Three-Dimensional Variational Data Assimilation of Ground-Based GPS ZTD and Meteorological Observations during the 14 December 2001 Storm Event over the Western Mediterranean Sea

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Abstract

The impact of GPS Zenith Total Delay (ZTD) measurements on mesoscale weather forecasts is studied. GPS observations from a permanent European network are assimilated into the Penn State/NCAR Mesoscale Model (MM5) using its three-dimensional variational assimilation (3DVAR) system. The case study focuses on a snow storm that occurred during the period of 14-15 December 2001 over the western Mediterranean sea.

The experiments show the most significant improvement in forecast is obtained when GPS ZTD data are assimilated together with local surface meteorological observations into the model within a cycling assimilation framework. In this case, the root-mean-square (rms) differences between forecasted and observed values are reduced by 1.7% in the wind component, 4.1% in the temperature variable and 17.8% in the specific humidity field. This suggests the deployment of GPS receivers at surface stations to better initialize numerical weather prediction models during strong storm mesoscale events.
1. Introduction

The distribution of water vapor is a highly variable function of both time and space, and can correlate poorly with surface humidity measurements. The structure of atmospheric precipitable water strongly reflects the dynamics of the atmosphere. Lack of precise and continuous water vapor data is one of the major sources of error in short-term forecasts of precipitation (Kuo et al. 1993, 1996). Improved monitoring of atmospheric water vapor and its assimilation in Numerical Weather Prediction (NWP) models will lead to more accurate forecasts of precipitation and severe weather. Ground-based techniques such as radiosondes are sensitive to the water vapor content of the atmosphere, but they are expensive to operate, which limits their launches to one or two a day. On the contrary, water vapor radiometers exhibit a very high temporal resolution (1-10 minutes) (Solheim et al. 1998). Their cost, however, currently prohibits their use in dense sampling networks.

Cost effective techniques sensitive to the spatial and temporal distribution of atmospheric water vapor are offered by networks of ground-based GPS receivers. Originally introduced for military purposes, the applications of GPS to environmental studies abound: geodesy, volcanology, oceanography, or glaciology to cite a few (see, e.g., Leick 1990; Dixon 1991). One of the most suitable atmospheric applications of GPS is perhaps the assimilation of water vapor content estimates into NWP and climate models. The fact that GPS can supply these data in near-real time (Rocken et al. 1997), and at low cost is changing, at the algorithmic level, the way these models are being used to assimilate the GPS estimates (Zou and Kuo 1996). For instance, De Pondeca and Zou (2001a) have studied the 4DVAR assimilation of ZTD measurements from a dense GPS network with the Penn State/NCAR MM5 mesoscale model. These authors found that the sole assimilation of the ZTD had a modest beneficial impact on the short-range precipitation forecast and a significant improvement was found when profiler-wind and RASS-virtual temperature observations where also included in the assimilation set-up. However, this
improvement on precipitation forecast skill was reduced when the ZTD was excluded from the set of observations being assimilated into the system.

The aim of this study is to analyze the impact of 3DVAR assimilation of GPS ZTD data gathered from the COST Action 716 “Exploitation of ground-based GPS for climate and numerical weather prediction applications” (e.g., Elgered 2001) on weather analysis and prediction. Our interest is to investigate the impact of the ZTD observations for operational weather forecasting applications. As a consequence, we are not trying to assess the sole impact of GPS observations as a surrogate data set, but we are rather studying how GPS observations can be “best” be combined with other standard meteorological observations already available at weather services. Our criterion to define the term “best” is related to regional model forecast skills and we address this issue by using the MM5 model and its 3-Dimensional variational data assimilation system. This paper describes a series of assimilation experiments that we carried out to study the potential benefit of GPS ground-based observational networks for the prediction of extreme events in the Mediterranean area. The case used in this study is a snow storm that took place over the western Mediterranean during the period of 14-15 December 2001. This area is frequently affected by heavy rainfall over localized areas and which are mostly the results of mesoscale convective systems (Ramis et al. 1994; Romero et al. 1998).

The structure of the paper is as follows: Section 2 describes the meteorological situation under study. An overview of the model simulation and observations used in the experiments is given in Section 3. The 3DVAR assimilation of the GPS observations is described in Section 4. Section 5 analyzes the results from the different experiments. Finally, the main conclusions are presented in Section 6.

2. Case description

The synoptic situation during the days prior to December 14 was characterized by a stationary anticyclone over northern Europe, with a 1042 hPa central pressure (Fig.1), which enhanced the development of a cold air mass over Siberia. Over the course of the preceding week,
the upper-level trough axis and the cold air migrated first from north to south toward Switzerland on December 13, and then to the west, reaching Catalonia (NE of the Iberian Peninsula) on December 14.

The NCEP AVN analysis of the synoptic meteorological conditions on December 14 are summarized in Fig. 2. At 00 UTC (Fig. 2a), at sea level, the high pressure area was located over Denmark (1044 hPa) and moved to Scotland at 24 UTC (Fig. 2c). At the same time, a low pressure area developed in the Mediterranean sea at 00 UTC (Fig. 2a) with a 1008 hPa central pressure over Corsica and a secondary minimum over the Catalan coast at 24 UTC (Fig. 2c). At 850 hPa, the cold sector of the temperature field was located over eastern Europe (Fig. 2b) at 00 UTC. During the following hours, the cold air mass migrated over the western Mediterranean bordering the Pyrenees, cooling northern Catalonia to –10C (The rest of the region recorded temperatures between –5C and –8C during the evolution of the storm as shown in Fig. 2d). At the same time, the low pressure system located over the Catalan east coast advected moist warm air from the Mediterranean sea onto the continent.

Precipitation began early on December 14 over the NE of Catalonia. During the hours that followed, several precipitation areas developed along the Catalan coastal range from North to South (Fig. 3). Due to the low temperatures that developed in the north of Catalonia, snowfall occurred over these areas early in the morning, and then later in the central part of Catalonia around noon (snow accumulations over Catalonia during the whole episode ranged between 10 and 95 cm). During the afternoon of December 14, the cold air mass that impinged on the eastern Pyrenees moved to the SW displacing warmer moist air aloft. The resulting frontal system produced considerable snowfall which intensified the preexisting storm system over the central part of Catalonia. Due to very cool surface temperature, this lead to significant accumulation of snow, even along the coast. The moist air progressed southward on December 15 and the snowfall began in southern Catalonia where the temperatures were already below zero degrees.

3. Methodology
a. Numerical model and simulation characteristics

The NCAR/Penn State MM5 model was used to simulate the meteorological situation under study. The MM5 is a primitive equation, finite-difference, non-hydrostatic, mesoscale model (Dudhia 1993).

We set up three (2-way nested) domains with grid spacing ranging from 54 km (D01), 18km (D02), to 6 km (D03) (Fig. 4). All domains had the same 31 vertical sigma levels. The physical options used were the high-resolution MRF planetary boundary layer, multi-layer soil model, the simple scheme of Dudhia (1993) for explicit moisture parameterization, and the clouds were explicitly solved for the finest domain (D03).

The model simulation was initialized about 12 hours before the onset of the heavy rains that affected Catalonia, at 00 UTC 14 December 2001. The initial and boundary conditions were provided by the NCEP AVN analysis every 12 hours from 00 UTC 14 December to 00 UTC 16 December 2001.

b. GPS and meteorological observations

Based on the entire GPS data set from the COST Action 716, a total of 23 stations were available for the study (Fig. 4). The temporal frequency of the data was around 1 h. The geographical location of the GPS sites tend to be clustered reflecting the various regional initiatives to deploy operational GPS networks, The sampling on the smallest domain 3 is, however, very homogeneous. The maximum altitude difference between the GPS stations is about 1500 m and reflects the complex topography of the Mediterranean coast.

The GPS precise orbits and clocks as well as consistent earth-rotation parameters provided by the International GPS Service (IGS) together with the GIPSY/OASIS-II (version 4) software package (Webb and Zumberge, 1993) were used to estimate the ZD at the GPS sites. The ZTD is the GPS observation used in this study. This measurement is composed of the Zenith
Hydrostatic Delay (ZHD) and the Zenith Wet Delay (ZWD). The ZHD is the largest term and can be accurately calculated if measurement of surface pressure are available (Saastamoinen, 1972). The ZWD is associated with the atmospheric water vapor (Bevis et al. 1992).

The 3DVAR system can assimilate most of the observations simply related to model variables (wind, temperature, pressure, dew point/humidity). In this study, in addition to GPS we have used WMO SYNOP and SHIP surface observations, TEMP radiosondes and rawisonde winds, temperature and relative humidity, PILOT wind observations, AIREP aircraft wind and temperature data, AMDAR wind, temperature and pressure observations, and METAR wind, temperature and humidity data.

To better investigate the potential impact of the GPS data over Catalonia, local surface meteorological observations from the Catalan Weather Service were also assimilated into the model in one of the experiments analyzed in Section 5.

Data assimilation procedure

a. Three-dimensional variational assimilation system

The assimilation system is based on the 3-dimensional variational algorithm in its incremental formulation (Courtier et al. 1994). Such an algorithm has been developed for MM5 in recent years and a technical description can be found in Barker et al. (2003a; 2003b). Briefly described, this is a model space-based multivariate incremental analysis system for observations of pressure, wind, temperature and relative humidity measurements. Currently, the system can assimilate conventional data as noted above. The cost function includes a background and an observational term. The observational error covariance matrix is assumed to be diagonal. The variances are prescribed for each variable and data source according to the observational profile error statistics compiled by NCEP which are available at http://lnx21.wwb.noaa.gov/oberr/reanl-obs.html.

Following Lorenc et al. (2000), the background error covariance matrix is designed so as to
project onto vertical modes allowing for a separate definition of the vertical and horizontal correlation functions. The vertical modes are obtained from the decomposition in EOFs of statistical model forecast error profiles. These profiles were generated by application of the NMC method (Parrish and Derber 1992) to the MM5 real-time system run daily at the US Air Force Weather Agency on a 210 km grid over Europe. Differences between 24 h minus 12 h forecasts valid daily at 12 UTC were averaged in time and space, so as to produce a mean forecast difference profile valid over Europe on a monthly basis. After projection onto the vertical modes, three-dimensional fields are normalized by the square root of the expected variance of the relevant vertical mode. These normalized fields are then passed through a series of recursive filters that create the smoothing effect of a convolution with a covariance matrix. In that particular case, a first order (exponential smoother) filter was repeatedly applied. The filter parameter (Lorenc 1992) was set so as to approximate Gaussian structure functions with an e-folding distance of around 180 km. These values were chosen from the study of Sattler and Huang (2002). The basic assumption under the application of the filter is that horizontal model forecast error correlations are homogeneous and isotropic.

A weak balance constraint is applied to the analysis through the choice of the analysis or control variables. In our application the model variables: wind, pressure, temperature and water vapor mixing ratio are transformed into unbalanced stream function, velocity potential, unbalanced pressure and relative humidity. This choice of control variables follows Lorenc at al. (2000) and was motivated by their relative independence, so that correlations between analysis variables can be neglected in the background covariance matrix. The square root of the background covariance matrix is used as preconditioning.

b. Assimilation of GPS observations

Assimilation of GPS ZTD observations is performed by addition of a new term in the cost function to the already existing background \( J_b \) and conventional observation \( J_{\text{conv}} \) terms:

\[
J \left( x' \right) = J_b + J_{\text{conv}} + J_{\text{GPS}}
\]
This new term $J_{GPS}$ is defined as:

$$J_{GPS} (x') = \frac{1}{2} (Hx'-y^0)^T R^{-1} (Hx'-y^0),$$

where $x'$ is the vector of analysis increments defined by:

$$x^a = x^b + x',$$

and $y^0$ is the ZTD observation increment.

$x^b$ is the background state (first guess) vector and $x^a$ the sought analysis, and $R$ is the covariance matrix of GPS observation errors. Since observational errors are assumed uncorrelated, the matrix $R$ is simply diagonal with the ZTD observational error variances as elements. $H$ is the linear approximation (operator) of the nonlinear operator $H$, which maps the model variables to the ZTD values at the location of the GPS sites and includes a nonlinear observational operator and space interpolation. The nonlinear observational operator is the model simulation of the ZTD and is composed of the ZHD and ZWD nonlinear operators (e.g., Cucurull et al. 2000).

Since the ZHD can be derived from surface pressure measurements, the ZHD operator basically estimates the surface pressure at the GPS sites from model pressure. We used a bilinear interpolation in the horizontal to interpolate the surface pressure values from the grid points of the domain to the location of the GPS sites. A more accurate treatment was needed for the interpolation in the vertical because the station pressure (and consequently the ZHD) strongly depends on the height of the GPS stations and these are not correctly modeled by MM5 due to the topography resolution used. The vertical interpolation of the model pressure at the GPS station location must be done very carefully. Small differences between the model terrain and the station elevation can introduce significant bias in the modeled ZTD (Cucurull et al. 2002). The methodology we used is based on De Pondeca and Zou (2001b).

The 3DVAR solution $x^a$ is obtained for the analysis increment $x'$ that minimizes the total cost function. It is, therefore, the model space vector that best fits simultaneously the background vector and both the conventional and GPS observation vectors. This fit is measured by the quadratic distance weighted by the background and observational error covariance matrices. The limited-memory quasi-Newton method (Liu and Nocedal 1989) is used to solve the minimization of cost function.
5. Results and discussion

Two different approaches were used to analyze the potential benefit of the GPS data on weather forecasts over Catalonia. The first approach consists in assimilating global meteorological observations and GPS measurements in the coarser domain only and then to interpolate the large scale analyzed fields on the smaller domains. The model was initialized at 00 UTC 14 September 2002 using the NCEP AVN analysis as 3DVAR background and first guess fields. Then 3DVAR was repeated every 12 h in a cycling mode, i.e. using the previous 12 h forecast as background and first guess fields of the new 3DVAR analysis. As GPS data are available at much higher rate than global observations, assimilations were repeated every 6 h instead of 12 h using the previous 6 h forecasts as background and first guess fields when the GPS measurements were also assimilated into the model. (A 6-h cycling time is probably the highest possible frequency operationally). Therefore, a total of 5 assimilations were performed every 12 h between 00 UTC 14 December and 00 UTC 16 December 2002 when only meteorological observations were assimilated, and 9 assimilations when GPS data were also ingested into the model. The second approach aims to take full advantage of the capability of the 3DVAR system and the data assimilation is performed in the three domains. The same observations (GPS and WMO surfaces and soundings) were assimilated in the two coarser domains, while only local (surface and GPS) observations provided by the regional Catalan Weather Service and COST Action 716 were used in the finest domain. As for the first approach, the 3DVAR was repeated every 12 h when only meteorological observations were assimilated into the model and decreased to 6 h when GPS data were also included in the assimilation. A summary of the different data assimilation experiments conducted in this study is given in Table 1.

We have compared and scored the forecasts from the two approaches in two ways. First, a special sounding from Barcelona was used which was not assimilated into the model since it is not part of the WMO network. This sounding was used to verify the 3DVAR analysis at particular times. In a second approach, a sounding from Mallorca was used to verify a forecast
initialized from the 3DVAR analysis. At the forecast time, the Mallorca observations have not yet been assimilated into the model.

In addition to the verification of vertical profiles, we have also analyzed the forecasts of the distribution of surface rainfall and compared the results with observations of precipitation.

a. Assimilation in the coarser domain only:

In this section, we assess the impact of the GPS observations on forecast skill over Catalonia when the observations are assimilated in the coarser domain only. We distinguish between a 12 h (free) forecast initialized at 00 UTC 14 December 2001 and a cycle of 3DVAR assimilation followed by a 12 h (6 h) forecast when meteorological (meteorological and GPS) observations are assimilated into the model between 00 UTC 14 December and 00 UTC 16 December 2001.

i. Initialization

Fig. 5 compares the relativity humidity profile obtained from the model in ANALD1 experiment (blue line) with the moisture profile from the verification sounding at Barcelona at 00 UTC 14 December (red line). Because of the limited vertical resolution, the model profile looks smoother than the sounding. In general, the model is found to be too dry at lower levels (between 700 hPa and 1000 hPa) and too humid between 200 hPa and 400 hPa. The model profile for ANALD1GPS (not shown) is very similar to the profile of ANALD1. It is noticeable that when only assimilated in the coarser domain, the GPS data have no significant impact on the local forecast at Barcelona.

Comparison of the forecast of the total precipitation accumulated in 24h in ANALD1 and ANALD1GPS experiments are shown in Fig. 6b and Fig. 6c, respectively. Although both patterns are very similar, the assimilation of GPS data tends to slightly increase the accumulated rainfall in some localized areas over the northeast of Catalonia. Observations of the precipitation accumulated during the same period are shown in Fig. 6a. Experiments ANALD1 and
ANALD1GPS forecast the rain band slightly southern from what it is observed, independently of the assimilation of the ZTD observations.

In order to verify the impact of the GPS observations during the free forecast, we have analyzed the evolution of the ZTD root-mean-square (rms) errors in ANALD1 and ANALD1GPS at 6 h intervals during the 12 h of prediction. As shown in Fig. 7, the ZTD rms increases quickly with time after 06 UTC for ANALD1 while results are more stable for ANALD1GPS, i.e. when GPS measurements are also assimilated into the model. As expected, in both cases the benefits of the assimilation at initial time are lost during the free forecast. However, the use of ZTD measurements seems to reduce the forecast error growth between 06 UTC and 12 UTC.

ii. Cycle experiment

Fig. 8 shows the surface relative humidity field of FCSTD1 (Fig. 8a) and FCSTD1GPS (Fig. 8b) experiments valid at 18 UTC 14 December 2001. The assimilation of GPS data produces an increase of moisture at the surface over the center of domain 3. As one would expect, the area of major impact coincides with the location of the GPS sites (see Fig. 4), and which is where the observations should have a biggest impact. Since the ZTD observed is higher than the modeled value and the temperature field at 18 UTC 14 December 2001 presents similar patterns in FCSTD1 and FCSTD1GPS, the 3DVAR system assimilation increases moisture to fit the observations. The meteorological stations available in the area recorded values of relative humidity higher than 90%. These observed values are thus better represented in FCSTD1GPS than in FCSTD1. In this approach, the assimilation of the GPS observations does not modify the temperature field.

The impact of the GPS observations can be also observed in the radar reflectivity plots. Fig. 9 shows the reflectivity field simulated in FCSTD1 and FCSTD1GPS at 18 UTC 14 December 2001 (Fovell and Ogura, 1988). The increase of the reflectivity from 25-30 dBz in FCSTD1 (Fig. 9b) to 30-35 dBz in FCSTD1GPS (Fig. 9c) along the location of the GPS stations agrees better
with radar observations (Fig. 9a), which show values of 30-35 dBz in the area.

To compare the vertical profile of moisture in FCSTD1 and FCSTD1GPS, Fig. 10 displays the relative humidity profile at Barcelona site valid at 12 UTC 14 December and compare the model simulations (blue thick and dotted lines) with the sounding launched at Barcelona at the same time (red line). It is observed from the picture, that the GPS data slightly dry the lower levels of the atmosphere by around 10%, which disagrees with the observed values (the radiosonde measured a relative humidity of around 80% at 1000 hPa). However, experiment FCSTD1GPS plays a better role at around 850 hPa, increasing the moisture from 68% to 72% (the value reported from the sounding was 80%).

The humidity profiles of the 12 h forecast in FCSTD1 and the 6 h forecast in FCSTD1GPS at Mallorca (see Fig. 4) valid at 00 UTC 15 December are shown in Fig. 11. Even if both profiles show similar trends, FCSTD1GPS (blue dotted line) decreases moisture between 850 hPa and 1000 hPa and increases the humidity profile between 700 hPa and 800 hPa. The WMO sounding launched at Mallorca site at 00 UTC 15 December (red line) is used to verify the 12 h and 6 h forecasts in FCSTD1 and FCSTD1GPS experiments, respectively. The decrease of moisture observed in the sounding at around 900 hPa is not observed in any of the experiments. However, the assimilation of GPS in FCST1DGPS catches slightly better this drop of moisture at lower levels. As was found in previous analysis, there is no impact of the GPS measurements in the temperature profile.

The rms errors calculated over sub-domain 3 are shown in Fig. 12. Every value corresponds to a forecast initialized from the last analysis cycle. Therefore, it is a 6 h forecast in FCSTD1GPS and a 12 h run in FCSTD1. The local meteorological observations are used to estimate the rms values for the horizontal wind, temperature and humidity fields. In both experiments, there is an increase of the rms error at 00 UTC 15 December for the wind variable, which is attributed to the passage of the frontal system over Catalonia. However, the error decreases quickly with time in FCSTD1 at the end of the assimilation cycle. The results show that the FCSTD1 experiment performs better than FCSTD1GPS. Similar trends are found for the temperature and specific humidity components. In all cases, the rms errors at the end of the assimilation cycle are lower in
FCSTD1, which indicates that the use of GPS data makes a negative impact when the observations are assimilated only in the coarse domain.

b. Assimilation in all domains

In a second part, we analyze the results of the assimilation of the observations in all domains. As before, the free forecast and the cycle experiment are considered separately.

Initialization

Profiles of moisture at the Barcelona site in ANALD3 and ANALD3GPS experiments (green line in Fig. 5) present similar trends, but the results are slightly different from those obtained when the assimilation was only conducted in the coarser domain. Compared to the results obtained in ANALD1GPS, ANALD3GPS shows slightly more moisture at all pressure levels. This rise in humidity is especially noticeable at surface, where the increase in relative humidity is around 10%. Differences between the two curves are caused by the assimilation of local meteorological observations, which are assimilated in domain 3 in ANALD3 and ANALD3GPS, but not in ANALD1 and ANALD1GPS. Unlike in the previous experiment, after assimilation the model is too moist, compared to the verification sounding, between 950 hPa and 1000 hPa. The fact that these regional observations are surface data and show large values of moisture (from 65% to 91% within a 100 km radius of the verification sounding), justifies the increase of humidity at lower levels after the assimilation.

Forecasts of precipitation in ANALD3 and ANALD3GPS are shown in Fig. 6d and Fig. 6e, respectively. Both forecasts are pretty similar, with a slightly decrease of rainfall (around 2mm) in ANALD3GPS over the areas of maximum precipitation, when comparing to ANALD3GPS. The assimilation of observations in all three domains results in an increase of accumulated precipitation in the center part of the domain, as compared to the results found in ANALD1 and
ANALD1GPS. However, the area of maximum precipitation is still misplaced by the model simulations.

When looking at the rms errors of the ZTD variable for the free forecast (Fig. 7), ANALD3 and ANALD3GPS show quite similar results. The use of GPS data in ANALD3GPS does not have a big impact on skill compared to ANALD3 but the prediction system shows a better skill (and a forecast error decrease) when the assimilation is carried out in all three domains.

ii. Cycle experiment

The assimilation of GPS observations in FCSTD3GPS results in an increase of moisture at lower levels compared to the FCSTD3 experiment (Fig. 8). As found in FCSTD1 and FCSTD1GPS, this increase in the relative humidity field is larger over the area where the GPS stations are located. When compared to the results found in FCSTD1 and FCSTD1GPS, the combination of the local meteorological observations and the GPS data produce the highest level of moisture over the domain, with larger impact over the GPS sites (Fig. 8d). The assimilation of the regional surface data in FCSTD3 increases the humidity at lower levels but it is the ingestion of the GPS data, which makes a significant impact (the observed values over the area in relative humidity were above 90%).

One characteristic of the assimilation of the observations in all domains is that, now, the GPS data are also found to have an impact on the temperature field over Catalonia (Fig. 13). This was not the case for experiments FCSTD1 and FCSTD1GPS, where the ZTD modified the humidity field at lower levels but hardly changed the temperature profile. As observed in Fig. 13b, the effect of the GPS data at 00 UTC 15 December 2001 compared to FCSTD3 is to cool down the surface temperature to below −5°C in the western part of the domain. The local meteorological network recorded values below −5°C over the same area during this period. As a result, it is the assimilation of both local and GPS observations in domain 3, which results in a better representation of the temperature field.
The assimilation of local data in experiments FCSTD3 and FCSTD3GPS dramatically changes the moisture level of the model at Barcelona site between 1000 hPa and 700 hPa (green thick and dotted lines in Fig. 10). The assimilation of meteorological surface observations boosts the humidity content with a maximum of 96% at 775 hPa, for an actual observed value of 86%. The addition of GPS ZTD moves this maximum to its correct location (950 hPa) and produces vertical structures that better follows, although more smoothly, the vertical structures of the verification sounding between the surface and 750 hPa. It cannot, however, correct the excess of moisture (up to 15%) that results from the assimilation of surface stations. This result is somewhat counterintuitive, as one would expect an improvement in the total humidity content, but not in the vertical structures, from integrated measurements like GPS ZTD observations. This indicates that combination of surface and GPS ZTD data might contain more vertical information than if both data sets were assimilated independently. It is interesting to see that the assimilation of meteorological stations only (plain blue and green lines) produce a maximum of moisture around 750 hPa, while the addition of GPS data (blue and green dotted lines) moves this maximum to lower levels, 850 hPa in FCSTD1GPS and 950 hPa in FCSTD3GPS. These differences illustrate the specificity of the GPS ZTD observation operator. During the assimilation, 3D-VAR is using observational information to correct for model deficiencies (characterized by high forecast error variances) and, therefore, the observational increment will be primarily projected at those levels. The forecast error variances are given by the eigenvalues, or modes, of the background error covariance matrix, which express the forecast error covariance matrix in the control variables space. Higher forecast errors are, therefore, expected where the vertical components eigenvectors of the most important modes, are the largest. In this case, more than 80% of the model relative humidity error total variance was explained by the first 5 modes. The model humidity maximum found at 750 hPa in FCSTD3 indicates that most of the surface observational increment has been projected on modes 2 and 4. Both modes have their maximal components at 750 hPa (not shown). At the contrary, the maximum of humidity at 950 hPa found when GPS ZTD data are assimilated (FCDSTD3GPS) indicates that the projection of ZTD observational increment wasn’t performed on any particular modes. In fact, most of the
vertically integrated information contained in GPS ZTD observational increments is found at the model surface. This is, probably, the result of the strong dependence of GPS ZTD information on surface pressure. Recall that the adjoint of the observation operator is used to map the ZTD observational increment into the model space before the vertical projection on eigenvectors can be applied. The increase of moisture in the low levels after ingestion of local data (FCSTD3 and FCSTD3GPS, green lines) is a second important feature on the plots of Fig. 10. The huge humidity increment seems solely due to surface stations assimilation. Model forecasts valid at 12 UTC on December 14, were much too dry at surface for both FCSTD3 (50%) and FCSTD3GPS (68%) compared to the sounding at the surface (80%) and the local surface observations that are assimilated. Those stations are reporting humidity measurements varying between 82% and 100% around the sounding location. As mentioned above, these large differences produce big observational increments of humidity at surface that are subsequently vertically redistributed in the lowest levels according to the structure of the background error covariance matrix. It has also to be noted, that among the four possible profiles, the vertical structure and humidity content of FCSTD3GPS (green dotted line) better match the verification sounding. So, at least quantitatively, from Fig. 10 it seems that the combination of both surface stations and GPS ZTD observations produce the best results. All forecasts failed to reproduce the humid layer between 575 hPa and 675 hPa. Indeed, there are no vertical modes with large eigenvectors components at those levels (the first mode has it maximum at 400 hPa and explains the small kink at that level in all profiles). Without such a kind of statistical information in the data assimilation system, it is not possible for the 3DVAR algorithm to correct the model with the use of surface and integrated measurements only.

The impact of the GPS data in forecasting the moisture profile at Mallorca site at 00 UTC 15 December is shown in Fig. 11b. The patterns of both figures are very different. The GPS data in FCSTD3GPS (green dotted line) decreases the amount of moisture between 850 hPa and 950 hPa. At around 900 hPa, the moisture drops from around 90% in FCSTD3 (green thick line) to 65% in FCSTD3GPS. This tendency was already shown in FSTD1GPS, but it is in FCSTD3GPS where this decrease in moisture is more noticeable. However, none of the
experiments can detect the big drop of moisture observed with the sounding, where the relative humidity decreases to around 20% at 900 hPa.

As opposed to the results found in FCSTD1 and FCSTD1GPS experiments, the assimilation of the GPS observations in all three domains has a positive impact on the rms errors at the end of the assimilation cycle. From Fig. 12, the lowest rms errors for wind, temperature and humidity fields are found in FCSTD3GPS experiment. Even if the rms error in the temperature variable shows a significant increment during the passage of the front at 00 UTC 15 December, this value decreases quickly during the following cycles. In general, FCSTD3 and FCSTD3GPS perform better than the FCSTD1 and FCSTD1GPS experiments at the end of the assimilation cycle.

Another feature of the picture is that FCSTD1 and FCSTD3 show similar tendencies at the end of the assimilation cycle. It is the assimilation of the GPS observations in FCSTD1GPS and FCSTD3GPS which have the largest impact on model forecasts. The GPS data tend to limit the forecast error growth in FCSTD3GPS, while they have a negative on FCSTD1GPS forecasts.

6. Concluding remarks

In this paper we have analyzed the impact of the 3DVAR assimilation of GPS ZTD observations during the evolution of a mesoscale convective system that affected the western Mediterranean during 14-15 December 2001.

Two different approaches were considered to analyze the impact of the assimilation on the model domain resolution. First, global WMO meteorological and GPS observations were only assimilated in a low resolution model domain. Second, the assimilation was carried out in three different domains with progressively higher resolution. For the fine 6-km resolution domain, regional surface meteorological observations available in the area were assimilated along with the GPS data. The configuration of this domain was prescribed to cover the geographical area of interest.

In order to explore the benefits of conducting the assimilation of the observations in a cycle framework rather than a free forecast from the model analysis, we also compared weather
forecasts in a 48 h assimilation cycle experiment with the predictions obtained from the free run starting at the initial time of the period of interest.

We found that the benefits of the assimilation of the GPS observations are quickly lost if the assimilation is only conducted in the coarser domain. However, the system has better skills when GPS data and regional observations are taken into account. This underlines the value of GPS ZTD observation for mesoscale studies and suggests that GPS data shall be preferably assimilated with the highest resolution model.

The impact of the GPS data in a cycle framework is found to be optimal (an average of 1.7% decrease of the rms error in the wind component, 4.1% in the temperature variable and 17.8 % in the specific humidity) when the assimilation is performed in all three domains and the local meteorological observations are also assimilated into the model. Since the GPS observations are strongly related to the content of moisture in the atmosphere, the decrease of the rms error is found to be larger for the humidity variable. It is very encouraging that the 3DVAR assimilation system in a cycling mode can improve the model analysis and weather prediction with the use of local meteorological and GPS observations. It is also interesting to note that the GPS stations deployed and maintained under COST Action 716 seem ideally placed on the frontogenesis of western Mediterranean storms, which maximizes the impact of the data on local forecast in Mediterranean regions such as Catalonia.

7. Acknowledgments

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References


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Table List

Table 1: Summary of the data assimilation experiments
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<table>
<thead>
<tr>
<th>Experiment name</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>ANALD1</td>
<td>assimilation of global meteorological observations in domain 1, Analysis at 00 UTC 14 December, free forecast</td>
</tr>
<tr>
<td>ANALD1GPS</td>
<td>assimilation of global meteorological and GPS observations in domain 1, Analysis at 00 UTC 14 December, free forecast</td>
</tr>
<tr>
<td>FCSTD1</td>
<td>assimilation of global meteorological observations in domain 1, Cycle experiment, 12 h assimilation time window</td>
</tr>
<tr>
<td>FCSTD1GPS</td>
<td>assimilation of global meteorological and GPS observations in domain 1, Cycle experiment, 6 h assimilation time window</td>
</tr>
<tr>
<td>ANALD3</td>
<td>assimilation of global meteorological observations in all domains, Analysis at 00 UTC 14 December, free forecast</td>
</tr>
<tr>
<td>ANALD3GPS</td>
<td>assimilation of meteorological and GPS observations all in domains, Analysis at 00 UTC 14 December, free forecast</td>
</tr>
<tr>
<td>FCSTD3</td>
<td>assimilation of meteorological observations in all domains, Cycle experiment, 12 h assimilation time window</td>
</tr>
<tr>
<td>FCSTD3GPS</td>
<td>assimilation of meteorological and GPS observations in all domains, Cycle experiment, 6 h assimilation time window</td>
</tr>
</tbody>
</table>
**Figure Captions**

Fig.1. Surface analysis from the UK Met Office of atmospheric flow at 00 UTC 13 December 2001.

Fig.2. Low resolution, NCEP AVN analysis maps of surface pressure and 500 hPa geopotential height at (a) 00 UTC 14 December 2001 and (c) 00 UTC 15 December 2001, and temperature field at 850 hPa at (b) 00 UTC 14 December 2001 and (d) 00 UTC 15 December 2001. The location of Catalonia is indicated in the NE of the Iberian Peninsula.

Fig.3. Accumulated precipitation during 00 UTC 14 December 2001 and 00 UTC 16 December 2001.

Fig.4. Domain configuration for the model simulation. Geographical location of Barcelona (+), Mallorca (o), and the GPS sites are also shown.

Fig.5. Profiles of relative humidity at Barcelona site from observations, experiments ANALD1-ANALD1GPS, and experiments ANALD3-ANALD3GPS at 00 UTC 14 December 2001.

Fig.6. Precipitation accumulated in 14h starting at 00 UTC 14 December 2001 from (a) observations, (b) ANALD1, (c) ANALD1GPS, (d) ANALD3, and (e) ANALD3GPS.

Fig.7. Root-mean-square errors with time. The assimilation of the observations is done at 00 UTC 14 December 2001.

Fig.8. Surface relative humidity in (a) FCSTD1, (b) FCSTD1GPS, (c) FCSTD3, and (d) FCSTD3GPS experiments valid at 18 UTC 14 December 2001.

Fig.9. Radar reflectivity field from (a) observations, (b) FCSTD1, and (c) FCSTD1GPS experiments valid at 18 UTC 14 December 2001.

Fig.10. Relative humidity profile at Barcelona (lat = 41.40, lon = 2.10) from observations and FCSTD1, FCSTD1GPS, FCSTD3, and FCSTD3GPS experiments valid at 12 UTC 14 December 2001.
Fig. 11. Relative humidity profile at Mallorca (lat = 39.55, lon = 2.61) from observations and FCSTD1, FCSTD1GPS, FCSTD3, and FCSTD3GPS experiments valid at 00 UTC 15 December 2001.

Fig. 12. Root mean square errors with time in FCSTD1, FCSTD1GPS, FCSTD3, and FCSTD3GPS experiments for (a) wind, (b) temperature, and (c) specific humidity variables.

Fig. 13. Surface temperature field in (a) FCST3 and (b) FCST3GPS valid at 00 UTC 15 December, 2001.
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Fig 6. Precipitation accumulated in 14h starting at 00 UTC 14 December 2001 from
(a) observations, (b) ANALD1, (c) ANALD1GPS, (d) ANALD3, and (e) ANALD3GPS.
Fig. 7. Root-mean-square errors with time. The assimilation of the observations is done at 00 UTC 14 December 2001.
Fig. 8. Surface relative humidity in (a) FCSTD1, (b) FCSTD1GPS, (c) FCSTD3, and (d) FCSTD3GPS experiments valid at 18 UTC 14 December 2001.
Fig. 9. Radar reflectivity field from (a) observations, (b) FCSTD1, and (c) FCSTD1GPS experiments valid at 18 UTC 14 December 2001.
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