**Mediterranean Storms**
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# 3DVAR ASSIMILATION OF GPS AND METEOROLOGICAL OSERVATIONS IN MM5 DURING THE DECEMBER 14TH 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 experiment focuses on a snow storm that occurred during the period of 14-15 December 2001 over the western Mediterranean sea.

Two different approaches were used for the 3DVAR assimilation study: (1) European GPS observations were assimilated along with global meteorological observations from the World Meteorological Organization (WMO) database, and (2) local GPS and meteorological observations over the NE of the Iberian Peninsula were also assimilated into the model to further analyze weather prediction over the region. The experiments show optimal results when local meteorological and GPS observations are assimilated into the model in a cycle assimilation framework. This suggests the deployment of more and denser GPS networks as a means to improve model forecasts during strong storm mesoscale events.

## 1 INTRODUCTION

Cost effective techniques sensitive to the spatial and temporal distribution of atmospheric water vapor are offered by networks of ground-based GPS receivers. The aim of this work is to analyze the impact of 3DVAR assimilation of GPS data gathered from the COST Action 716 "Exploitation of ground-based GPS for climate and numerical weather prediction applications" on weather analysis and prediction. We address this issue by using the Penn State/NCAR Mesoscale MM5 model (Cucurull et al., 2002b).

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 situations connected with heavy rainfall over localized areas and which are mostly the results of mesoscale convective systems (Romero et al., 1998). In this paper, we describe a series of assimilation experiments to assess the potential impact of the ground-based GPS observations on regional weather analysis and prediction over the Mediterranean area. In order to take full advantage of the available observations, local and global meteorological data are also assimilated into the model.

## 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, 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.

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). At the same time, a low pressure system located over the Catalan east coast advected moist, and 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 ranges from North to South. 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

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 distance ranging from 54 km down to 6 km (Figure 1). 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. 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.

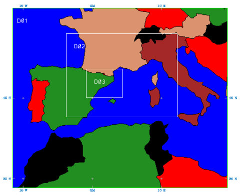

**Figure** 1. Domain configuration for the model simulation.

Based on the entire GPS data set from the COST Action 716, a total of 23 stations were available for the study (Figure 2). The temporal frequency of the data is around 1 h. The geographical location of the GPS sites samples quite equally the model domain. 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 Zenith Total Delay (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 measurement of surface pressure are available (Saastamoinen, 1972). The ZWD is associated with the atmospheric water vapor (Bevis et al. 1992).

In addition to GPS we have used global WMO observations. 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.

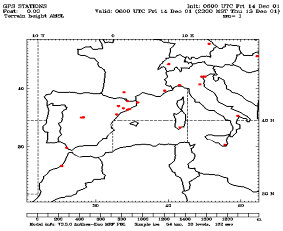

**Figure 2.** Geographical location of the used GPS sites from the European permanent network.

## 4 DATA ASIMILATION

The assimilation system is based on the 3-dimensional variational algorithm in its incremental formulation. Such an algorithm has been developed for MM5 in recent years and a technical description can be found at http://www.mmm.ucar.edu/3dvar/3dvar_home.html. The cost function includes a background and an observational term. Assimilation of GPS ZTD observations is performed by addition of a new term in the cost function to the already existing background and conventional observation terms:

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

This new term $J_{GPS}$ is defined as:

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

where $x'$ is the vector of analysis increments defined by $\mathrm{x}^{\mathrm{a}} = \mathrm{x}^{\mathrm{b}} + \mathrm{x}'$ ,

and $y^{o'}$ is the ZTD observation increment. $\mathrm{X}^{\mathrm{b}}$ is the background state (first guess) vector and $\mathrm{X}^{\mathrm{a}}$ 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. The nonlinear operator *H* 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. 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 (Cucurull et al., 2002a). The methodology we used is based on De Pondeca and Zou (2001). The 3D-VAR solution $x^a$ is obtained for the analysis increment $x'$ that minimizes the total cost function

## 5 RESULTS AND DISCUSSION

Two different strategies were employed to analyze the potential benefit of the GPS data over Catalonia. First, global meteorological observations and GPS measurements were assimilated in the coarser domain only and the analyzed fields were then interpolated to the smaller domains. In order to take full advantage of the capability of the 3DVAR system, the data assimilation was carried out in all three domains in a second approach. In this case, GPS and global meteorological observations were assimilated in domains 1 and 2, while local meteorological data from the regional Catalan Weather Service were ingested in the finer domain. Now we analyze the impact of the GPS measurements in both cases and compare the two approaches. For each strategy used, we discuss the impact of the GPS data when they were used to initialize the model forecast at 00 UTC 14 December 2001 and, secondly, when the data was assimilated instead in a cycle framework for a period of 48 h ending at 00 UTC 16 December 2001. The time interval for the assimilation cycle was 12 h when only meteorological observations were assimilated into the model and 6 h when GPS data were also ingested in order to take advantage of the high frequency measurements provided by the GPS ground receivers. A summary of the different data assimilation experiments conducted in this study is given in Table 1.

### 5.1 Assimilation in the coarser domain

### 5.1.1 Initialization

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 interval during the first 12 h of prediction. As shown in Figure 3, 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 has a positive impact in stabilizing the error between 06 UTC and 12 UTC.

### 5.1.2 Cycle experiment

To compare the vertical profile of moisture in FCSTD1 and FCSTD1GPS, Figure 4 displays the relative humidity profile at Barcelona site valid at 12 UTC 14 December and compares the model simulations with the sounding launched at Barcelona at the same time. It is observed from the picture, that the GPS data slightly dries the lower levels of the atmosphere by around 10%, which disagrees with the observed values (the radiosonde measured at relative humidity of around 80% at 1000 hPa). However, experiment FCSTD1GPS plays a better role at 850 hPa, increasing the moisture from 63% to 72% (the value reported from the sounding was 80%).

The rms errors calculated over sub-domain 3 are shown in Figure 5. Every value corresponds to a forecast initialized from the last analysis cycle. Therefore, it is a 6 h forecast in FCSTD3GPS and a 12 h run in FCSTD3. 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 does not make a good impact when the observations are assimilated only in the coarse domain.

## 5.2 Assimilation in all domains

### 5.2.1 Initialization

The rms errors of the ZTD variable for the free forecast (Figure 3), ANALD3 and ANALD3GPS show quite similar results and these are more stable than the ones found in ANALD1 and ANALD1GPS. The use of GPS data in ANALD3GPS does not make a big impact compared to ANALD3 but the prediction system shows a more stable performance skill (and a more stable error statistics) when the assimilation is carried out in all three domains.

### 5.2.2 Cycle experiment

Figures 4d and 4e show the relative humidity profile for experiments FCSTD3 and FCSTD3GPS, respectively. The GPS data has a huge impact at lower levels of the atmosphere. Note the increase of moisture by more than 15% at surface level. This situation was not reproduced when the GPS observations were assimilated only in domain 1 (FCSTD1GPS). In that case, the effect of the GPS was rather inaccurate in reproducing the amount of moisture at surface. Also, even if the profile in FCSTD3 is better than the ones simulated in FCSTD1 and FCSTD1GPS because increases moisture at lower levels, it is the assimilation of both local meteorological and GPS data which results in a better simulation of the observed values (Figure 4a).

As opposite 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 Figure 5, 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 makes a larger impact on the performance skill of the model. The GPS data stabilizes the error statistics in FCSTD3GPS, while the impact is negative in FCSTD1GPS. 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.

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## Tables

| Experiment name | Remarks |
|---|---|
| ANALD1 | assimilation of global meteorological observations in domain 1,<br>Analysis at 00 UTC 14 December, free forecast |
| ANALD1GPS | assimilation of global meteorological and GPS observations in domain 1,<br>Analysis at 00 UTC 14 December, free forecast |
| FCSTD1 | assimilation of global meteorological observations in domain 1,<br>Cycle experiment, 12 h assimilation time window |
| FCSTD1GPS | assimilation of global meteorological and GPS observations in domain 1,<br>Cycle experiment, 6 h assimilation time window |
| ANALD3 | assimilation of global meteorological observations in all domains,<br>Analysis at 00 UTC 14 December, free forecast |
| ANALD3GPS | assimilation of meteorological and GPS observations all in domains,<br>Analysis at 00 UTC 14 December, free forecast |
| FCSTD3 | assimilation of meteorological observations in all domains,<br>Cycle experiment, 12 h assimilation time window |
| FCSTD3GPS | assimilation of meteorological and GPS observations in all domains,<br>Cycle experiment, 6 h assimilation time window |

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

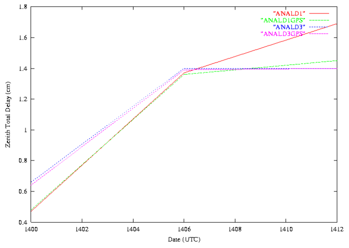

**Figure 3.** Root-mean-square errors with time. The assimilation of the observations is done at 00 UTC 14 December 2001.

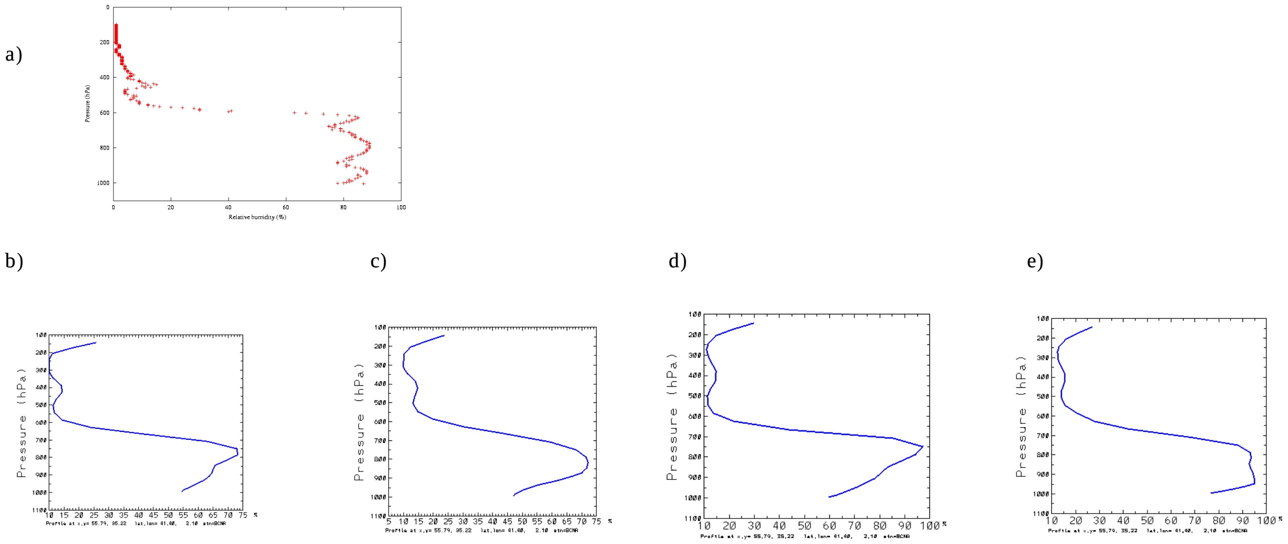

**Figure 4**. Relative humidity profile at Barcelona (lat = 41.40, lon = 2.10) from (a) observations, (b) FCSTD1, (c) FCSTD1GPS, (d) FCSTD3, and (e) FCSTD3GPS experiments valid at 12 UTC 14 December 2001.

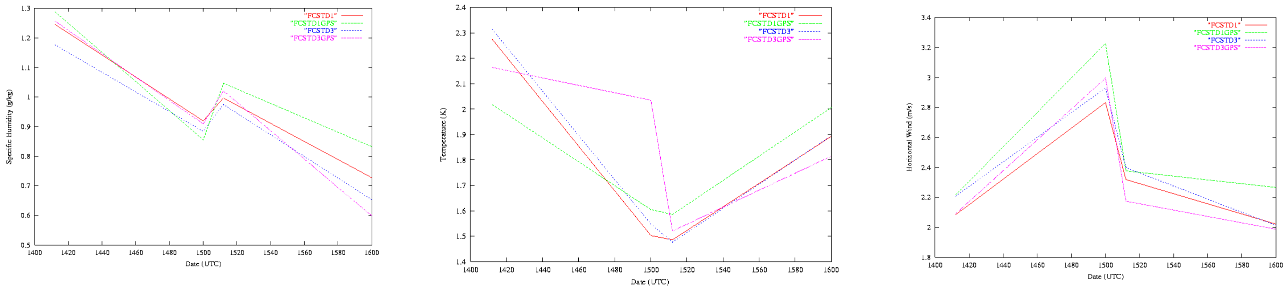

**Figure 5.** Root mean square errors with time in FCSTD1, FCSTD1GPS, FCSTD3, and FCSTD3GPS experiments for (a) wind, (b) temperature, and (c) specific humidity variables.