Report on

INM ASSIMILATION RESULTS

as deliverable 46 and 32 for the TOUGH project

by

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1. - INTRODUCTION.

Between June 2003 and January 2006 INM has participated in TOUGH European project by being involved in two different Wok Packages: WP7200 and WP5000.

The aim of WP7200 is to conduct *case studies and extensive impact studies with GPS data assimilation* and that of WP5000 is to do an *Optimisation of GPS/surface humidity assimilation*. Both of them have been developed at INM, together with other meteorological centres, according with TOUGH objectives.

For WP7200 several series of parallel experiments have been carried out at INM using different versions of the INM HIRLAM suite with two horizontal resolutions. Four time periods have been chosen to run these experiments, in order to see the impact of assimilating GPS Zenith Total Delay (ZTD) data with the HIRLAM 3Dvar system for different seasons.

Depending on the period, different number of ZTD GPS observations from GPS ground based stations have been fetched, depending on the number of processing centres that were available for TOUGH.

The periods chosen to run the experiments are:

1) Summer period: July 2003
2) 1st Autumn period: October 2003
3) Spring period: April-May 2004
4) 2nd Autumn period: October-December 2004

The impact on forecasts produced by the assimilation of GPS ZTD data apart of conventional observations has been tested over the summer period using two different background error constraint approaches through a set of assimilation experiments.

A GPS ZTD bias correction scheme has been tested for the 1st autumn period using a statistical background constraint approach.

Four different series of parallel experiments have been conducted at INM for the spring period to test different aspects of assimilating GPS ZTD data: one of them has been a study of the impact of increasing the number of GPS sites over the Iberian Peninsula, other two series have been conducted with the joint assimilation of both surface and GPS humidity observations without and with a tuning of the Quality Control parameters, and some preliminary experiments assimilating GPS ZTD observations in the HIRLAM 4DVar system have also been conducted at INM for this period.

Extensive GPS impact studies in quasi-operational conditions have been run using the INM computer facilities for a two month autumn period of 2004 to test the impact of assimilation of GPS ZTD data.

Diagnostics of the assimilation have been obtained for all the experiments at each period in order to understand the sensitivity of the HIRLAM system to GPS data assimilation.

Apart of performing an objective verification against surface synoptic stations and radiosondes over Europe for all the experiments, an objective verification against rain gauge data from the INM Climate Stations Network has been conducted. This network contains around 3500 stations all over the Iberian Peninsula with accumulated precipitation measurements every 24 hours. As verification of deterministic forecast against observations is very much conditioned by the represented spatial scales of both forecast and observations network, superobservations of precipitation at each grid box by averaging rain gauge at the available individual stations have been created in order to approach the scales of model forecasts and observation network. In this way, 209 superobservations have been calculated every day over Spain representing the upscaled rain gauge from the 3500 stations of the INM Climate Network to the 55km horizontal resolution of the HIRLAM experiments, and then compared with the 55km-model output, and around 1000 superobservations have been calculated every day over Spain representing the upscaled rain gauge from the 3500 stations of the INM Climate Network to the 22km horizontal resolution of the HIRLAM experiments and then compared with de 22km-model output. So, two different sets of precipitation data, upscaled INM rain gauge and synop rainfall, have been used to obtain contingency tables of observed/forecast precipitation for different forecast lengths corresponding to different precipitation thresholds and Contingency Tables of observed/forecast precipitation for different forecast lengths corresponding to different precipitation categories were obtained.

For WP5000 (*Optimisation of GPS/surface humidity assimilation*) several series of parallel experiments have been conducted at INM along the spring time period, in order to investigate the impact of assimilating surface humidity data with the HIRLAM 3Dvar system just as the joint assimilation of both surface and GPS humidity observations (WP5200), with the aim of helping the analysis to distribute in the vertical the error in the integrated water vapour content given by the information contained in GPS ZTD observations.

For this purpose, an appropriate observation operator for 2mRH in the HIRLAM assimilation system that translated the model variables into the measured quantities was needed. The 2mRH observation operator that existed in this system had not been updated according to the development of new land surface parametrization introduced in the HIRLAM model. Therefore, a new observation operator that has allowed assimilating two meter relative humidity observations in the HIRLAM variational data assimilation system, along with the corresponding tangent linear and its adjoint has been developed and tested at INM as it is described at TOUGH Deliverable D31 (WP5100).

All the experiments performed at INM for TOUGH project are being described in this document, distributed by time periods.

2. – SUMMER PERIOD.

An assimilation exercise has been run for a 15 days time period from 1st to 15th July 2003. It includes a severe weather event affecting the south-western coast of France. Météo-France reported for these days very high rainfall rates and strong wind speeds during the storm that hit the Arcachon Bay in the evening of 15th July.

HIRLAM 6.1.0. version with 55 km resolution has been used and the experiments have been carried out using the ECMWF computer facilities, in a wide area covering the North Atlantic and Europe, with a maximum forecast length of 48h in a 6h assimilation cycle of HIRLAM 3Dvar system.

Two alternative background constraint formulations available in the HIRLAM 3Dvar system have been used. They imply different cross covariances between errors of the model variables producing analysis corrections significantly different in both approaches (mainly in wind and humidity), although the observation usage is the same (observation operators and observation error statistics). The so-called analytical balance (Gustafsson et al. 2001) is based on a geostrophic balance for the wind components and the humidity analysis is unvaried. The alternative statistical balance (Berre, 2001) makes use of linear regressions between errors of vorticity, divergence, temperature and surface pressure, and humidity, thus allowing errors of this last variable to be linked to those of the rest.

The impact on forecasts produced by the additional assimilation of GPS ZTD data has been tested over this summer period using the different background error constraint approaches through a set of assimilation experiments:

- RAN (No GPS usage, analytical background constraint)
- GAN (GPS ZTD assimilated, analytical background constraint)
- RST (No GPS usage, statistical background constraint)
- GST (GPS ZTD assimilated, statistical background constraint)

GPS ZTD data were allowed to be introduced passively in the HIRLAM 3Dvar system in those experiments that did not assimilate GPS data. In this way the simulated by the model ZTD was calculated and compared to observations during the experiment run although GPS data were not assimilated. A simple redundancy check has been introduced to screen the ZTD data in the HIRLAM 3D variational system. It produces to only use in the analysis the observation closest to the analysis time from each GPS station. The observation error standard deviation for ZTD was initially set to 15mm, the same order of magnitude of the value of first guess ZTD error. As part of the observations screening a first guess check was switched on to remove from the minimization ZTD data with gross errors. No bias correction scheme has been yet applied to the data. All ZTD observations available for this period in the Met Office *thorn* server were presented to the analysis.

All experiments have assimilated the same conventional observation types apart of GPS ZTD: surface geopotential observations from land stations, ships and buoys, aircraft temperature and wind measured data, and vertical profiles of wind (PILOT balloons and radiosondes), temperature and humidity (radiosondes). No satellite data from geostationary or polar platform instruments have been assimilated in these experiments.

Some assimilation diagnostics have been produced. In particular, the root mean square (rms) of innovations (observation minus first guess values) and analysis residuals (observation minus analysis values) of ZTD for the whole period have been obtained for each GPS station. The rms of innovations seems to be decreased when GPS ZTD data are assimilated, as it is shown in figures 1 and 2 for the experiments RST and GST based on the same statistical background constraint. The rms of innovations is of the order of 13mm. Some stations in Spain and Scandinavia show larger departures of model ZTD from observations.

The root mean square of humidity analysis increments for each experiment has been obtained. Humidity analysis increments in model level 26 (around 850 hPa), are shown in figures 3 (RST), 4 (RAN), 5 (GST) and 6 (GAN). Contouring interval is 0.5g/kg. Main features are observed over Europe in all experiments. The largest analysis increments appear in experiments using the analytical background constraint (RAN and GAN). The impact of assimilating GPS ZTD data produces higher analysis increments over Scandinavia and the Iberian Peninsula whatever the background constraint approach was used. These areas correspond to the largest ZTD innovations according to figure 1. Also rms of the differences between humidity analyses for the different experiments has been calculated. Maps of these differences at 850hPa are shown in figures 7 (RAN vs. RST), 8 (GAN vs. RAN), 9 (GST vs. RST) and 10 (GAN vs. GST). Figures 7 and 10 indicate that the different background error constraint formulation is affecting mainly to the southern part of the model area, in particular over the Atlantic Ocean. As it is shown in figures 3 to 6 the analysis increments are negligible in this area, so these differences seem to be produced during the model integration. Figure 10 also shows that the assimilation of GPS data with the different background constraints is also affecting the humidity analysis in northern Scandinavia. The impact of GPS data assimilation is again observed in those areas showing the largest innovations, (Scandinavia, the Iberian Peninsula and Italy) according to figures 8 and 9. They also show some areas over the Atlantic influenced by the assimilation of GPS data.

The fit of first guess and analysis to humidity radiosonde measurements has been calculated for the different experiments to investigate the impact of GPS measurements in the assimilation cycle (figures 11, 12 and 13). In both background constraint formulations the distance to the first guess from radiosonde humidity observations seems to be same in the vertical whatever the experiment assimilated or not GPS data, with the exception of the lowest atmospheric levels. Below 800hPa, the usage of ZTD data increases the distance of radiosonde humidity observations to first guess. In these figures it is also observed that the fit of the analysis to radiosonde humidity is larger in case of experiments based on the analytical background error constraint. However this closer distance is lost during the next model integration.

Objective verification against radiosondes of the subsequent forecasts does not show any impact of GPS data on any variable with the exception of humidity. Verification of the reported precipitation in land synoptic stations has been produced as part of the HIRLAM suites. Contingency Tables of observed/forecast precipitation for different forecast lengths corresponding to different precipitation categories have been obtained. Some standard scores have been calculated from them showing a clear impact of the usage of GPS data in both background constraint formulations.

As it has been already mentioned, this trial period includes a severe weather event over France in the evening of 15th July 2003. Météo France reported strong winds and intense rainfall in south west France. INM radar located in the Basque Country also detected heavy precipitation over this area. Maps of forecast precipitation valid for this date from each of four experiments are shown in figures 14 to 17. The impact of GPS assimilation is clear in this case. Both experiments assimilating GPS are able to predict significant precipitation over a coastal area in south-western France although the maximum is shifted towards the north of the region where it produced.

3. – 2003 AUTUMN PERIOD.

A series of parallel experiments have been run for a 24 days long period in the autumn 2003. These experiments have been carried out with the HIRLAM 6.2. system using the ECMWF computer facilities, in a wide area covering the North Atlantic and Europe (55km horizontal resolution. 31 vertical levels), with a maximum forecast length of 48h in a 6h assimilation cycle of HIRLAM 3Dvar system.

The time period chosen to carry out the experiments, October 2003, was very rainy at the Iberian Peninsula. Around mid-October several heavy precipitation events happened in eastern Spain, with more than 100 mm rainfall in a few hours in some places in Levante and Cataluña.

The HIRLAM 3D variational data assimilation system setup has been based, for these experiments, on the statistical formulation of background constraint, in which the analysis of the humidity variable is coupled to that of the mass and wind variables. All experiments have assimilated the same conventional observation types apart of GPS ZTD: surface geopotential observations from land stations, ships and buoys, aircraft temperature and wind measured data, and vertical profiles of wind (PILOT balloons and radiosondes), temperature and humidity (radiosondes). No satellite data from geostationary or polar platform instruments have been assimilated in these experiments.

For this period a bias correction of GPS ZTD innovations has been used in one of the experiments, introducing the bias correction scheme developed at SMHI by Ridal and Gustafsson. The bias removal of GPS ZTD innovations has been also applied separately to each time of day due to innovation at some GPS sites seems to present diurnal cycle.

The experiments or this period have been four:

- RST (Reference experiment)
- GST (Assimilation of GPS observations without any bias reduction)
- GSB (Assimilation of GPS observations with bias correction)
- GSD (Assimilation of GPS observations with bias correction taking into account the diurnal cycle)

The difference between RST and GST is just the assimilation that GST has done of GPS ZTD data apart of the conventional observations. And so GSB but using the bias reduction scheme developed by SMHI. In experiment GSD a different bias file is applied to innovations depending on the time of the day (00, 06, 12 and 18 UTC).

Although RST experiment doesn't assimilate GPS data, GPS ZTD data were allowed to be introduced passively in the HIRLAM 3Dvar system. In this way it was possible that the simulated by the model ZTD was calculated and compared to observations during the experiment run.

Comparison of RST and GST has allowed to see the sensitivity of the HIRLAM forecasts to the assimilation of GPS data for this period, while comparing results of GST, GSB and GSD we can find the impact of the bias reduction in the same period, and the bias reduction strategy more appropriate.

GPS ZTD Near Real Time observations coverage is good for this time period from nine different processing centres. Some FORTRAN routines have been coded to read the data from the different centres, according with its own file format, and choosing for each one of them a list of GPS stations in order to avoid redundancy of any GPS station. The lists of GPS stations selected for each processing centre have been the same for the whole period. Once all this data has been introduced, a simple redundancy check has been done to screen the ZTD data in the HIRLAM 3D variational system that selects the observation closest to the analysis time from each GPS station to be used in the analysis.

The observation error standard deviation for ZTD was initially set to 10 mm, the same order of magnitude of the assumed value of first guess ZTD error (12 mm).

As part of the observations screening, a first guess check was switched on to remove from the minimization ZTD data with gross errors.

Similar assimilation diagnostics to those obtained previously have been produced for these experiments. In particular, the root mean square (rms) of innovations and analysis residuals of ZTD for the whole period has been obtained for each GPS station. The rms of innovations seems to decrease when GPS ZTD data are assimilated. In RST and GST experiments, rms of innovations is of the order of 13 mm. The places where model equivalent ZTD values are closer to the observations are located over Central Europe whereas for Spain, Pyrenees, Italy, and S-W Scandinavia, values are tiny higher.

The root mean square of the humidity analysis increments for each experiment and the rms of the differences between the humidity analysis for the different experiments have been calculated.

Humidity analysis increments in model level 26 (around 850 hPa), are shown in figures 18 (RST), 19 (GST) and 20 (GSB) with a contouring interval of 0.5g/kg. It is clear the impact of introducing GPS data in the assimilation system, especially on the areas that correspond to the largest ZTD innovations. Humidity analysis increments higher than 0.5g/kg appear in some areas of Scandinavia, England, France, Spain and Italy. Figure 20 shows that the humidity analysis increment pattern in the GSB experiment is almost the same that in GST experiment (and so the GSD). The introduction of the bias correction scheme in GSB only reduces locally in some places in Central Europe and Scandinavia the magnitude of the analysis increment.

The rms of the differences between humidity analysis for the different experiments has been calculated. Maps of these differences at 850hPa are shown in figures 21 (RST vs. GST) and 22 (GST vs. GSB). The assimilation of ZTD data produces significant differences in the humidity analysis not only where the analysis increments pattern differ but also over a wide area over the Atlantic in the southern part of the model domain. The effect of the bias correction of ZTD innovations is very small with the exception of the same area over the ocean to the southwest of Spain, where the differences between analysis reach locally 1g/kg.

Also the fit of first guess and analysis to humidity radiosonde measurements have been obtained (not shown here). For the four experiments, the distance to the first guess from radiosonde humidity observations seems to be same in the vertical whatever the experiment assimilated or not GPS data, (and whatever reducing or not the bias) with the exception of the lowest atmospheric levels. Below 800hPa, the usage of ZTD data increases the distance of radiosonde humidity observations to first guess. The introduction of the bias reduction scheme produces a decreasing of the bias of the humidity first guess with respect to radiosonde data, although the rms of this distance is kept to the same observed in GST experiment.

Apart of obtaining objective verification scores against surface synoptic stations and radiosondes over Europe, rain gauge data from the INM Climate Stations Network have been used for a better verification of the model precipitation of these three experiments. Superobservations of precipitation at each grid box by averaging rain gauge at the available individual stations have been calculated. In this way, 209 superobservations have been calculated every day over Spain that represent the upscaled rain gauge from the 3500 stations of the INM Climate Network to the 55km horizontal resolution of the HIRLAM experiments.

Two different sets of precipitation data, upscaled INM rain gauge and synop rainfall have been used to obtain contingency tables of observed/forecast precipitation for different forecast lengths corresponding to different precipitation thresholds. Some standard scores have been calculated like True Skill Score (TSS), Equitable Threat Score (ETS), Hit Rate, Probability of Detection, False Alarm Rate and Frequency Bias. The results obtained using the different datasets differ. Looking at those obtained with upscaled rain gauge data (figure 23), both TSS and ETS scores agree that the assimilation of GPS ZTD improves the model precipitation for almost all precipitation thresholds (0.1,0.3,1.,3.,10. mm in 24h), with the exception of the last category corresponding to rainfall larger than 30mm in 24h. The benefit seems to be related to a higher probability of detection, by keeping the same false alarm rate. The impact of the bias reduction scheme is only noticed for the category corresponding to 10mm threshold, for which it seems to improve to experiment GST. Looking at the frequency bias, it is observed that all experiments tend to slightly overperdict the model precipitation, specially for model rainfall larger than 30mm in 24h. The assimilation of GPS data still enhances this behaviour, GST experiment the most.

Although time series of innovation and bias correction at single GPS stations show that the relative effect of bias reduction is more relevant in GSD than in GSB experiment, verification of precipitation of both experiments against INM climate stations rain gauge (figure 23) doesn't show a remarkable improvement of GSD experiment. Just in lowest and highest categories of precipitation GSD shows better forecast than GSB**,** but as much, reaching the quality of experiment GST (with no bias reduction).

When looking at the same scores calculated using 12h accumulated precipitation reported in synops from Iberia (not shown here) it can be seen that they do not reproduce the same conclusions obtained using the upscaled rain gauge data. Moreover, the absolute value of ETS and TSS is smaller that those found with upscaled rain gauge data. In some categories ETS and TSS disagree. The observed frequency bias is completely different to that obtained with upscaled observations. It indicates a much more overprediction of model precipitation for the small precipitation amounts, and underestimation for the categories corresponding to the largest thresholds. These results suggest that the usage of the proper dataset to evaluate the model precipitation is critical to avoid misleading conclusions.

4. – SPRING PERIOD.

The series of parallel experiments run for this period have been performed with the HIRLAM 6.3.5 version using the ECMWF computer facilities, in a wide area covering the North Atlantic and Europe but at a larger horizontal and vertical resolution (22 km horizontal resolution and 40 vertical levels) similar to the HIRLAM-INM operational domain, with a maximum forecast length of 48h in a 6h assimilation cycle of HIRLAM 3Dvar system.

The HIRLAM 3D variational data assimilation system setup has been based, for these experiments, on the statistical formulation of background constraint. Background error statistics used in this implementation have been calculated at INM using NMC method applied to forecast differences from FMI operational run in spring 2003. A tuning of *sigmab* value has been carried out through BGOS, and a new value of observation error standard deviation, *sigmao*, (18 mm) for GPS ZTD assimilation has been tuned by using the results on correlations of ZTD innovations found by B.Stoew and G.Elgered 2005 being this value introduced in the GPS ZTD assimilation code higher than the one used for other periods (10mm and 15mm). In order to optimise background and observation errors, the method proposed by Desroziers et al. (2005) to diagnose observation and background error variances derived from innovations and residuals has been applied to GPS ZTD observations. The procedure has produced a *sigmab* and *sigmao* values of 9mm and 8mm respectively, indicating an overestimation of the assumed error statistics in the HIRLAM variational assimilation code.

No bias reduction scheme has been applied to GPS ZTD observations at any experiment.

The time period chosen to carry out the experiments, 15April-15May 2004, was very wet in most of Spain, with heavy rain events in Levante and Andalucia at the beginning of May. Two different case studies have been selected from this period: 2nd may 2004 that was very rainy in southern the Iberian Peninsula (Andalucia), with precipitations that reached more than 60 mm in Cadiz, and 11th may 2004 that was rainy in eastern Spain, with more than 80mm rainfall in a few hours in Levante.

Four different series of parallel experiments have been conducted at INM for this period, in one of them the impact of increasing the number of GPS sites over the Iberian Peninsula has been studied, in other the joint assimilation of both surface and GPS humidity observations has been performed, for the third serie of experiments a tuning of some Quality Control parameters have been conducted and at last, some preliminary experiments assimilating GPS ZTD observations in the HIRLAM 4DVar system have been carried out at INM.

4.1.- Impact of addition of new GPS stations from Spanish Geographical Institute

Apart of the GPS ZTD data available for TOUGH and due to the poor coverage of GPS ground based stations over the Iberian Peninsula, new GPS data from the Spanish Geographical Institute (IGN) has been introduced in HIRLAM to see the impact of increasing the ground based GPS ZTD network density over Iberia and surroundings for the same period and with the same model features.

The GPS data distribution is shown in figure 24. First one represents the TOUGH network , currently available, and the second one this network together with the IGN network, with around 30 stations that covering Spain, Portugal, Canary Island, Azores, and Northern Africa.

Two experiments have been performed in this case: experiment GP8 just assimilating GPS data from the TOUGH network and GP9 assimilating GPS ZTD data from both TOUGH and IGN networks.

Verification of the model precipitation for the two experiments is shown in figure 25 Contingency tables comparing precipitation rain gauge from the INM Climate station network, with 24 hours forecast have been calculated, and it can be observed that for accumulated precipitation higher than 3 mm in 24 hours, there is an improvement of the precipitation forecast when increasing the number of GPS sites (GP9 better than GP8), again linked to a better probability of detection and a cuasi-equal false alarm rate.

Maps of model 24 hours accumulated precipitation for each experiment have been plotted to compare with INM Climate Stations Network rain gauge for the case study of 2nd may 2004,very rainy in southern the Iberian Peninsula (Andalucia). This is shown in figure 26 and it is possible to appreciate how the precipitation pattern is more realistic on GP9 (with more GPS sites) experiment, both in southern and eastern of Spain.

4.2.- Testing combined GPS ZTD/ surface humidity assimilation.

As part of Work Package 5000, a new RH2m observation operator has been developed at INM. The old RH2m observation operator for near surface parameters that is available in the HIRLAM three dimensional variational assimilation (3DVAR) system is based on Monin-Obukhov similarity theory for the surface layer and it follows the method proposed by Geleyn (1988) for the vertical interpolation between the lowest model level and the surface. At the time when it was developed an older parameterisation for the land surface processes was installed in the HIRLAM forecast model. But the present one is based on a mosaic scheme in which the land tiles follow the ISBA scheme what has produced that the computation of model two meter relative humidity in the observation operator is not already valid, as it is mentioned in TOUGH deliverable report D30. In order to allow the assimilation of surface relative humidity observations, new FORTRAN routines for a simple observation operator for two-meter relative humidity (RH2m), the tangent linear and its adjoint have been coded, tested, and then introduced in the HIRLAM 3DVAR assimilation system by INM. This observation operator assumes that relative humidity is constant in the unstable surface layer, so RH2m can be directly compared to RH in the lowest model level. The smaller coupling between the near surface and the uppermost atmosphere in stable case is taken into account by increasing substantially the observation error what produces the RH2m observations to have no weight in the upper air analysis in this case.

This new observation operator for RH2m, the tangent linear and its adjoint have been first tested in a series of parallel experiments over this period and then tested through a serie of parallel tests. So, the sensitivity of HIRLAM forecasts to the assimilation of GPS Zenith Total Delay (ZTD) data, to the assimilation of RH2m observations from synoptic stations and to the combined usage of both near surface humidity and GPS ZTD observations has been investigated in this period.

With respect to RH2m observations, observation error variance for 2mRH assimilation has been assigned similarly to radiosonde observations. An empirical regression of errors of relative humidity dependent on temperature is used (Lindskog et al., 2001) and it produces values of 2mRH error standard deviation around 10% over Europe in spring time.

The 2mRH background error standard deviation can be estimated using a Monte Carlo technique installed as option within (Schyberg et al 2003) the HIRLAM 3D-Var assimilation code that follows the method suggested by Fisher and Courtier (1995), and it produces an average background error standard deviation of 2mRH around 7% over land.

The observation error to background error ratio for 2mRH has been also separately estimated from the HIRLAM surface analysis innovations. The obtained *sigmao* to *sigmab* ratio value for the error statistics calculated from the HIRLAM surface analysis at daytime is smaller than those used in the HIRLAM upper air variational assimilation system.

The impact of RH2m and GPS ZTD respectively, as its combination has been tested in the following experiments:

- RE5 (Reference experiment: passive GPS ZTD and RH2m observations)
- RH9 (Passive GPS ZTD obs. + Assimilation of RH2m observations)
- GP9 (Assimilation of GPS ZTD observations + Passive RH2m obs.)
- RG1(Assimilation of GPS ZTD and RH2m observations).

GPS ZTD observations for this time period have been fetched from ten different processing centres and from the Spanish Geographical Institute (IGN) network.

Apart of GPS ZTD and RH2m observations, all experiments have assimilated the same conventional observation types: surface geopotential observations from land stations, ships and buoys, aircraft temperature and wind measured data, and vertical profiles of wind (PILOT balloons and radiosondes), temperature and humidity (radiosondes). No satellite data from geostationary or polar platform instruments have been assimilated in these experiments.

Control experiment, RE5, has been run with all available GPS ZTD and RH2m observations introduced passively through the HIRLAM 3Dvar system.

RH9 experiment assimilates RH2m observations from land surface stations over the model domain. GP9 assimilates GPS ZTD data from TOUGH dataset together with the Spanish Geographical Institute (IGN) network, and RG1, assimilates both types of observation at the same time.

Comparison of RE5 with RH9 or GP9 has allowed studying the sensitivity of the HIRLAM forecasts to the assimilation of RH2m observations or GPS data respectively for this period, while RG1 has permitted to investigate the impact of the combined assimilation of GPSZTD/RH2m humidity observations.

All the GPS ZTD observations available from three hours before the analysis time until two hours later to this time were presented to the analysis. Once all these data have been introduced, a simple redundancy check has been done to screen the ZTD data in the HIRLAM 3D variational system, which selects the observation closest to the analysis time from each GPS station to be used in the analysis. No bias reduction scheme has been applied to GPS ZTD observations at any experiment.

The statistical balance formulation has been used as background constraint in the HIRLAM 3D variational assimilation system in all experiments.

Similar assimilation diagnostics to those obtained for other impact experiments have been produced.

The root mean square (rms) of the humidity analysis increments for each experiment and the rms of the differences between the humidity analysis for the different experiments have been calculated at 12 UTC.

Humidity analysis increments at 12UTC for experiments RE5, RH9, GP9 and RG1 at model level 30 (around 850 hPa) are shown in figure 27 , and at the lowest model level (40) are shown in figure 28 (0.5g/kg contouring interval). The assimilation of RH2m observations produces larger humidity analysis increments at the lowest model level (as it is observed in figure 28), whereas the assimilation of GPS ZTD observations produces the largest impact at 850 hPa. Maps of rms analysis differences of specific humidity between control and the rest of experiments at model levels 30 and 40 have also been obtained and it can be observed that the differences appear not only over Europe but also over Africa and the Atlantic. The combined assimilation of GPS ZTD and RH2m observations is producing the largest differences, not only in magnitude but also in extension. At the lowest model level, the assimilation of RH2m observations produces similar differences with control in RH9 and RG1 experiment, as it is observed in northern Europe. Around 850hPa if GPS ZTD data are assimilated, the differences increase and spread over Europe. The largest amplitudes appear over the Ocean in all experiments.

Verification of model variables at four different model levels (Surface, 850 hPa, 500hPa, 250 hPa) has been calculated for different station lists. The largest impact is seen in relative humidity over Spain, (figure 29) where GPS experiments GP9 and RG1 are moister than RH9 and control RE5, what improves the bias when assimilating GPS ZTD. This impact is higher for the lower levels and it is lost when increasing the forecast length. Verification against EWGLAM station list shows the same features that against Spanish stations but they are less noticeable.

Verification of the model precipitation for the different experiments has revealed a clear sensitivity to the assimilation of near surface humidity or/and ground based GPS data, as it had been found in other experiments. Validation of the model precipitation has been based on upscaled rain gauge from the high-resolution INM Climate stations network in order to approach to model resolved scales, as it has been already mentioned previously. Superobservations of precipitation at each grid box have been created by averaging rain gauge at the available individual stations, so around 1000 superobservations have been calculated every day over Spain and they represent the upscaled rain gauge from the 3500 stations of the INM Climate Network to the 22km horizontal resolution of the HIRLAM experiments.

Contingency tables of observed/forecast precipitation for different forecast lengths corresponding to different precipitation thresholds (0.1, 0.3, 1., 3., 10., 30., 100. mm in 24 hours) have been obtained and some standard scores like True Skill Score (TSS), Equitable Threat Score (ETS), Hit Rate, Probability of Detection, False Alarm Rate and Frequency Bias have been calculated. Contingency table for 24 hours forecast length is shown in figure 30 and it can be seen that for accumulated precipitation higher than 3 mm in 24 hours, the highest TSS and ETS scores are reached by GP9 experiment and then by RG1, followed by RH9**,** being control RE5 the experiment that shows the lowest values. It seems that the assimilation of any kind of humidity observation has a positive impact, and that assimilation of GPS ZTD observations without surface humidity produces the largest improvement of the model precipitation for moderate to intense precipitation events. The benefit appears to be related to a higher probability of detection, by almost keeping or slightly decreasing the false alarm rate. The impact of the assimilation of RH2m observations together with GPS data seems to be positive and bigger than assimilating just RH2m observations but it is smaller than assimilating only ZTD data.

Maps of model 24 hours accumulated precipitation in each experiment have been plotted to compare with INM Climate Stations Network rain gauge for two different case studies: 2nd may 2004 that was very rainy in southern the Iberian Peninsula (Andalucia), with precipitations that reached more than 60mm in Cadiz, and 11th May 2004 that was rainy in eastern Spain, with more than 80mm rainfall in a few hours in Levante. In the first case (figure 31) GP9 seems to be the experiment that best predicted rainfall, locating the maximum of precipitation where it took place in the southern coast of Andalucia, and even better than RG1, that didn't extend the precipitation pattern towards the Levante coast enough. RH9 improved very little the control RE5 and none of these two runs could see the observed precipitation pattern out of Andalucia and central Spain. In the second case study (not shown here) although the differences are less noticeable it seems that GP9 and RH9 could predict slightly better the maximum of precipitation that occurred in Levante than the other two experiments and the run that assimilated RH2m observations was the one that could see better the general precipitation pattern. It seems that for both case studies, any inclusion of humidity observation improves the forecast.

4.3.- Testing combined GPS ZTD/ surface humidity assimilation with new QC parameters.

Parallel experiments have been conducted at INM for this period, to study the impact of tuning some Quality Control (Q.C.) parameters of the First Guess Check and the Variational Quality Control on the assimilation of GPS ZTD observations, near surface humidity observations, and the joint assimilation of both surface and GPS humidity observations apart of the rest of conventional observations.

Histograms of ZTD innovations and analysis residuals have been calculated in order to identify the first guess and analysis departures from observations corresponding to non Gaussian errors, and they have been used to tune new quality control parameters in the first guess check and Variational quality control according to Andersson and Järvinen (1999).

Rejection limits for the first guess quality control (FgQC) have been determined from normalized histograms of observation departures from the background and VarQC parameters have been determined from transformed histograms of normalized departures from the analysis. The histograms were transformed according to

$$\hat{f} = \sqrt{-2\ln\left[f \big/ \max(f) \right]}$$

where f is the number of data in each bin of the histogram (Hollingsworth, 1989). These FgQC rejection limits and the VarQC parameters have been determined such that rejection would occur for data values with significantly higher frequencies than is compatible with an assumption of a Normal distribution.

Some preliminary experiments (not shown here) have been performed at INM assimilating both ZTD GPS and surface humidity observations having adjusted both the FgQC and the VarQC. VarQC adjustment consisted on increasing the probability of gross error of the observations (ZTD GPS observation and RH2m observations) and FgQC adjustment was done by decreasing the rejection limits. The results obtained have shown that both QC adjustments together were too tight and too many data were rejected. As a result of this, the objective verification showed that the impact of assimilating humidity data with these new FgQC and VarQC settings was not positive.

After these preliminary experiments, a simple adjustment of FG check by keeping the original VarQC parameter has been tested.

The experiments can be described as:

- GP9 (Assimilation of GPS ZTD observations)
- PP0 (Assimilation of GPS ZTD observations and NEW VarQC)

- RH9 (Assimilation of RH2m observations)
- RH0 (Passive GPS ZTD obs and NEW VarQC)

- RG1 (Assimilation of GPS ZTD and RH2m observations)
- RP0 (Assimilation of GPS ZTD and RH2m observations and NEW VarQC)

Apart of GPS ZTD and RH2m observations, all experiments have assimilated the same conventional observation types: surface geopotential observations from land stations, ships and buoys, aircraft temperature and wind measured data, and vertical profiles of wind (PILOT balloons and radiosondes), temperature and humidity (radiosondes). No satellite data from geostationary or polar platform instruments have been assimilated in these experiments.

All the GPS ZTD observations available from three hours before the analysis time until two hours later to this time were presented to the analysis. Once all these data have been introduced, a simple redundancy check has been done to screen the ZTD data in the HIRLAM 3D variational system, which selects the observation closest to the analysis time from each GPS station to be used in the analysis. No bias reduction scheme has been applied to GPS ZTD observations at any experiment.

The statistical balance formulation has been used as background constraint in the HIRLAM 3D variational assimilation system in all experiments.

GP9 and GP0 assimilate GPS ZTD data from TOUGH dataset together with the Spanish Geographical Institute (IGN) network, being GP0 QC more strict than GP9 QC, specifically the FgQC, where a ZTD GPS innovation (first guess minus observation) rejection limit of 56 mm is permitted to enter to the analysis (while before it was 87mm).

RH9 and RH0 experiments assimilate RH2m observations from land surface stations over the model domain being RH0 more restrictive than RH9. While RH9 permitted a 2mRH innovation rejection limit of 57% to enter to the analysis, RH0 just permits 40%.

In RG1 and RP0 experiments, apart of conventional observations, both types of humidity observations are assimilated at the same time and have the same features than the experiments before: RP0 is more restrictive on the First Guess Quality control than RG1 in assimilation of both ZTD GPS and RH2m observations, having a ZTD GPS innovation (first guess minus observation) rejection limit of 56 mm to enter to the analysis and a 2mRH innovation rejection limit of 40%.

Contingency tables of observed/forecast precipitation for different forecast lengths corresponding to different precipitation thresholds (0.1, 0.3, 1., 3., 10., 30., 100. mm in 24 hours) have been obtained and some standard scores like True Skill Score (TSS), Equitable Threat Score (ETS), Hit Rate, Probability of Detection, False Alarm Rate and Frequency Bias have been calculated. Contingency table for 24 hours forecast length for GP9 and PP0 experiments is shown in figure 32 and it can be seen that the tuning of FgQC has a neutral impact on assimilation of ZTD GPS data, while, as is shown in figure 33, the impact is positive for accumulated precipitation higher than 10 mm in 24 hours when assimilating RH2m observations. Contingency table for 24 hours forecast length for RG1 and RP0 experiments is shown in figure 34 and it can be seen that the impact of this tuning is negative for all the precipitation thresholds. So it seems that being more restrictive on First Guess Quality Control has a slight positive impact on the model precipitation for moderate to intense precipitation events when assimilating RH2m observations, has a neutral impact when assimilating ZTD GPS data and has a negative impact in case of combined assimilation of surface and GPS humidity.

Verification of the model precipitation for the experiments before tuning the FgQC showed that for accumulated precipitation higher than 3 mm in 24 hours, the highest TSS and ETS scores were reached by GP9 experiment and then by RG1, followed by RH9, being the three of them better than control experiment. It was found that the assimilation of any kind of humidity observation had, in general, a positive impact, and the impact of the assimilation of RH2m observations together with GPS data seemed to be positive and bigger than assimilating just RH2m observations but it was smaller than assimilating only ZTD GPS data. Looking at the verification of the model precipitation for the experiments after having tuned the FgQC (figure 35) the highest TSS and ETS scores is reached by the experiment that just assimilated GPS, PP0, for accumulated precipitation higher than 3 mm in 24 hours, and then by RH0, then by control and by RP0, having this combined experiment the worst skill.

On the other hand, verification of the model forecasts has been done for surface (figure 36) and upper air, and the experiment assimilating GPS ZTD and RH2m together shows to be moister, removing the dry bias observed in the other experiments and then improving the surface humidity as seen in its corresponding rms.

So, tuning of FgQC parameters (of ZTD and surface humidity observations) seems to be positive according to verification scores of relative humidity, although the combined GPS and RH2m assimilation doesn’t seem to produce better precipitation forecast for heavy rain events.

4.4. - GPS data impact with 4Dvar

Preliminary tests have been performed over the 9-12 May 2005 case study to see the impact of assimilating GPS data with the recently developed HIRLAM 4DVAR assimilation system. The synoptic environment (figures not shown here) corresponds to a typical weather situation producing heavy precipitation in the Mediterranean Spanish coast. At 500hPa a cutoff low is located between the southeastern Spanish coast and northern Africa. At the lowest levels a cyclogenesis took place in front of the Valencia coast. In this situation a strong easterly and moist flow is reaching the Balearic Islands and the Levante coast at the lowest atmospheric levels.

Two 4DVAR experiments with a 6hours assimilation window have been run without/with GPS ZTD data, apart of all conventional observation types. The 4DVAR configuration is based on a multi-incremental approach in which the assimilation increments are progressively found at 66km and 44km, using the HIRLAM grid point model for the computation of the non-linear trajectory and the tangent linear and adjoint of the HIRLAM spectral model within the minimization inner loop. Météo France simplified physics is employed to parametrize vertical diffusion and large scale condensation processes within the tangent linear and adjoint forecast model.

A subjective verification of the model precipitation for this case study is shown in figure 37. It is possible to see how the pattern of the predicted rainfall is better cached by the 4DVAR experiment that assimilated GPS ZTD data, in particular the extension of moderate precipitation to central Spain and the intensity of precipitation over several areas, as e.g. the Balearic Islands. It has also been observed that the gradient, location and pressure of centre of the low are better simulated by the 4DVAR experiment assimilating the available GPS ZTD data (TOUGH and IGN networks).

5. – 2004 AUTUMN PERIOD

Extensive GPS impact studies in quasi-operational conditions have been run using the INM computer facilities. Two parallel experiments have been conducted for a two month autumn period starting on the 13th October 2004 to test the impact of assimilation of GPS ZTD data.

- ONR (Reference experiment: passive GPS ZTD observations)
- ONG (Assimilation of GPS ZTD observations)

Both runs are based on the HIRLAM operational system at INM taking the INM domain with 17 km horizontal resolution and 40 vertical levels, using ECMWF forecasts as boundaries and assimilating conventional and satellite observations, (geopotential from surface sea and land reports, wind and temperature from aircraft reports, radiosonde and pilot balloon data and AMSU-A brightness temperatures received through EUMETCAST system) apart of ZTD GPS data. GPS ZTD data from all available processing centres were introduced in passive mode in the control experiment, ONR, and assimilated in the experimental run ONG.

Verification of the model forecasts has been done in the same way that the previously described experiments carried out on the ECMWF computer facilities over spring 2004 (Figures 38 to 42). Apart of obtaining the standard verification scores for surface and upper air, rain gauge data from the INM Climate stations network has been used to asses the model precipitation. The results obtained agree with those found in other periods: the impact of GPS ZTD assimilation is visible in near surface humidity decreasing with forecast length and in model precipitation. The experiment assimilating GPS ZTD shows to be moister, removing the dry bias observed in the control experiment and then improving the surface humidity as seen in the corresponding rms. The time evolution of two-meter relative humidity errors shows that it is not only a constant lift of model humidity. The improvement becomes more noticeable when the model error increases, as it is shown over France 24-26 October 2004. On the other hand, it is observed that in December 2004 the impact of assimilating GPS ZTD persists longer and also benefits the near surface temperature forecast in all areas studied (Europe, Spain and Portugal, France) and using the EWGLAM stations list. Verification of model precipitation over Spain shows that the assimilation of GPS ZTD improves the model skill for precipitation amounts larger than 1mm in 24h. The frequency bias indicates that ONG experiment still overestimates more the model precipitation than control for all categories below 30mm in 24h. With the exception of the smaller precipitation amounts, the better skill seems to be due to a larger improvement in the probability of detection with respect to the deterioration produced in the false alarm rate when assimilating GPS ZTD data.

6. – SUMMARY.

Between June 2003 and January 2006 INM has been intensively working on TOUGH Work Packages 5000 and 7200.

Four different periods have been chose to perform impact studies of assimilation of ZTD GPS data in HIRLAM model. The impact on forecasts produced by the assimilation of GPS ZTD data apart of conventional observations using two different background error constraint approaches has been tested through a set of assimilation experiments over a summer period. A GPS ZTD bias correction scheme using a statistical background constraint approach has been tested for a 2003 autumn period. A study of the impact of increasing the number of GPS sites over the Iberian Peninsula, and of the impact of assimilating both surface and GPS humidity observations without and with a tuning of the Quality Control parameters, and some preliminary experiments assimilating GPS ZTD observations in the HIRLAM 4DVar system have been conducted at INM for a spring period. Extensive GPS impact studies in quasi-operational conditions to test the impact of assimilation of GPS ZTD data have been run at INM for a two month autumn period of 2004.

The general conclusions after having performed all of these impact studies could summarize as:

1) The main impact of assimilating ground based GPS data is observed on humidity and precipitation fields. Positive impact is found not only for heavy precipitation but also for moderate precipitation amounts.

2) GPS ground based data assimilation produces a moister initial state and a lift of precipitation forecast but also an improvement of the model skill (POD improvement larger than FAR degradation).

3) Better GPS data coverage leads to an improvement of the model skill.

4) After a tuning of QC parameters (of ZTD and surface humidity observations) the combined GPS+RH2m assimilation doesn’t produce better precipitation forecast for heavy

rain events. However this combined assimilation seems to be positive according to Verification of relative humidity.

5) The impact of assimilation of GPS ZTD data has been found through parallel experiments performed over an extended period (in the autumn 2004) in quasi-operational conditions. The results show that assimilation of GPS ZTD data carried out produces an improvement of model mean sea level pressure (November 2004), the 2m-Temperature (December 2004), the surface humidity (October, November, December 2004), and the model precipitation.