differences between the GPS station and the model orography, therefore reducing errors due to the interpolation/extrapolation of the model fields above/below the model terrain inside the GPS ZTD observation operator. The benefit of a finer-scale first guess on the assimilation process will also be assessed, and we hope to benefit from a more frequent update cycle (3 hours). Another topic of interest is the potential impact of GPS ZTD data that could be collected in the future by platforms deployed in the Mediterranean Sea, either on buoys or on ships, for example within the future HyMeX (Hydrological Cycle in the Mediterranean eXperiment) field campaign (<http://www.cnrm.meteo.fr/hymex/>).

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