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 fifth-generation Pennsylvania State University–NCAR Mesoscale Model (MM5) using its three-dimensional variational data 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 that 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 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 min) (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 four-dimensional variational data assimilation (4DVAR) of zenith total delay (ZTD) measurements from a dense GPS network with the fifth-generation Pennsylvania State University–National Center for Atmospheric Research (Penn State–NCAR) Mesoscale Model (MM5). These

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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 radio acoustic sounding system (RASS) virtual temperature observations were also included in the assimilation setup. However, this improvement of precipitation forecast skill was reduced when the ZTD data were excluded from the set of observations being assimilated into the system.

The aim of this study is to analyze the impact of three-dimensional variational data assimilation of (3DVAR) of GPS ZTD data gathered from the European Cooperation in the Field of Scientific and Technical Research (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 dataset, but we are rather studying how GPS observations can be best 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 and its three-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 that are mostly the result 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 of the GPS observations is described in section 4; section 5 analyzes the results from the different experiments, and the main conclusions are presented in section 6.

2. Case description

The synoptic situation during the days prior to 14 December was characterized by a stationary anticyclone over northern Europe, with a 1042-hPa central pressure (Fig. 1) that 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 13 December and then to the west, reaching Catalonia, Spain (NE of the Iberian Peninsula), on 14 December.

The National Centers for Environmental Prediction (NCEP) Aviation Model (AVN) analysis of the synoptic meteorological conditions on 14 December are summarized in Fig. 2. At 0000 UTC (Fig. 2a), the sea level high pressure area was located over Denmark (1044 hPa) and moved to Scotland at 2400 UTC (Fig. 2c). At the same time, a low pressure area developed in the Mediterranean Sea at 0000 UTC (Fig. 2a) with a 1008-hPa central pressure over Corsica and a secondary minimum over the Catalan coast at 2400 UTC (Fig. 2c). At 850 hPa, the cold sector of the temperature field was located over eastern Europe (Fig. 2b) at 0000 UTC. During the following hours, the cold air mass migrated over the western Mediterranean bordering the Pyrenees, cooling northern Catalonia to −10°C. (The rest of the region recorded temperatures between −5° and −8°C 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 14 December over the northeast of Catalonia. During the hours that followed, several precipitation areas developed along the Catalan coastal range from north to south (Fig. 3). Because of 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 14 December, the cold air mass that impinged on the eastern Pyrenees moved to the southeast, displacing warmer moist air aloft. The resulting frontal system produced considerable snowfall, which intensified the preexisting storm system over the central part of Catalonia. Because of very cool surface temperatures, this led to significant accumulation of snow, even along the coast. The moist air progressed southward on 15 December, and the snowfall began in southern Catalonia where the temperatures were already below 0°C.

3. Methodology

a. Numerical model and simulation characteristics

The Penn State–NCAR Mesoscale 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 (D01), to 18 (D02), to 6 km (D03) (Fig. 4). All domains had the same 31 vertical sigma levels. The physical options used were the high-resolution Medium-Range Forecast (MRF) planetary boundary layer model, a multilayer soil model, the simple scheme of Dudhia (1993) for explicit moisture parameterization, and clouds explicitly solved for the finest domain (D03).

The model simulation was initialized about 12 h before the onset of the heavy rains that affected Catalonia,
at 0000 UTC 14 December 2001. The initial and boundary conditions were provided by the NCEP AVN analysis every 12 h from 0000 UTC 14 December to 0000 UTC 16 December 2001.

b. GPS and meteorological observations

Based on the entire GPS dataset 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 (D03) 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 GPS-inferred positioning system and orbit analyses simulation (GIPSY/OASIS-II; version 4) software package (Webb and Zumberge 1993), were used to estimate the ZTD 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 measurements 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, dewpoint/humidity). In this study, in addition to GPS we have used World Meteorological Organization (WMO) Synoptic (SYNOP) and Ocean (SHIP) surface observations; TEMP radiosondes and rawinsonde winds, temperature and relative humidity; PILOT wind observations; AIREP aircraft wind and temperature data; aircraft meteorological data relay (AMDAR) wind, temperature, and pressure observations; and METAR (translated roughly from the French as aviation routine weather report) 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.

4. Data assimilation procedure

a. Three-dimensional variational assimilation system

The assimilation system is based on the three-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. (2003, 2004). 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.

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

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**Fig. 2.** Low-resolution NCEP AVN analysis maps of surface pressure (isopleths) and 500-hPa geopotential height (gray shades) at (a) 0000 UTC 14 Dec 2001 and (c) 0000 UTC 15 Dec 2001, and temperature and wind fields at 850 hPa at (b) 0000 UTC 14 Dec 2001 and (d) 0000 UTC 15 Dec 2001. The location of Catalonia is indicated [by a small box in (b)] in the northeast of the Iberian Peninsula.
EOFs of statistical model forecast error profiles. These profiles were generated by application of the National Meteorological Center (NMC) method (Parrish and Derber 1992) to the MM5 real-time system run daily at the U.S. Air Force Weather Agency on a 210-km grid over Europe. Differences between 24-h minus 12-h forecasts valid daily at 1200 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 streamfunction, velocity potential, unbalanced pressure, and relative humidity terms. This choice of control variables follows Lorenc et al. (2000) and was motivated by their relative independence, so that correlations between analysis variables can be neglected in the background covariance matrix.

b. Assimilation of GPS observations

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

$$J(x') = J_b + J_{\text{conv}} + J_{\text{GPS}}.$$  

This new term $J_{\text{GPS}}$ is defined as

$$J_{\text{GPS}}(x') = 1/2((Hx' - y'0)'R^{-1}(Hx' - y'0)),$$

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

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

and $y'0$ is the ZTD observation increment, $x^b$ is the background state (first guess) vector, $x^e$ is the sought analysis, and $R$ is the covariance matrix of GPS observation errors. Since observational errors are assumed to be uncorrelated, the matrix $R$ is simply diagonal with the ZTD observational error variances as elements, and $H$ 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 inter-
politation 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 because of 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 \( x^* \) 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 to weather forecasts over Catalonia. The first approach consists of assimilating global meteorological observations and GPS measurements in the coarser domain only and then interpolating the large-scale analyzed fields on the smaller domains. The model was initialized at 0000 UTC 14 December 2002 using the NCEP AVN analysis as 3DVAR background and first-guess fields. Then 3DVAR was repeated every 12 h in a cycling mode, that is, using the previous 12-h forecast as background and first-guess fields of the new 3DVAR analysis. Since GPS data are available at a 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 that can be considered operationally.) Therefore, a total of five assimilations were performed every 12 h between 0000 UTC 14 December and 0000 UTC 16 December 2002, when only meteorological observations were assimilated, and nine assimilations were performed 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 surface and sounding data) 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, we used special sounding from Barcelona, Spain, that 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, Spain, 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 0000 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 0000 UTC 14 December and 0000 UTC 16 December 2001.

#### 1) Initialization

Figure 5 compares the relative humidity profile (black line) obtained from the model in the ANALD1

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**Table 1. Summary of the data assimilation experiments.**

<table>
<thead>
<tr>
<th>Experiment name</th>
<th>Description</th>
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<tbody>
<tr>
<td>ANALDI</td>
<td>Assimilation of global meteorological observations in domain 1, analysis at 0000 UTC 14 Dec, free forecast</td>
</tr>
<tr>
<td>ANALD1GPS</td>
<td>Assimilation of global meteorological and GPS observations in domain 1, analysis at 0000 UTC 14 Dec, 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 0000 UTC 14 Dec, free forecast</td>
</tr>
<tr>
<td>ANALD3GPS</td>
<td>Assimilation of meteorological and GPS observations in all domains, analysis at 0000 UTC 14 Dec, 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>
experiment (Table 1) with the moisture profile from the verification sounding at Barcelona at 0000 UTC 14 December (dark gray 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 and 1000 hPa) and too humid between 200 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.

Comparisons of the forecast of the total precipitation accumulated in 24 h in ANALD1 and ANALD1GPS experiments are shown in Figs. 6b and 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 rainband slightly south from where 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 0600 UTC for ANALD1, while results are more stable for ANALD1GPS, that is, 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 0600 and 1200 UTC.

2) CYCLE EXPERIMENT

Figure 8 shows the surface relative humidity field of the FCSTD1 (Fig. 8a) and FCSTD1GPS (Fig. 8b) experiments valid at 1800 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 that is where the observations should have a biggest impact. Since the ZTD observed is higher than the modeled value, and the temperature field at 1800 UTC 14 December 2001 presents similar patterns in FCSTD1 and FCSTD1GPS, the 3DVAR system 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 also be observed in the radar reflectivity plots. Figure 9 shows the reflectivity field simulated in FCSTD1 and FCSTD1GPS at 1800 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) that 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 the Barcelona site valid at 1200 UTC 14 December and compares the model simulations (thick and dotted black lines) with the sounding launched at Barcelona at the same time (dark gray 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 0000 UTC 15 December are shown in Fig. 11. Even if both profiles show similar trends, FCSTD1GPS (black dotted line) decreases moisture between 850 and 1000 hPa and increases the humidity profile between 700 and 800 hPa. The WMO sounding launched at the Mallorca site at 0000 UTC 15 December (dark gray line) is used to verify the 12- 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 FCSTD1GPS catches slightly better this drop of moisture at lower levels. As was found in previous analysis,
FIG. 6. Precipitation accumulated in 14 h starting at 0000 UTC 14 Dec 2001 from (a) observations, (b) ANALD1, (c) ANALD1GPS, (d) ANALD3, and (e) ANALD3GPS.
there is no impact of the GPS measurements in the temperature profile.

The rms errors calculated over subdomain 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 0000 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.

1) INITIALIZATION

Profiles of moisture at the Barcelona site in ANALD3 and ANALD3GPS experiments (light gray 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 the 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 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 Figs. 6d and 6e, respectively. Both forecasts are fairly similar, with a slight decrease of rainfall (around 2 mm) in ANALD3GPS over the areas of maximum precipitation, when comparing to ANALD3. 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.
Fig. 9. Radar reflectivity field from (a) observations and (b) FCSTD1 and (c) FCSTD1GPS experiments valid at 1800 UTC 14 Dec 2001.
2) CYCLE EXPERIMENT

The assimilation of GPS observations in FCSTD3 GPS 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 that 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 data 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 0000 UTC 15 December 2001 compared to FCSTD3 is to cool down the surface temperature to below $-5^\circ$C in the western part of the domain. The local meteorological network recorded values below $-5^\circ$C over the same area during this period. As a result, it is the assimilation of both local and GPS observations in domain 3 that 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 the Barcelona site between 1000 and 700 hPa (light gray 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 data moves this maximum to its correct location (950 hPa) and produces vertical structures that better follows, although more smoothly, the vertical structure 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 such as GPS ZTD observations. This indicates that the combination of surface and GPS ZTD data might contain more vertical information than if both datasets were assimilated independently. It is interesting to see that the assimilation of meteorological stations only (plain black and light gray lines) produces a maximum of moisture around 750 hPa, while the addition of GPS data (black and light gray 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, 3DVAR 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 five modes. The model humidity
maximum found at 750 hPa in FCSTD3 indicates that most of the surface observational increment has been projected onto modes 2 and 4. Both modes have their maximal components at 750 hPa (not shown). On the contrary, the maximum of humidity at 950 hPa found when GPS ZTD data are assimilated (FCSTD3GPS) indicates that the projection of ZTD observational increment was not performed on any particular modes.

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 and wind fields in (a) FCST3 and (b) FCST3GPS valid at 0000 UTC 15 Dec 2001.
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, light gray dotted line) is a second important feature on the plots of Fig. 10. The huge humidity increment seems solely due to the assimilation of surface stations. Model forecasts valid at 1200 UTC on 14 December were much too dry at the 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 the surface that are subsequently vertically redistributed in the lowest levels according to the structure of the background error covariance matrix. It also has to be noted that among the four possible profiles, the vertical structure and humidity content of FCSTD3GPS (light gray 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 and 675 hPa. Indeed, there are no vertical modes with large eigenvector components at those levels (the first mode has its maximum at 400 hPa and explains the small kink at that level in all profiles). Without this 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 the Mallorca site at 0000 UTC 15 December is shown in Fig. 11b. The patterns of both figures are very different. The GPS data in FCSTD3GPS (light gray dotted line) decreases the amount of moisture between 850 and 950 hPa. At around 900 hPa, the moisture drops from around 90% in FCSTD3 (light gray 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 in 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 0000 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 that have the largest impact on model forecasts. The GPS data tend to limit the forecast error growth in FCSTD3GPS, while they have a negative impact on FCSTD1GPS forecasts.

6. Concluding remarks

In this paper we have analyzed the impact of the 3DVAR 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 finest resolution domain (6 km), 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 skill 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 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.

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