Application of GPS derived water vapour for Numerical Weather Prediction in Switzerland

Inauguraldissertation
der Philosophisch-naturwissenschaftlichen Fakultät
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Summary

This PhD thesis investigates the applicability of the Global Positioning System (GPS) to Numerical Weather Prediction. The work was carried out in the group Radiometric Methods for Environmental Monitoring of the Microwave Department at IAP, which is concerned with the development and operation of Water Vapour Radiometers for measurement of tropospheric water vapour and liquid water. For the first time in the group an application of the water vapour measurements for weather prediction was considered. The GPS provides high temporal and spatial resolution measurements of water vapour, which have recently become available for operational Numerical Weather Prediction (NWP). The first step in investigating the potential of the GPS derived water vapour was validation of the data with the standard humidity observations as well as NWP model validation. This work is described in the first part of this thesis. Through participation of the IAP in the COST Action 716 and the active co-operation of the Federal Office of Meteorology and Climatology (MeteoSwiss) it was possible to proceed with investigating the direct impact of assimilation of GPS measurements on the performance of the operational mesoscale system of MeteoSwiss - the aLpine Model (aLMo). Four assimilation experiments with aLMo have been computed and analysed. Those are summarised in the second part of this thesis. This thesis is dedicated, firstly, to validation of GPS derived Integrated Water Vapour (IWV) with independent humidity observations, and secondly, to validation of IWV field of the NWP models. In the validation work only post-processed GPS data were considered as having the best accuracy. The validation of GPS data with the radiosonde IWV showed a very good agreement in winter time. However, in low stratus winter conditions the radiosonde was occasionally found to overestimate IWV amount as a result of the slow recovery time of the humidity sensor after cloud passage. The yearly intercomparison gives contradictory results for the midnight and midday sounding, possibly due to changes in the GPS processing. The model validation using GPS shows a seasonal dependence of the bias and the standard deviation. The model tends to underestimate the IWV in summer, but this differs from

year to year, being more significant in 2002 than in 2001. The investigated diurnal IWV cycle in the summer months confirms the dry bias in the model, which is possibly coupled with reported precipitation overestimation. The overestimation of precipitation is a known deficiency of the model and can possibly be overcome by direct assimilation of the GPS data in the model and parameterization improvements.

The four Observing System Experiments (OSE) conducted in Switzerland involved near-real time GPS data assimilation in aLMo. The near-real time GPS data were requested for operational NWP time window 1h 45min after the observation, and they were provided by the COST 716 processing centres. Assimilated in the model were 100 European sites in three different weather regimes in summer, winter and autumn. The following can be concluded: GPS data were successfully used in the nudging process to correct the IWV deficiencies present in the reference analysis. The GPS IWV impact on aLMo forecast was found to be large in summer, moderate in the autumn and minor in winter OSE. The model forecasts of 2m temperature and dew point have been slightly improved via GPS assimilation. The impact of GPS on precipitation analysis and forecast were investigated in details. In the first OSE the precipitation statistics for Switzerland was improved and improvements in the diurnal cycle of precipitation were achieved through improved IWV diurnal cycle. The subjective verification of precipitation using the radar data gave mixed results. In the forecast the impact was limited to the first six forecast hours and to strong precipitation events. The positive impact was seen through reconstruction of a missing precipitation pattern in the summer OSE. One case with negative impact on precipitation analysis was reported due to exaggerated conversion of water vapour into liquid water and in turn precipitation.

Based on the work presented in this thesis it can be concluded that the use of GPS in NWP has a foreseeable long-term future due to the good spatial coverage, temporal availability and quality of these data. The future potential of GPS will be further extended with the new European project, GALILEO (the European Satellite Navigation System), which will be in operational service from 2008. The GPS derived water vapour gradients could further help improving the spatial spreading of humidity in active weather regimes and in regions with strong water vapour inhomogeneity. One further improvement could be the retrieval of GPS humidity profiles (tomography). The operational use of GPS derived water vapour in Switzerland will continue at MeteoSwiss, staring with the implementation of GPS IWV as an operational model validation tool. The assimilation experiments will continue with a one month impact experiment in 2004, and based on the results a decision for routine operational assimilation will be made.

Contents

Chapter 1

Introduction

Significance of Water Vapour

Water vapour is the major greenhouse gas of the troposphere, the carrier of latent heat in the global energy redistribution, and also the most mobile form of water in the hydrologic cycle of the Earth.
Water is the only substance in the Earth's environment that exists naturally in significant quantities in all three states: solid-ice, liquid-water and gas-water vapour. It is primarily in the vapour phase that water substance is transported into the air on a global scale. Its condensation leads to clouds which in turn produce precipitation. Although the atmosphere contains only 0.001 % of the water on the Earth, it transports enormous amount of water vapour and energy, in form of the latent heat, redistributing those so to maintain a balance of water and energy all over the globe.

Water vapour reaches the atmosphere primarily through evapotranspiration from water sources at the Earth surface (figure 1.1). Evapotranspiration includes open-water evaporation (from the ocean, lakes and rivers), sublimation from ice and snow surfaces and transpiration from vegetation. Water vapour of the atmosphere has a relatively short lifetime, one week to 10 days, and its complex life cycle includes vertical and horizontal transports, mixing, condensation, precipitation and evaporation. Due to the complexity of the water vapour distribution, linked to its relation to atmospheric dynamics and the role of phase changes, it is of essential importance for climate and Numerical Weather Prediction and simultaneously very demanding to observe.
Three independent ground-based methods for measuring the atmospheric water vapour will be discussed here. A summary of their characteristics is given in table 1.1 (Bouma, 2002). The most widely used method is balloon-radio sounding (radiosonde). The radiosondes are equipped with sensors for measuring the temperature, pressure and humidity as well as wind speed and

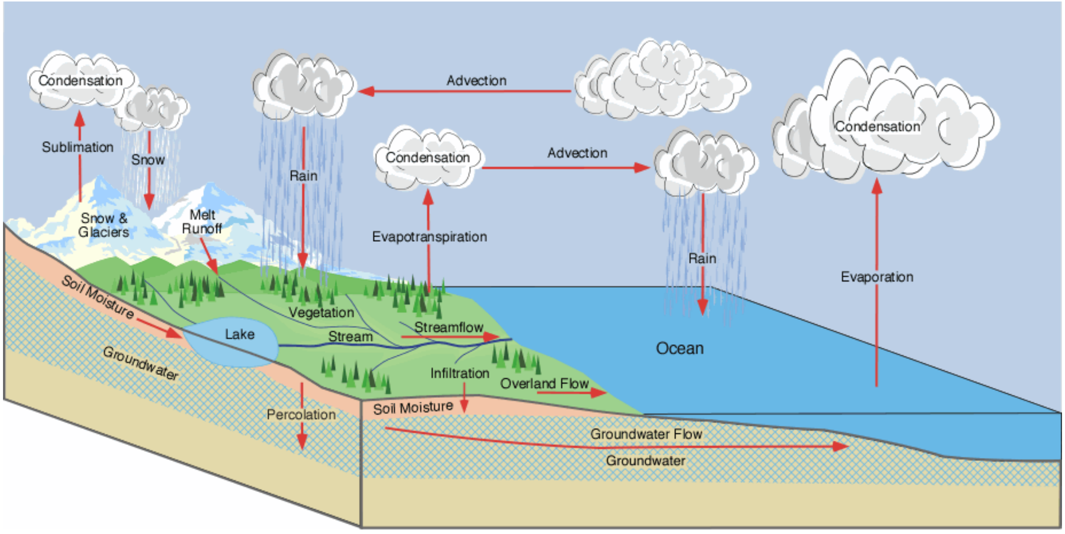

Figure 1.1: Water cycle of the Earth and participation of water vapour.

direction. The soundings are performed typically twice a day and the spatial coverage of the network is 250 km or more. The second and the third techniques exploit the fact that the propagation of electromagnetic waves is affected by the atmosphere, providing a unique opportunity to derive information about its water vapour content. The second technique is microwave radiometry referred to as Water Vapour Radiometer (WVR). The WVR measures the sky emission at 21 and 31.4 GHz, which is influenced by water vapour, liquid water and oxygen. The measured sky brightness temperature is directly related to the wet path delay. The microwave technique allows high temporal resolution, but is not applicable in rain events, and due to its significant cost is mainly used in research. The third method for sensing the atmospheric water vapour is by using the Global Positioning System.

Introduction to Global Positioning System

The Global Positioning System (GPS) is a worldwide radio-navigation system developed and deployed by the U.S. Department of Defence. The system was designed to provide high-accuracy, real-time position, velocity and time for military users on a variety of platforms. It operates worldwide, in all weather conditions, 24 hours a day. For civil users GPS is a reliable low cost system for highly accurate geodetic surveys to the centimetre level.

GPS has two prime segments, the space-based segment of the GPS satellites and the ground-based network of reference receivers. The space segment

Table 1.1: Intercomparison of independent techniques for measurement of atmospheric water vapour. Adapted from Bouma (2002).

	Radiosonde	Microwave radiometry	GPS
temporal resolution	low	high	high
spatial resolution	low	low	high
vertical resolution	high	low	low
cloud/rain waterproof	no	no	yes
cost	high	high	low
dataset length	about 40 years	since 1990	since 1990

consists of 24 satellites located in six orbit planes with an inclination of 55° with respect to Earth's equator and orbit periods of about 12 hours. The GPS constellation, presented in figure 1.2, provides a global coverage with four to eight simultaneously observable satellites above an elevation angle of 15°. The key role of the GPS satellite is to transmit precisely timed GPS signals at two L-band frequencies 1.57 and 1.22 GHz. The antenna array, incorporated in the body of the satellite, consists of 12 antennas placed in two concentric circles. The transmitted radio frequency signal is detected by the reference receiver on the Earth's surface. The ground-based antennas receiving the GPS signal are able to observe simultaneously all satellites in view. Worldwide dense GPS receiver networks have been installed in Japan (more than 1000 stations), U.S. (about 500) and Europe (more than 500 stations). The Automated GPS Network of Switzerland (AGNES), operated by the Swiss Federal Office of Topography, consists of 29 reference stations used primarily for geodetic survey applications.

Introduction to GPS Meteorology

As the GPS signal passes through the atmosphere from the satellite to the user (figure 1.3), the signal encounters a number of propagation effects. The magnitude of those effects depends on the elevation angle of the signal path and the atmospheric environment where the user is located. The atmosphere causes small but non negligible effects, including: a.) ionospheric group delay and scintillation b.) group delay caused by wet and dry troposphere and stratosphere and c.) atmospheric attenuation in the troposphere and stratosphere.

The ionosphere is the part of the upper atmosphere at the altitude between approximately 100 and 500 km, formed by ionised gases. The total ion con-

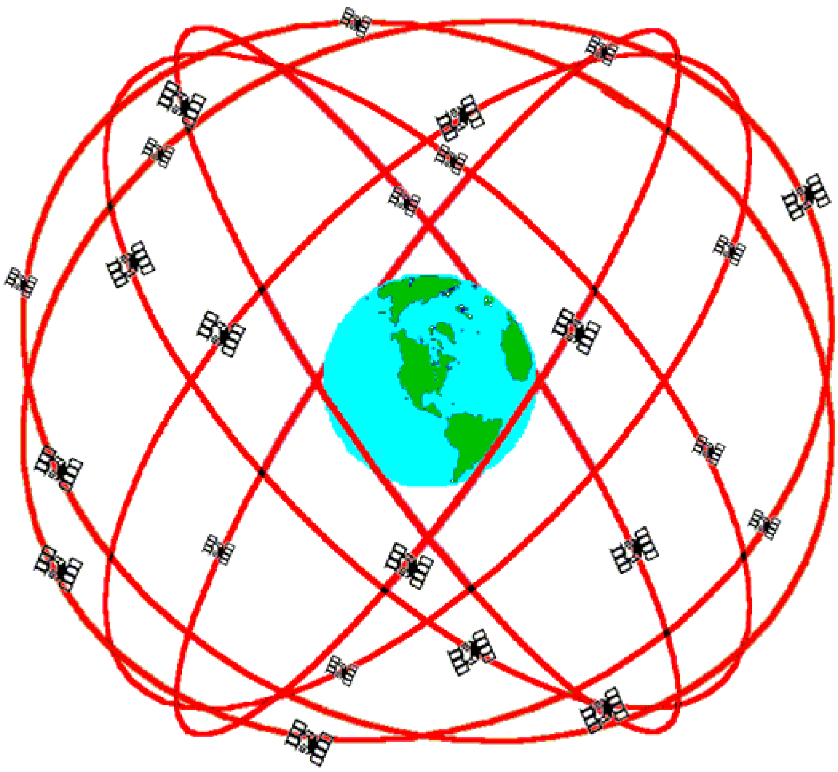

Figure 1.2: GPS satellite constellation: 24 satellites in six orbit planes.

tent varies widely from day to day and with solar conditions and has a large diurnal fluctuation. The ionosphere electron content peaks at an altitude in the vicinity of 200-400 km and can vary by as much as two orders of magnitude between day and night. The refractive index for the ionosphere varies with the frequency and by making observation at two frequencies it can be taken into account.
The troposphere is the part of lower atmosphere between 0 to approximately 12-18 km altitude, formed by dry air and water vapour. The major constituents of dry air are N_2, O_2, Ar and CO_2. At the GPS frequencies, oxygen is the dominant source of tropospheric attenuation, and this effect is normally small. The tropospheric group delay caused by tropospheric refractivity is the prime source of error in GPS. There are two major delay effects in the troposphere. The first and larger effect is a dry air excess delay, referred to as Zenith Hydrostatic Delay (ZHD), caused primarily by N_2 and O_2. The ZHD corresponds to approximately 2.1 m at sea level, and varies with local temperature and atmospheric pressure in a predictable manner. The ZHD temporal variation is less than 1 % in a few hours. The second effect - water

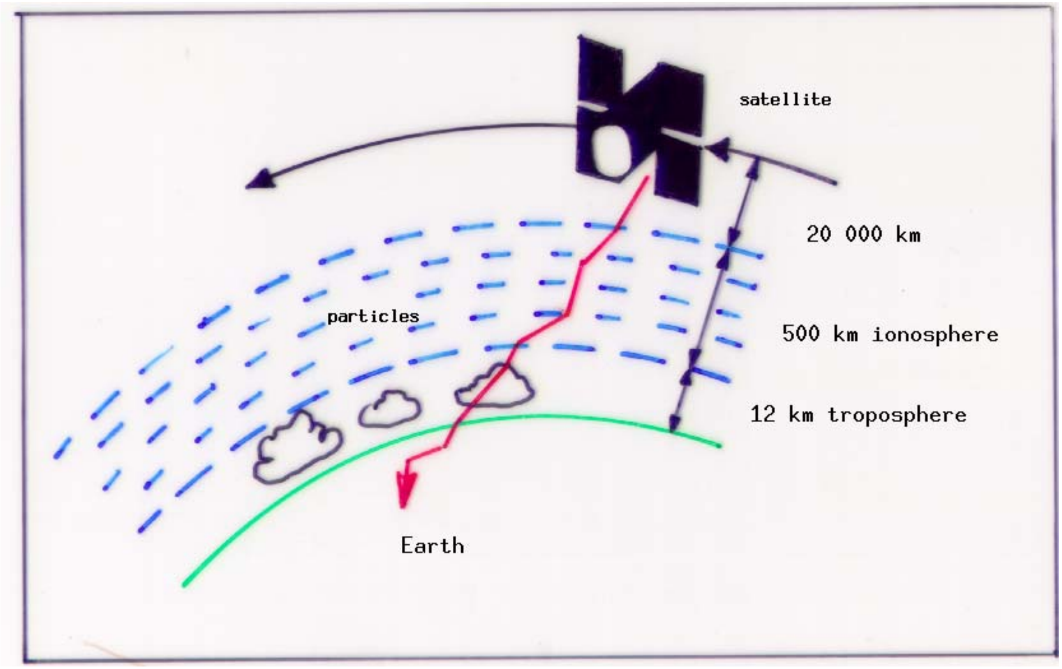

Figure 1.3: Schematic presentation of the GPS satellite signal path to the ground-based receiver station.

vapour effect, referred to as Zenith Wet Delay (ZWD) - is generally smaller, 1-80 cm at zenith, but it varies markedly. The ZWD temporal variation can exceed 10-20 % in a few hours and is less predictable. The demonstration of troposphere effects can be found in the first paper of Chapter 2 of the thesis. The Integrated Water Vapour (IWV) is obtained from the ZWD using:

$$IWV = \frac{10^6}{(k_3/T_m + k_2{}')R_v} ZWD \tag{1.1}$$

$$\tag{1.2}$$

where k_3, k_2' and R_v are constants and T_m is the weighted mean atmospheric temperature. The change in atmospheric refractivity due to presence of water vapour is defined by:

$$ZWD = 10^{-6} \int_O (k_2{}' \frac{e}{T} + k_3 \frac{e}{T^2}) ds \tag{1.3}$$

here e is water vapour pressure T is temperature and $\int_O ds$ is the propagation path of the signal.
The use of the Global Positioning System in Meteorology was suggested in

1992 by M. Bevis (Bevis et al. 1992). Since then a number of projects have investigated the accuracy of GPS derived IWV and its application in Meteorology. In Europe two projects, funded by the EU, have been dedicated. The first, the MAGIC project (Haase et al. 2002 and Vedel et al. 2003), studied the variability of the GPS derived water vapour measurements in the western Mediterranean area. The second, COST Action 716 (Elgered 2001), initiated in 1999, has as its main objective to exploration of the application of GPS data to operational Numerical Weather Prediction (NWP) in Europe.

Introduction to COST Action 716

The focus of the European COST Action 716 "Exploitation of ground based GPS for climate and numerical weather prediction application" was to evaluate the applicability of GPS in operational Numerical Weather Prediction (NWP) and climate (Elgered et al., 2003). For this purpose the GPS data from more than 200 European sites have been collected in near real - time (COST 716) and provided for validation and Observing System Experiments (OSE).
The work on COST Action 716 in Switzerland was initiated March 2000 as a collaboration between the Swiss Federal Office of Topography, the Federal Office of Meteorology and Climatology and the Institute of Applied Physics, University of Bern. The Swiss Federal Office of Topography, (Swisstopo, Wabern) operates the GPS Network of Switzerland and is one of the COST 716 processing centres providing the real - time GPS data (Brockmann et al. 2001). The Numerical Weather Prediction Department at the Federal Office of Meteorology and Climatology, (MeteoSwiss, Zurich) is engaged in the development and operation of the Numerical Weather Prediction system of MeteoSwiss, the aLpine Model. A detailed description of the model and the data assimilation in the model is to be found in the second paper of Chapter 3. At the Institute of Applied Physics, University of Bern (IAP UniBe, Bern) expertise in the measurement of atmospheric water vapour has been acquired through the development of Water Vapour Radiometers for measurements in the troposphere (Martin 2002 and Ingold et al. 2000) and the stratosphere (Kämpfer et al. 2003). At IAP, the first use of GPS derived water vapour was a validation of GPS station Bern with the data from the water vapour radiometer TROWARA (Peter and Kämpfer, 1992), reported by Rohrbach (1999). Through participation in COST Action 716 this work was further extended with GPS validation using radiosonde data from Payerne (reported in the first paper of Chapter 2) the sunphotometer data presented in Mätzler et al. (2002) and validation of the aLpine Model with 20 Swiss sites, reported in the third paper of Chapter 2. The Swiss contribution to COST 716 work

was. however, not limited to validation studies using the GPS derived water vapour. In close co-operation with MeteoSwiss the first GPS Observing System Experiment (OSE) was computed at the end of 2001. The results of this two week assimilation are presented in the second paper of Chapter 3. Based on the promising results of this first OSE three new OSEs were carried out in summer 2002. The findings are presented in the third paper of Chapter 3.

This thesis consists of two parts. Chapter 2, the first part, is dedicated to the applications of GPS derived IWV for verification of the limited area mesoscale models used in operational NWP in Switzerland and Germany. The second part, Chapter 3, summarises the results from four GPS assimilation experiments with the aLpine Model (aLMo) and one OSE with the Local Model (LM). A short introduction to Chapters 2 and 3 is given below.

Introduction to Part I: Model validation using GPS observations

In chapter 2 the emphasis is on the validation of the Numerical Weather Prediction Models using the GPS derived IWV. Validation of the mesoscale models is an important task in evaluating their performance. The meteorological offices routinely monitor the following model fields on a monthly basis: temperature, pressure, wind speed and direction, precipitation and cloud cover. Using the GPS derived water vapour a new unique opportunity is provided for validation of humidity analysis and forecast. In this part of the thesis the operational mesoscale models of MeteoSwiss are validated against IWV from GPS observations.

The first paper[1] of part I is dedicated to validation of two mesoscale NWP models with the Swiss GPS Network (AGNES). This work was the first step in evaluating the potential of GPS in NWP in Switzerland. The GPS observations of Zenith Total Delay from six AGNES sites have been converted to IWV following Bevis et al. (1992) and compared to the radiosonde data and the model output from the Swiss Model and the Swiss implementation of the Local Model (LM). Validation of the GPS-derived IWV with the IWV from the collocated radiosonde station in Payerne gives a monthly bias in the range

[1] Validation of NWP mesoscale models with Swiss GPS Network AGNES. G. Guerova et al. *J. Appl. Meteorol., 42, 1, 141-150, 2003.*

of 0.27 to 0.64 kg/m^2 over the period November 2000 to March 2001. In cases of low stratus clouds and temperature inversion the radiosonde was found to overestimate the water vapour amount. The possible reason can be the slow recovery time of the radiosonde humidity sensor after cloud passage. The verification of the hydrostatic Swiss Model indicates good agreement during the winter and high variability and bias in the summer. The monthly mean IWV values from GPS and LM show a systematic deviation over the Swiss Plateau region and a good agreement for the high-altitude alpine station, Andermatt. At the high-altitude station Jungfraujoch ($\sim$ 3600 m asl.) negative GPS IWV values are sometimes reported, due to the incorrectly modelled antenna phase centre. The GPS data sensitivity to high temporal resolution atmospheric phenomena has been demonstrated via atmospheric front passage over Switzerland.

The second paper[2] deals with monitoring of the Local Model in both Germany and Switzerland. Monitoring the IWV amount of the limited area forecast model has been performed using the ground-based GPS data from 94 sites from GFZ and AGNES (Brockmann et al., 2001) networks in the period, April November 2001. The model performance for Germany and Switzerland gives consistent results. The model tends to underestimate the water vapour content of the atmosphere, and this tendency is very well pronounced in the summer months between June and September. The diurnal cycle of the model was investigated for summer 2001. In the hours between 6 and 21 UTC the model analysis and forecast systematically underestimate the IWV.

The third paper[3] presents the aLpine Model (aLMo) monitoring for Switzerland in the period January 2001 to June 2003. The post-processed AGNES data with one hour temporal resolution are compared to the aLMo 00 UTC forecast from 0 to +23 h. The monthly bias and standard deviation are found to have a well pronounced seasonal dependence. In summer 2002 the model significantly underestimates the IWV amount measured by GPS. This dry bias of the model is well pronounced in the diurnal cycle. The precipitation verification with ANETZ synop observations indicates a significant overestimation of the light precipitation amounts. Thus it is expected that

[2]Monitoring IWV from GPS and limited - area forecast model. G. Guerova and M. Tomassini, *Research Report 03-15*, University of Bern, Switzerland, 2003.

[3]Verification of the aLpine Model with the GPS data in the period 2001-2003. G. Guerova et al., to be submitted to Meteorol. Atmos. Phys..

a coupling between dry IWV bias and overestimation of precipitation exists.

The monitoring of the operational NWP model of MeteoSwiss using the GPS measurements provides a unique opportunity to validate the model performance in forecasting the humidity content of the atmosphere. Since summer 2003 the validation of aLMo has been included as a standard validation tool in MeteoSwiss.

Introduction to Part II: Assimilation experiments

The Swiss contribution to the assimilation work in COST 716 are four OSE with the aLpine Model (aLMo). The GPS impact on aLMo, is reported in this part of the thesis.

The first paper[4] of Part II is dedicated to the Short Term Scientific Mission, to the Deutsche Wetterdienst in April 2001, supported by COST Action 716. The objective of this mission was to check and improve the GPS assimilation subroutines in the Local Model (LM). LM is the limited area nonhydrostatic model developed by the Consortium for Small - Scale Modelling (Doms et al., 2001). From the assimilation experiment conducted it can be concluded that the Local Model is sensitive to the assimilation of GPS derived water vapour and this sensitivity is demonstrated in correcting the model IWV field during cold front passage by up to 20%. No marked impact on temperature, cloud cover and precipitation fields was found. The LM monitoring with the real time GPS observations resulted in identification of an incorrect radiosonde observation. The work initiated during the mission was a starting point in introduction and experiments using GPS data in Switzerland. It was an opportunity for exchange of knowledge and experience on modelling and data assimilation. The GPS observations, their quality and possible problems in the assimilation process have also been considered.

The second paper[5] covers the results from the first OSE performed with

[4] GPS observing system experiment with the Local Model. Report from the COST 716 Short Term Scientific Mission. G. Guerova, *Research Report 03-16*, University of Bern, Switzerland, 2003.

[5] Assimilation of the GPS-derived Integrated Water Vapour (IWV) in the MeteoSwiss Numerical Weather Prediction model - a first experiment. G. Guerova et al., *Phys. Chem. Earth.,* 2002 in press.

the aLpine Model (aLMo). A high resolution limited area model-aLMo is used for operational Numerical Weather Prediction (NWP) at MeteoSwiss since November 2001. A continuous data assimilation scheme, based on the Newtonian relaxation-nudging (Schraff, 1997), produces the initial conditions for the forecast. The goal of this OSE was to evaluate the benefit of assimilating GPS-derived Integrated Water Vapour (IWV), provided for COST action 716 "Exploitation of ground based GPS for climate and Numerical Weather Prediction application". A two week period in mid September 2001, characterised by an advective weather regime and intense precipitation events, has been selected for this first OSE. On average observations from 80 European GPS sites are assimilated by the model. Results are based on the aLMo assimilation cycle. This experiment shows a tendency for GPS data to increase the model IWV amounts in the day-time, and shows a substantial impact of GPS in the southern part of the model domain where the relative change can reach up to 30 % relative change. The verification of aLMo over Switzerland reveals a clear positive impact of GPS on the IWV daily cycle and on the precipitation. The precipitation score statistic confirms the positive impact of GPS data assimilation. In one case, assimilation of GPS data resulted in a substantial increase of IWV. This could be traced back to inadequate spreading of humidity increments. Thus it can be concluded that additional GPS information, such as gradients and slant path estimates, will be beneficial in correctly shaping the model structure function. The impact of GPS IWV assimilation in aLMo gave encouraging first results. The GPS assimilation work continued with three new OSEs for different weather regimes and decreased radius of the observation increments spread.

The third paper[6] deals with the three additional GPS assimilation experiments with aLMo performed after tuning the nudging scheme, i.e. decreasing the radius of influence parameter. In total 17 days of analyses and two 30 hour daily forecasts were computed, with 100 GPS sites assimilated for three selected periods in autumn 2001, winter and summer 2002. First, the Near Real Time (NRT) data (van de Marel et al. 2003) quality has been compared with the Post - Processed data. A bias of 3 mm level and standard deviation of 8 mm was found in the Zenith Total Delay, corresponding to an IWV bias below 0.5 kg/m^2. The NRT data are successfully used in the nudging process to correct the IWV deficiencies present in the reference analysis; stronger

[6]Assimilation of COST 716 Near Real Time GPS data in the nonhydrostatic limited area model used at MeteoSwiss. G. Guerova et al. *Meteorol. Atmos. Phys.*, submitted Aug. 2003.

forcing with a shorter time scale could, however, be recommended. Comparing the GPS derived IWV with radiosonde observations, a dry radiosonde bias was found over northern Italy. Second, the GPS IWV impact on the aLMo forecast was found to be large in June 2002, moderate in September 2001 and minor in January 2002 OSE. The January OSE is inconclusive due to inconsistent use of the humidity correction scheme. During the June OSE a substantial IWV impact is seen up to the end of the forecast. The 2m temperature and dew point have been slightly improved over the whole aLMo domain. The subjective verification of precipitation gives mixed results. In the forecast the impact is limited to the first six hours and to strong precipitation events. A missing precipitation pattern has been recovered for one case in June OSE. One case with negative impact on precipitation analysis is reported for the same period.

Based on the assimilation experiments performed it can be concluded that the application of GPS in NWP has a foreseeable long-term future due to the good spatial coverage, temporal availability and quality of these data. The future potential of GPS will be further extended with the new European project - GALILEO (the European Satellite Navigation System), in operational service from 2008. The GPS derived water vapour gradients could further help improving the spatial spreading of humidity in active weather regimes and in regions with strong water vapour inhomogeneity. One further improvement could be the retrieval of GPS humidity profiles (tomography), with the limiting factor being accurate Slant Path estimates. The operational use of GPS in NWP models depends also on future data availability; GPS networks belong mainly to the geodetic community and are not incorporated in the WMO Meteorological Observing System.

References

Bouma, H., 2002: Ground-Based GPS in Climate Research. Technical Report 456L, Department of Radio and Space Science, Onsala Space Observatory, Chalmers University of Technology, Göteborg, Sweden.

Bevis, M., S. Businger, T.A. Herring, C. Rocken, R.A. Anthes, and R.H. Ware, 1992: GPS Meteorology: Remote sensing of atmospheric water vapor using the Global Positioning System. *J. Geophys. Res.,* **97,** 15 787-15 801.

Brockmann, E., G. Guerova, and M. Troller, 2001: Swiss activities in combining GPS with meteorology. *Subcommission for the European Reference Frame (EUREF), Publication 10*, J. A. Torres and H. Hornik, Eds., in press.

COST-716, 2000: GPS Meteorology. (http://www.oso.chalmers.se/geo/cost716.html — WG2 — Documents).

Doms G, and U. Schaettler, 2001: COSMO Newsletter No 1, 114 pp. [Available from Deutscher Wetterdienst, P.O.Box 100465, 63004 Offenbach, Germany.]

Elgered G., 2001: An overview of COST Action 716: Exploitation of ground-based GPS for climate and numerical weather prediction applications. *Phys. Chem. Earth. (A)* **26**, 399-404.

Elgered G., H.-P. Plag, H. van der Marel, S. Barlag, and J. Nash, 2003: Ground-Based GPS for Climate and Numerical Weather Prediction Applications. *The EGGS,* **4,** 22-24. Available online at: www.the-eggs.org/data/eggs_4.pdf

Guerova G., and M. Tomassini, 2003: Monitoring IWV from GPS and limited - area forecast model.*Research Report 03-14*, University of Bern, Switzerland.

Haase J., M. Ge, H. Vedel, and E. Calais, 2002: Accuracy and variability of GPS Tropospheric Delay Measurements of Water Vapour in the Western Mediterranean. *Bull. Am. Meteor. Soc.*, submitted Oct. 2002.

Ingold, T., B. Schmid, C. Matzler, P. Demoulin, and N. Kampfer, 2000: Modeled and empirical approaches for retrieving columnar water vapour from solar transmittance measurements in the 0.72, 0.82, and 0.94 μm absorption band. *J. Geophys. Res.,* **105,** 24 327-24 343.

Kämpfer N., B. Deuber, D. Feist, D. Gerber, Ch. Mätzler, L. Martin, J. Morland, and V. Vasic, 2003: Microwave remote sensing of water vapor in the atmosphere. *Geographica Helvetica*, **58,** 2, 81-89.

Martin L., 2002: ASMUWARA - The All-Sky Multi Wavelength Radiometer. *Research Report 02-12*, University of Bern, Switzerland.

Mätzler Ch., L. Martin, G. Guerova, and Th. Ingold, 2002: Assessment of integrated-water-vapour data at Bern from GPS, sun photometry, microwave radiometry and radiosonde. available at http://op.gfz-potsdam.de/D1/COST716, Conference: 2nd Workshop of COST Action 716, Exploitation of ground-based GPS for Meteorology, Potsdam, Germany, 2002-01-28.

Ohtani R., I. Naito, 2000: Comparisons of GPS - derived precipitable water vapours with radiosonde observations in Japan.*J. Geophys. Res.*, **105**, 26 917-26 929.

Peter R., and N. Kämpfer, 1992: Radiometric determination of water vapour and liquid water and its validation with other techniques. *J. Geophys. Res.,* **97,** D16, 18 173-18 183.

Rohrbach A., 1999: Wasserdampfmessungen mit GPS. IAPMW ID: 143 Diplomarbeit, University of Bern.

Tomassini M., G. Gendt, G. Dick, M. Ramatschi, Ch. Schraff, 2002: Monitoring of integrated Water Vapour from ground-based GPS observations and their assimilation in a limited area model. *Phys. Chem. Earth.*, **27**, 341-346.

Schraff, Ch., 1997: Mesoscale data assimilation and prediction of low stratus in the Alpine region. *Meteor. Atmos. Phys.,* **64,** 21-50.

Van der Marel H., E. Brockmann, S. de Haan, J. Dousa, J. Johansson, G. Gendt, O. Kristiansen, D. Offiler, R. Pacione, A. Rius, F. Vespe, 2003: COST-716 Near Real-Time Demonstration Project. *Jap. Meteor. Soc. J.*, submitted March 2003.

Vedel H., X.Y. Huang, J.Haase, M. Ge, E. Calais, 2003: Impact of GPS zenith tropospheric delay data on the precipitation forecasts in Mediterranean France and Spain. *Geophys. Res. Lett.* submitted February 2003.

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Thanks!

Chapter 2

Part I: Model validation using GPS observations

1. **Validation of NWP mesoscale models with Swiss GPS Network AGNES. G. Guerova, E. Brockmann, J. Quiby, F. Schubiger, and Ch. Mätzler** ***J. Appl. Meteorol., 42, 1, 141-150, 2003***

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Validation of NWP mesoscale models with Swiss GPS Network AGNES

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Abstract. The importance of water vapour for the hydrological cycle of the Earth and the atmosphere is well known but difficult to study and sample. In this respect, the vertically Integrated Water Vapour (IWV) derived from Global Positioning System (GPS) delay is a potential source of valuable weather information. Due to the relatively dense station distribution, both the temporal and horizontal variability of water vapour is well captured by the GPS. This makes GPS data well suited for Numerical Weather Prediction (NWP) models.
In this paper the Swiss GPS Network (AGNES) is used, for calculation of IWV and for comparison with radiosonde data and two NWP mesoscale models from MeteoSwiss named Local Model (LM) and Swiss Model (SM). Reasonably good agreement between GPS and radiosonde data is reported. It has been identified that in some particular weather situations with low stratus clouds and temperature inversion, the radiosonde significantly overestimates the water vapour amount. The LM and SM verification with GPS data indicates good agreement during the winter period (November 2000 - March 2001) and high variability and bias in the summer period (August 2000). The monthly mean IWV values from GPS and LM show a systematic deviation over the Swiss Plateau region and a very good agreement for the high-altitude alpine station, Andermatt. The capability of GPS in monitoring the atmospheric phenomena has been demonstrated. Unrealistic IWV at Jungfraujoch ($\sim$ 3600 m asl.) due to GPS antenna problems are reported.
This work is in the frame of the Swiss contribution to COST Action 716 and is considered a first step in preparation for assimilation of GPS measurements in LM.

1. Introduction

The importance of water vapour for the overall state of the atmosphere in both short and long time scales has been acknowledged for many years, and a number of instrumental techniques have been developed to study it. While the most widely used method world-wide, radiosonde, is superior in providing vertically resolved water vapour profiles;

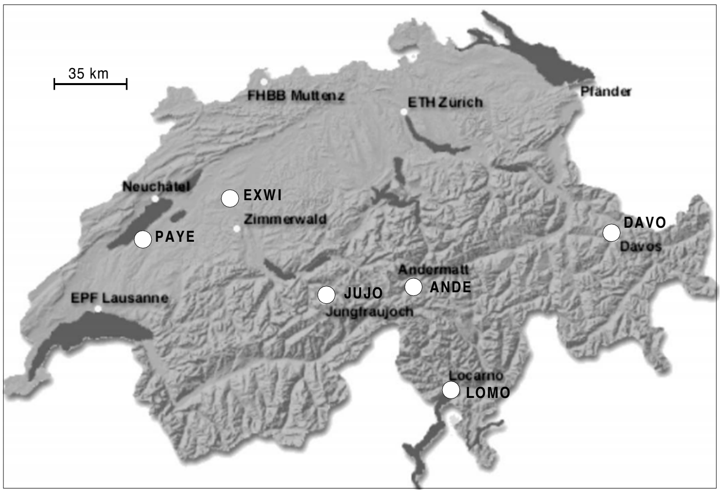

Figure 1. Map of Switzerland showing a selection of stations (white dots) from the automated GPS Network of Switzerland - AGNES. In this study the data from: Payerne (PAYE), Bern (EXWI), Jungfraujoch (JUJO), Andermatt (ANDE), Locarno (LOMO) and Davos (DAVO) were used.

it is on the other hand, relatively expensive to maintain and consequently limited in number of sites. Microwave radiometry is another approach to the problem, providing information for vertically Integrated Water Vapour (IWV) and cloud water. In the last two decades it has been substantially developed and is extensively used for validation studies and field campaigns (Liou et al. 2001). However, in addition to the difficulty in data processing, its main limitations remain poor spatial coverage and poor performance in rain conditions (Gueldner et al. 1999). The prime objective of the Global Positioning System (GPS), developed three decades ago, was exact position determination (i.e. location on the Earth's surface). Later the use of GPS was extended to a number of scientific applications (Ware et al. 2000), one of which is derivation of IWV. It has to be acknowledged, however, that a significant effort was required to achieve accuracy in determination of water vapour from the GPS signal, and the possibility of producing a profile from the GPS observation is still a challenging task (Flores et al. 2000; MacDonald and Xie 2000, MacDonald et al. 2001).

On the other hand, the development of very fine resolution mesoscale models for Numerical Weather Prediction (NWP) became possible with the improvements of both numeric and parameterization schemes and the increased power of supercomputers. A non-hydrostatic concept has been introduced in the last decade in order to achieve, among other things, the refinement of the model mesh and to provide more realistic parameterization of atmospheric waves and convection (Doms and Schaettler 1999). When mesoscale models are used to resolve boundary layer structure and dynamics, the need for reliable water vapour data is even more apparent (Schraff 1997; Weygandt and Seaman 1994; Stauffer and Seaman 1994). In addition, for realistic representation of cumulus cloud formation and decay good parameterization schemes are required along with as accurate as possible estimates of water vapour profiles. This is the main motivation for the implementation of GPS-derived IWV in the mesoscale models (Kuo et al. 1996).

The objective of this study is to validate the water vapour field of two operational mesoscale models against GPS observed IWV and to draw conclusions about future assimilation of IWV in the Local Model (LM). In section 2 a description of IWV extraction from GPS, radiosonde, LM and SM (Swiss Model) is given. The comparison between GPS and radiosonde IWV is discussed in section 3 and LM validation with GPS for the period November 2000 - March 2001 is presented. For summer 2000, SM output is compared with IWV from GPS. A summary and conclusions can be found in section 4.

2. Description of the data used

2.1. *Global Positioning System (GPS) data*

2.1.1. SWISS GPS NETWORK AGNES The Swiss Federal Office of Topography has deployed and operates the Swiss GPS network - AGNES. AGNES is mainly used for navigation and surveying purposes (post - processing and real time) in a homogeneous reference frame (called LV95). It consists of 12 permanent receivers with a sampling rate of one second and will contain 28 stations at the end of 2001 (Brockmann et al. 2001). The data from all stations are processed using the Bernese 4.2 software package (Rothacher and Marvart 1996; Schneider et al. 2000) with a delay of one week. For estimation of hourly Zenith Total Delay (ZTD), GPS data above 10° elevation are used. The Niell mapping function (Niell 1996) is used to map the slant delays to the zenith. In this study the data from six AGNES sites are used. Their locations are represented by white dots in Figure 1. They are from west to east : Payerne (PAYE), Bern (EXWI), Jungfraujoch (JUJO), Andermatt (ANDE), Locarno (LOMO) and Davos (DAVO).

2.1.2. DERIVATION OF IWV FROM GPS MEASUREMENTS The IWV is retrieved from the Zenith Total Delay (ZTD) following the concept described in Bevis et al. (1992) and Emardson et al. (1998). First, the hydrostatic delay ZHD (m) is calculated via its dependence on surface pressure p_s (hPa) and a factor $f(\theta, h)$, describing the height (h) and latitude (θ) variation of the gravitational acceleration, as follows:

$$ZHD = (2.2768 \pm 0.0024)\frac{p_s}{f(\theta, h)} \quad (1)$$

$$f(\theta, h) = 1 - 0.00266cos(2\theta) - 0.00028h. \quad (2)$$

Second, the IWV in mm is obtained using:

$$IWV = K(ZTD - ZHD) \quad (3)$$

$$K = \frac{10^6}{(k_3/T_m + {k_2}')R_v} \quad (4)$$

where $k_3 = (3.776 \pm 0.004)\,10^5\,(K\,hPa^{-1})$, $k_2' = (17 \pm 10)$ $(K\;hPa^{-1})$, $R_v = 461.51\,(J\,kg^{-1}K^{-1})$ is the specific gas constant for water vapour and T_m is the weighted mean atmospheric temperature (K). The surface pressure (p_s) and temperature (used for derivation of T_m) are obtained from the collocated meteorological stations from the Swiss surface station network (ANETZ).
The difference (ZTD - ZHD) is often referred to as zenith wet delay (Bevis et al. 1992). The conversion constant K is of the order of 0.15. The uncertainty in derivation of ZHD (specified in equation 1) is of order of 0.2 %. However the uncertainty introduced in IWV varies from ±0.25 mm to ±0.35 mm for IWV amounts of 10 mm and larger than 10 mm, correspondingly. The uncertainty in estimation of the parameter K (specified in equation 4) is reported to be 2 % (Ohtani and Naito 2000). The overall accuracy of IWV estimation is reported to be better than 1.5 mm (Rocken et al. 1993, 1995).

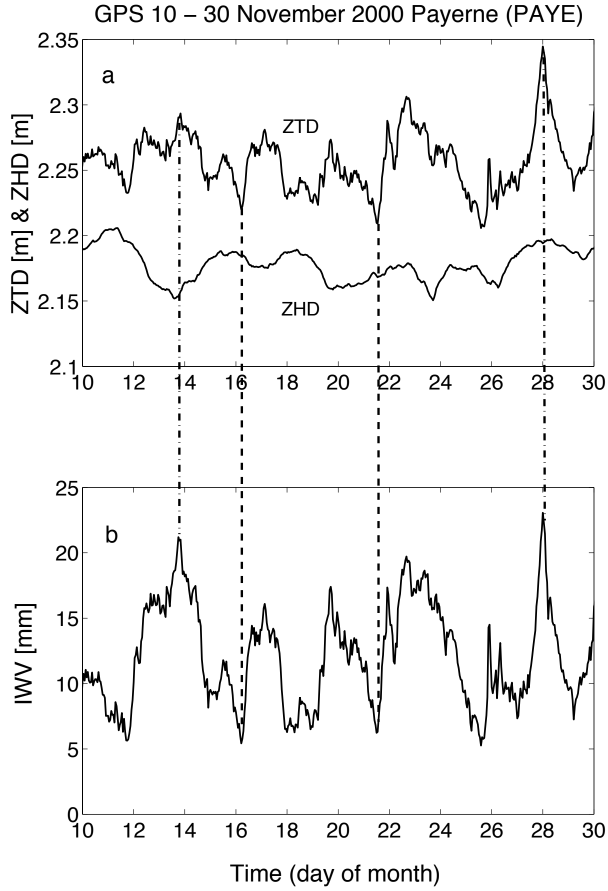

Figure 2. a) Zenith Total Delay (ZTD) and Zenith Hydrostatic Delay (ZHD) versus time for the period 10 to 30 November 2000 at Payerne (PAYE). b) Integrated Water Vapour (IWV) in mm at Payerne as derived from (3).

One demonstration of the GPS concept can be found in Figure 2 where ZTD, ZHD and IWV are plotted for the GPS station Payerne (PAYE). From the first plot (Figure 2a) it can be clearly seen that the ZHD variation for the period of 20 days is between 2.15 and 2.20 m (2150 - 2200 mm). The ZTD however varies in the range of 2.20 - 2.35 m (2200 - 2350 mm). It is obvious that the high time fluctuation in the ZTD signal has less to do with the hydrostatic component of the delay (ZHD), but is essentially contributed by the wet delay. Thus, being in the range of 0.05 - 0.15 m, the wet delay induced by the water vapour content of the lower tro-

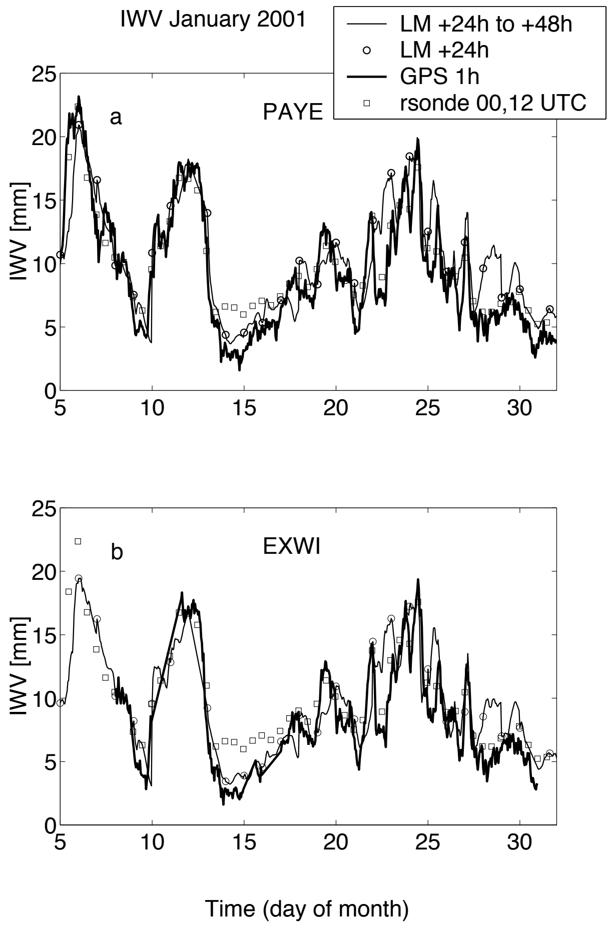

Figure 3. Radiosonde and GPS derived IWV in January 2001. a) Radiosonde (squares), GPS observation (thick line) and LM forecast of 00 UTC +24h to +48h (thin line) with circle indicating forecast hour +24 at Payerne (PAYE). b) The same as a) at EXWI-Bern with radiosonde data from Payerne.

posphere, is a prime source of high temporal variability in the GPS signal. Indeed, the dashed and dash-dotted lines give evidence for the good correspondence between the low and high values of IWV (Figure 2b) and ZTD (Figure 2a).

2.2. *Numerical Weather Prediction (NWP) Models*

2.2.1. LOCAL MODEL (LM) The increase in the capability and speed of supercomputers has provided an opportunity for the implementation of a new generation high resolution nonhydrostatic models for mesoscale numerical weather prediction. At the Federal Office of Meteorology and Climatology (MeteoSwiss) a nonhydrostatic model, called the Local Model (LM), has been running operationally twice every day (at 00 and 12 UTC) since 1 April 2001 with a preoperational test period from September 2000 to March 2001. The model horizontal grid of 7 x 7 km covers the region of central, south-western Europe and part of the Atlantic Ocean. The model has 45 vertical levels from the surface up to 20 hPa in a generalized terrain-following coordinate system (Doms and Schaettler 1999, 2001). The vertical resolution in the lowest 2 km of the atmosphere is about 100m. Since November 2000 filtered orography was introduced into the model to solve for unrealistic precipitation forecasts in mountain regions (Gassmann 2001). The LM analyses are obtained via interpolation of driving model analyses - German Global Model (GME). The model prognostic variables are : temperature, perturbation pressure, horizontal and vertical wind velocity, water vapour, cloud water and air density. The LM has been developed in close cooperation with Deutscher Wetterdienst (DWD) within the framework of COSMO (Doms and Schaettler 2001). The COnsortium of Small scale MOdelling (COSMO) integrates the national weather services of Germany, Switzerland, Italy and Greece.

2.2.2. SWISS MODEL (SM) The Swiss Model (SM) is a hydrostatic limited area mesoscale model. It has a horizontal resolution of 14 km and a grid mesh of 145 x 145 points. The domain covers western and central Europe (from Ireland, Denmark and Poland in the north, to Spain and southern Italy in the south). The vertical domain is divided into 31 layers. It has been used for operational weather forecasts by MeteoSwiss since 1994 and it has been developed in collaboration with DWD. The SM analysis is obtained via interpolation of the GME analysis using the method of Majewski (1985). The SM data were used for GPS validation in summer 2000.

2.2.3. DERIVATION OF IWV FROM LM AND SM The Integrated Water Vapour (IWV) is calculated from the model specific humidity fields so that it can be compared with the GPS observations. For the comparison the model grid points have been selected based on the smallest height difference to the GPS antenna. The spatial search radius is about 10 km and 20 km, correspondingly, for LM and SM. In addition the starting integration level is taken to be as close as possible to the height of the GPS site, i.e. the model IWV is calculated from the level with smallest height difference. The integration is performed using:

$$IWV = \frac{1}{\rho_w} \int_{h_0}^{h_{top}} \rho_{wv}(h) dh \qquad (5)$$

where ρ_{wv} is water vapour density, h is height in meters and ρ_w is density of liquid water and IWV is in mm. For intercomparison with GPS the LM forecast initialised at 00 UTC is used. The forecast hours from +6h to +30h are compared with corresponding GPS measurements. In only one case the LM forecast period from +24 to +48 hour (next day forecast) is used.

2.3. *Radiosonde data*

There is one radiosonde sounding site in Switzerland located at Payerne (Swiss Plateau region). A balloon sounding (sonde type SRS 400, MeteoLabor, Switzerland) is performed twice a day (00 and 12 UTC) measuring temperature, pressure, humidity and wind profiles. The IWV amount is calculated using equation (5).
A fast response VIZ ACCU-LOK carbon hygristor is used to measure relative humidity. During the radiosonde preflight procedure, the lock-in humidity resistance is introduced in the data acquisition software and the sensor. The operating range extends from 0 to 100 % relative humidity (RH), and from - 60 to +40 °C, with an accuracy of 2 % RH (rms) (Richner 1999).

3. Validation study

3.1. *Comparison of IWV derived from GPS and radiosonde*

In order to validate the GPS IWV a comparison with the collocated radiosonde in Payerne is performed. The monthly mean difference between radiosonde and GPS over the period of November 2000 to March 2001 is in the range of 0.27 to 0.64 mm, showing a slight dry bias of GPS. This dry GPS bias however is below the estimated GPS error range of ±1 mm. From this comparison it was identified that during some particular weather situations in winter (low stratus clouds and temperature inversion) when very low amounts of water vapour were measured by GPS the radiosonde measurements had a significant positive bias. Such a case is presented in Figure 3a and 3b. It can be clearly seen that between January 14th and 16th the radiosonde (squares) and GPS IWV (thick line) have a significant offset for the GPS antenna in Payerne (PAYE) as well as for the GPS site EXWI in Bern (the distance between Payerne and Bern is about 40 km). The same situation was observed on 23rd December 2000 (Figure 5a).
The LM forecast (thin line) is also plotted in Figure 3a and 3b. The model forecast +24 to +48h is chosen in order to minimize the observation (e.g. assimilated radiosonde data) influence. It can be observed that the model predicts IWV amounts, which are close to the GPS-derived one and as well below 5 mm. The histograms in Figure 4 show the bias (radiosonde minus GPS) and the GPS-derived IWV for four months in the period November 2000 to March 2001 (the data from February are not presented as the number of comparisons is small). From the histograms in 4b and 4c the periods with very low IWV at the end of December and mid January can be identified. It is to be noticed that for these particular cases, the bias can reach up to 5 mm. It can also be seen that the bias is mostly positive and particularly high for IWV amounts below or close to 10 mm. For example, from 17 cases in December when the difference is in the range of ±1 mm to ±2 mm, 12 cases have a positive sign (excluding the already discussed case with very low IWV at the end of December).
Independent measurements of IWV at Bern by a sunphotometer (Ingold et al. 2000) were available on January 15 at 13 UTC. The IWV from the sunphotometer is 5.23mm and from the collocated GPS site EXWI the amount measured is 5.0 mm, i.e. the difference is about 0.3 mm. At approximately the same time (12 UTC) but in Payerne the GPS derived IWV is 4.2 mm while the radiosonde measures 6.66 mm, i.e. 2.4 mm more.

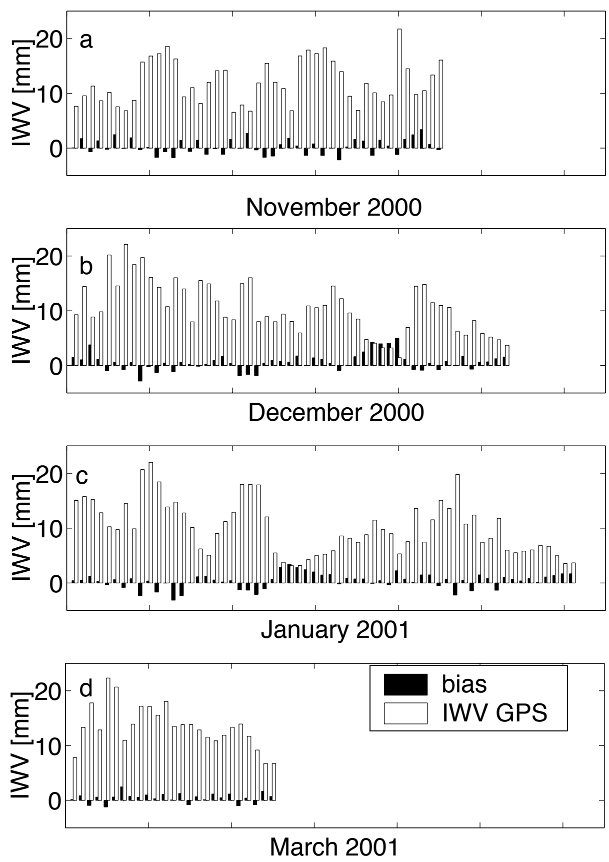

Figure 4. Histograms of the bias (radiosonde minus GPS) and the GPS IWV for period November to March. a) November 2000, Payerne (PAYE). b) December 2000, Payerne. c) January 2001, Payerne. d) March 2001, Payerne.

3.2. *Verification of LM water vapour field with GPS observations*

Since November 2000 the verification of the Local Model has began. This work is a first step in investigating the potential use of ZTD measurements in numerical weather prediction in Switzerland. Comparisons of hourly IWV from LM and GPS are performed. Results for four GPS sites and corresponding model grid points are presented in Figure 5. The site selection is based on availability of collocated surface meteorological measurements from ANETZ.
The period of 5th to 31st December 2000 is plotted in Figure 5. Additionally the corresponding bias (LM minus GPS) and standard deviation (std) values are given. With only one exception (PAYE) the bias is well below 1 mm. However some days with substantial differences between LM IWV (thin line) and GPS IWV (thick line) are observed. One case is the +6 to +30h model forecast on December 13 (+6h is marked by an arrow on Figure 5a). For Payerne (Figure 5a) a substantial offset is visible towards the end of the forecasting period, while for Andermatt (Figure 5d) and Davos (Figure 5c) the IWV variation is poorly predicted over the entire forecast period. A careful investigation of the 12 UTC surface pressure map from 13 December indicates a cold front passing through Switzerland. Indeed the IWV minimum is associated with the cold air advection. The LM forecast for Andermatt and Davos correctly predicts the minimum IWV values but with time offsets of 9 and 12 hours, respectively. Thus, it is to be concluded that the forecast failure is due to inaccurate modeling of the atmospheric processes after frontal zone passage.
The second half of the month shows reasonably good agreement except for the forecast on 23 December where the very first forecast hours (+6h to +12h) are particularly poorly predicted for grid point Payerne. The reason is once again humidity overestimation from the radiosonde (squares in Figure 5a). This demonstrates the model sensitivity to the radiosonde data. It must be emphasized that in general good agreement between the model and GPS was obtained during the winter period under study.

3.3. *Monthly mean water vapour amounts from the LM and GPS*

Monthly mean IWV estimates from LM and GPS are presented in Figure 6 using one hour time resolution data. The sites are as follows: Payerne (PAYE) and Bern (EXWI) located on the Swiss Plateau, Andermatt (ANDE), Davos (DAVO) and Jungfraujoch (JUJO) located in the Swiss Alps and Locarno (LOMO) in Southern Switzerland. In Table 1, the heights above sea level (asl.) of GPS antenna and model topography are listed.

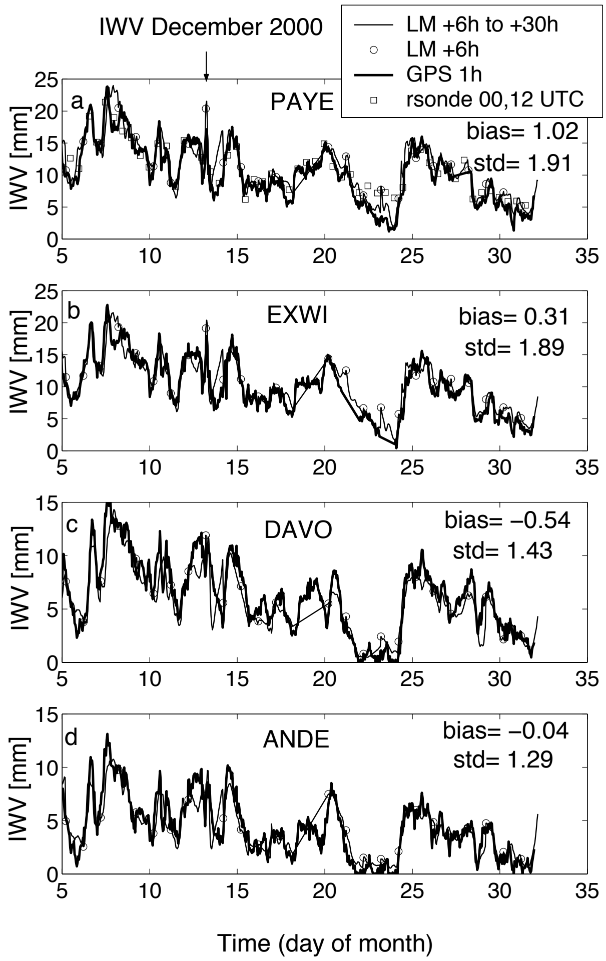

Figure 5. IWV from GPS and LM versus time in days of December 2000. a) IWV from GPS (thick line), radiosonde (squares) and LM forecast of 00 UTC +6h to +30h (thin line) with circle indicating forecast hour +6 for PAYE - Payerne ($\sim$ 500 m asl.). b) the same as a) for EXWI - Bern ($\sim$ 550 m asl.). c) the same as a) for DAVO - Davos ($\sim$ 1600m asl.). d) the same as a) for ANDE - Andermatt ($\sim$ 2300 m asl.)

The results over the monitored period from November 2000 to March 2001, shown in Figure 6, reveal that GPS (black bar) and LM (grey bar) have good correspondence. It can be clearly seen that the lowest IWV measured at PAYE and EXWI is in the middle of the period, namely in January 2001. However it should be noted that for Payerne and Bern the amounts from LM are always higher than those of GPS. Keeping in mind that the height differences between the model grid point and the GPS antenna are 30 and 79 m (see Table 1), respectively, it is logical that the forecast IWV amount should be lower than that measured by the GPS. This leads to the conclusion that LM overestimates the wa-

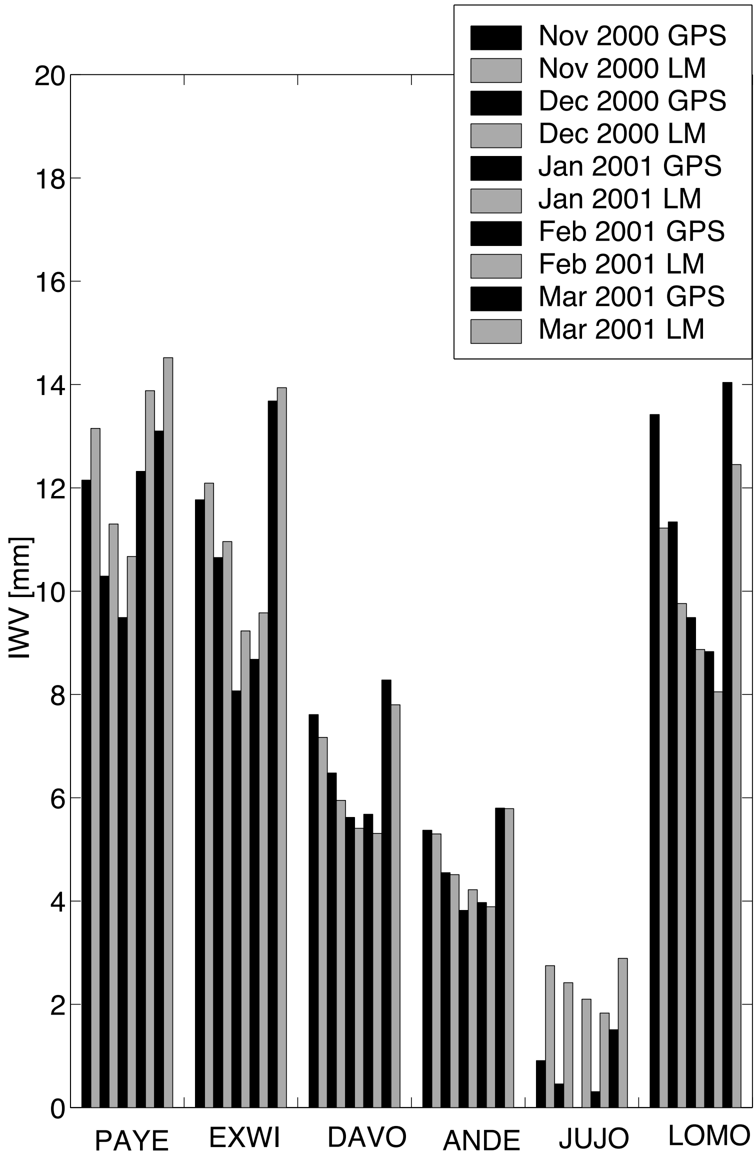

Figure 6. Monthly mean IWV from GPS (black bar) and LM (grey bar) for the period November 2000 to March 2001.

Table 1. GPS, LM, GPS - LM and SM heights

GPS site	GPS height [m] asl.	LM height [m] asl.	GPS - LM difference [m]	SM height [m] asl.
Payerne (PAYE)	498	528	-30	
Bern (EXWI)	577	656	-79	601
Davos (DAVO)	1598	1815	-217	1783
Andermatt (ANDE)	2317	2360	-43	2367
Jungfraujoch (JUJO)	3584	3599	-15	
Locarno (LOMO)	388	805	-417	

ter vapour amount in the Swiss Plateau region. A further comparison between LM, radiosonde and GPS shows a positive model bias of 0.8 mm relative to the radiosonde and 1.1 mm relative to the GPS for November 2000 at Payerne. This trend remains valid for the entire period of investigation. From the third set of bars in Figure 6 it is seen that the GPS receiver in Davos (DAVO) measures slightly more water vapour in all cases compared with the values obtained from LM (grey bars). The excess amount reported by the GPS varies from 3.7 % to 7.7 % and correlates well with the fact that the height difference is a little more than 200 m. For the station at Andermatt (ANDE) the bars show very good agreement between GPS and LM. In addition it is to be noted that the values are below 6 mm due to the high altitude of the site (2300 m). On the other hand this good agreement is an indication of correct representation of WV amounts in the model layers above 2300 m.

The results for Jungfraujoch (JUJO 3600 m asl.) show strong discrepancy between LM and GPS. The reason is unrealistic IWV amounts from GPS (including negative estimates). The problem was identified to be the unmodeled antenna phase centre of this special antenna, which is covered by a heated dome to protect the antenna against the impact of snow. After detection of the problem the antenna was calibrated, and from now on more realistic values of GPS IWV at Jungfraujoch are expected.

The last set of bars in the histogram (Figure 6) is for Locarno (LOMO), the southernmost GPS site in Switzerland. The IWV minima for LOMO is not measured in January (as it is for Payerne) but instead in February 2001. This is probably due to the fact that the atmospheric circulation in this region is influenced by the Mediterranean circulation patterns. Unfortunately the model orography is 400 m above the antenna height, so any conclusions about the model WV field are not feasible. However it should be pointed out that the 400 m difference adds from 6.5 % to 16.4 % to the overall amount reported by LM.

In order to solve the problem of height difference between GPS and LM grid point (eg. Davos and Locarno) an additional experiment was performed. First, the IWV amounts for a layer thickness of 200 and 400 m are calculated, assuming constant relative humidity (observed at ANETZ station height). Second, the GPS IWV values are extrapolated to the corresponding LM height by subtracting IWV amounts due to the height difference. As a result a substantial decrease of the GPS value is obtained with a negative offset compared with the LM (opposite to the one plotted on Figure 6). It is to be concluded that such a simple approach does not provide representative validation results. The reason is mainly the complex spatial and vertical variability of water vapour in the lower troposphere. Therefore the assimilation of GPS data from stations with substantial height differences could produce questionable results and should be either avoided or treated with special care. This problem is particularly important for Switzerland where the model orography poorly matches steep slopes and narrow valleys in the Alps.

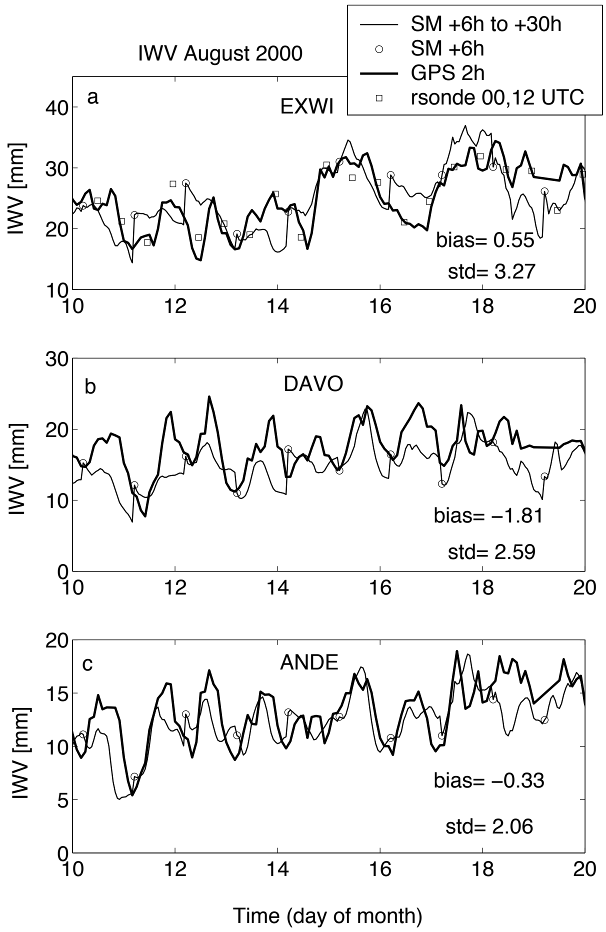

Figure 7. Comparison between GPS (thick line) and SM forecast of 00 UTC +6h to +30h (thin line) for summer period 10 to 20 August 2000. a) IWV as measured and modeled at EXWI - Bern (∼ 550 m asl.) b) IWV as measured and modeled at DAVO - Davos (∼ 1600 m asl.) c) IWV as measured and modeled at ANDE - Andermatt (∼ 2300 m asl.).

3.4. *Investigation of summer water vapour with the Swiss Model (SM)*

As the LM forecast was not available in the summer of 2000, the hydrostatic Swiss Model was used for comparison with GPS. The summer periods are of particular interest

for countries like Switzerland as they are characterized with high IWV amounts and strong cumulus convection and precipitation. One further reason is that the SM has the same parameterization schemes as LM. The main differences being the doubled mesh distance and non - compressibility of the flow in SM. For the summer period of 2000, the ZTD data derived by GPS are available with a 2 hour time resolution. No measurements were collected at the Payerne GPS station because the GPS receiver was used in a field campaign. In Figure 7 a comparison between SM (thin line) and GPS (thick line) IWV is plotted for 10 days in mid August 2000 for Bern (Figure 7a), Davos (Figure 7b) and Andermatt (Figure 7c). The day-to-day variation of IWV is poorly modeled, and differences of 5 mm and more occur. The bias and std values also indicate increased variability. For the GPS station at Davos the bias in the summer period is twice that in winter. For completeness the radiosonde data are plotted in Figure 7a, and it is to be noted that they are in relatively good agreement with the GPS data.
The SM validation over the winter period of 2000 to 2001 showed similar results to the one already discussed in section 3.b (LM verification). Therefore it may be concluded that it is more difficult to accurately predict the IWV amount in summer.

3.5. *Tracking regional and temporal variability of IWV*

The potential of GPS retrieved water vapour as a valuable source of information for mesoscale numerical modeling, lies in its ability to track short-term local variations in the water vapour field. This is illustrated in Figure 8, where the IWV amounts are plotted for the period of 26th to 30th November 2000 with one hour time resolution. It is observed that at mid - day on November 27th, a gradual increase in IWV is initiated in Payerne (dotted solid line on both figures 8a and 8b). The maximum amount is reached on 00 UTC of November 28th. Compared with Payerne a short delay of one hour is observed for the IWV maxima at Andermatt. The maxima at Davos (squares on Figure 8b) has a 3 hour delay relative to Payerne. A careful investigation of the weather situation on this day confirms that this time delay correlates well with a warm atmospheric front passing from west to east. As seen from Figure 1 Payerne is located in the west part of Switzerland and the distances to Andermatt and Davos are 120 km and 220 km, respectively. The sensitivity of the GPS IWV to the atmospheric phenomena on short temporal and spatial scales can be observed over the entire period presented. The daily cycle of IWV is a topic of further interest, related to the IWV dynamics in the boundary layer, which could be studied with GPS; however this has not yet been done.

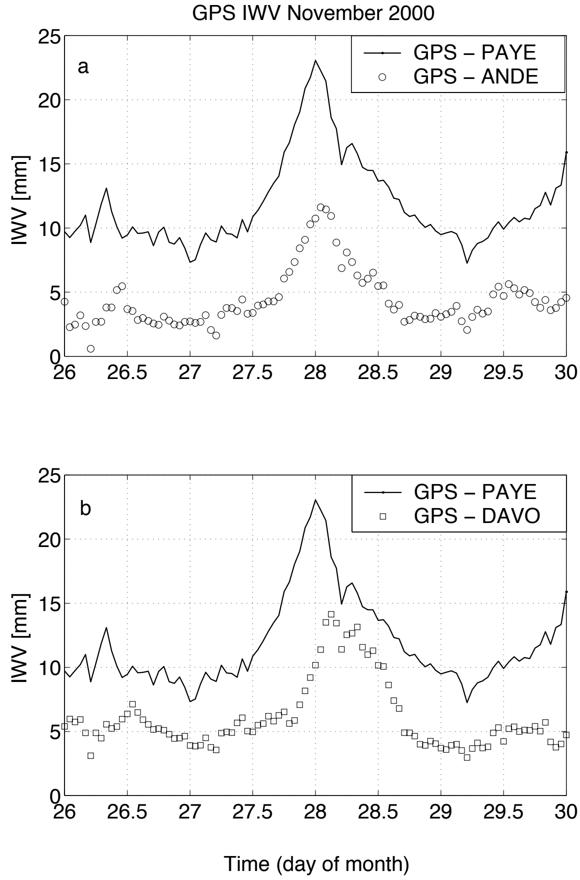

Figure 8. GPS IWV for Payerne, Andermatt and Davos. a) IWV at Payerne (PAYE - dotted solid line) and Andermatt (ANDE - circles) between 26 and 30 November 2000. b) IWV at Payerne (PAYE - dotted solid line) and Davos (DAVO - squares).

4. Conclusions

Atmospheric water vapour has well-pronounced temporal and spatial variability, which is far from being satisfactory determined. Humidity data is particularly important for country like Switzerland as it is a "crossroad" for different weather circulation patterns. Thus monitoring IWV in the atmosphere using the Swiss GPS network, AGNES, provides a unique opportunity to gain insight into the local variation of water vapour. It also proves to be a good tool in verifying the NWP models's performance.
In this paper, one goal is to validate the GPS-derived IWV with the IWV from the collocated radiosonde station in Payerne. The agreement of monthly mean difference is in the range of 0.27 to 0.64 mm over the period November 2000 to March 2001. In some cases of low stratus cloud and temper-

ature inversion the radiosonde was found to overestimate the water vapour amount. One possible reason is the slow recovery time of the humidity sensor after cloud passage. The validation of the NWP mesoscale models was performed for GPS sites at Payerne, Bern, Davos and Andermatt. Comparison of LM forecasted IWV with GPS data in December shows very good agreement with some exceptions where substantial differences are observed indicating partial failure of model forecasts. LM monthly mean IWV amounts indicate systematic overestimation for the Swiss Plateau region and agreement for the high altitude station at Andermatt ($\sim$ 2300 m asl.). The IWV variation during the summer period is relatively poorly matched by the SM forecast. The bias and standard deviation are significant in summer. The GPS data sensitivity to high temporal resolution atmospheric phenomena i.e. atmospheric fronts has been demonstrated. The passage of a warm front from west to east have been traced. It introduces time shifts of the IWV maxima, with respect to Payerne, of 1 and 3 hours for Andermatt and Davos, respectively. The IWV data from the alpine station Jungfraujoch ($\sim$ 3600 m asl.) give unrealistic, i.e. some negative, values due to the unmodeled effects of this particular antenna. Based on the study of the impact of height difference it is concluded that care should be taken when assimilating GPS data from stations with model-to-station height differences of more than 200 m, for instance Davos and Locarno.
As demonstrated in this paper, the GPS retrieved IWV is a useful tool for monitoring atmospheric humidity. Although humidity information provided by GPS is not in the form of a profile, its temporal and horizontal coverage is better than that provided by the meteorological sounding network. If treated properly, the GPS information could fill the existing gap in model data input. This is the main motivation to continue the work for more efficient use of GPS data in LM. It is planned to start assimilation via nudging of GPS ZTD. The assimilation work will be performed in close cooperation with the DWD, Swiss Federal Office of Topography and MeteoSwiss and will be part of the Swiss contribution to COST Action 716.

Acknowledgement. This work is supported by the Swiss Federal Office of Education and Science under Grant C97.0027.

References

Bevis, M., S. Businger, T.A. Herring, C. Rocken, R.A. Anthes, and R.H. Ware, 1992: GPS Meteorology: Remote sensing of atmospheric water vapor using the Global Positioning System. *J. Geophys. Res.,* **97,** 15 787-15 801.

Brockmann, E., G. Guerova, and M. Troller, 2001: Swiss activities in combining GPS with meteorology. *Subcommission for the European Reference Frame (EUREF), Publication 10*, J. A. Torres and H. Hornik, Eds., in press.

Doms, G., and U. Schaettler, 1999: The nonhydrostatic limited-area model LM (Local-Modell) of DWD, Part I: Scientific Documentation. Deutscher Wetterdienst LM F90 1.35. 172pp.[Available from Deutscher Wetterdienst, P.O.Box 100465, 63004 Offenbach, Germany.]

Doms, G., and U. Schaettler, 2001: Consortium for Small-Scale Modelling (COSMO). Newsletter Consortium for small-scale modeling, 1, G. Doms and U. Schaettler, Eds., 114 pp. [Available from Deutscher Wetterdienst, P.O.Box 100465, 63004 Offenbach, Germany.]

Emardson, T. R., G. Elgered, and J. Johanson, 1998: Three months of continuous monitoring of atmospheric water vapor with a network of Global Positioning System receivers. *J. Geophys. Res.,* **103,** 1807-1820.

Flores, A., G. Ruffini, and A. Ruis, 2000: 4D tropospheric tomography using GPS slant wet delays. *Ann. Geophys.,* **18,** 223-234.

Gassmann, A., 2001: Filtering of LM-orography. Newsletter Consortium for small-scale modeling, 1, G. Doms and U. Schaettler, Eds., 71-78. [Available from Deutscher Wetterdienst, P.O.Box 100465, 63004 Offenbach, Germany].

Gueldner, J., and D. Spaenkuch, 1999: Results of year-round remotely sensed integrated water vapour by ground based microwave radiometry. *J. Appl. Meteorol.,* **38,** 981-988.

Ingold, T., B. Schmid, C. Matzler, P. Demoulin, and N. Kampfer, 2000: Modeled and empirical approaches for retrieving columnar water vapour from solar transmittance measurements in the 0.72, 0.82, and 0.94 μm absorption band. *J. Geophys. Res.,* **105,** 24 327-24 343.

Kuo, Y. H., X. Zou, and Y. R. Guo, 1996: Variational assimilation of precipitable water using a nonhydrostatic mesoscale adjoint model. Part I: Moisture retrieval and sensitivity experiments. *Mon. Wea. Rev.,* **124,** 122-147.

Liou, Y.-A. Y.-T. Teng, T. Van Hove, and J. Liljegren, 2001: Comparison of precipitable water observations in the near tropics by GPS, microwave radiometer, and radiosondes. *J. Appl. Meteorol.,* **4,** 5-15.

MacDonald, A. E., and Y. Xie, 2000: On the use of slant observations from GPS to diagnose three-dimensional water vapor using 3DVAR. *Fourth Symp. on Integrated Observing Systems, Amer. Meteor. Soc,* Long Beach, CA, 62-73.

MacDonald, A. E., Y. Xie, and R. Ware, 2001: Diagnosis of three-dimensional water vapor using slant observations from a GPS network. *Mon. Wea. Rev.,* in press.

Majewski, D., 1985: Balanced initial and boundary values for limited area model. *Contrib. Atm. Phys.,* **58,** 147-159.

Niell, A. E., 1996: Global mapping functions for the atmosphere delay at radio wavelengths. *J. Geophys. Res.,* **101,** 3227-3246.

Ohtani, R., and I. Naito, 2000: Comparisons of GPS-derived precipitable water vapors with radiosonde observations in Japan. *J. Geophys. Res.,* **105,** 26 917-26 929.

Rothacher, M., and L. Mervart, 1996: Bernese GPS Software Version 4.0. Astronomical Institute University of Bern.

Richner, H., 1999: Grundlagen aerologischer Messungen speziell mittels der Schweizer Sonde SRS 400. *Veroeffentlichungen der SMA-MeteoSchweiz* **61,** 137. [Available from SMA-MeteoSchweiz, Kraehbuehlstrasse 58, CH-8044, Zuerich, Switzerland.]

Rocken, C. R., R. Ware, T. VanHove, F. Solheim, C. Alber, J. Johnson, M. Bevis, and S. Businger, 1993: Sensing atmospheric water vapor with the Global Positioning System. *Geophys. Res. Lett.,* **20,** 2631-2634.

Rocken, C. R., T. VanHove, J. Johnson, F. Solheim, R. Ware, M. Bevis, S. Chiswell, and S. Businger, 1995: GPS/STORM-GPS sensing of atmospheric water vapor for meteorology. *J. Atmos. Oceanic Technol.,* **12,** 468-478.

Schneider, D., E. Brockmann, U. Marti, A. Schlatter, and U. Wild, 2000: Introduction of a precise Swiss Positioning Service "swipos" and progress in the Swiss national height network (LHN95). *Subcommission for the European Reference Frame (EUREF) Publication 9*, J. A. Torres and H. Hornik, Eds., 315-322.

Schraff, Ch., 1997: Mesoscale data assimilation and prediction of low stratus in the Alpine region. *Meteor. Atmos. Phys.,* **64,** 21-50.

Stauffer D. R., and N. L. Seaman, 1994: Multiscale four-dimensional data assimilation. *J. Appl. Meteor.,* **33,** 416-434.

Ware, R. H., D. W. Fulker, S. A. Stein, D. N. Anderson, S. K. Avery, R. D. Clark, K. K. Droegemeier, J. P. Kuettner, J. B. Minster, and S. Sorooshian, 2000: SuomiNet: A real-time national GPS network for atmospheric research and education. *Bull. Amer. Meteor. Soc.,* **33,** 677-694.

Weygandt, S. S., and N. L. Seaman, 1994: Quantification of predictive skill for mesoscale and synoptic-scale meteorological features as a function of horizontal grid resolution. *Mon. Wea. Rev.,* **122,** 57-71.

2. Monitoring IWV from GPS and limited - area forecast model. G. Guerova and M. Tomassini, *Research Report 03-15*, University of Bern, Switzerland

Monitoring IWV from GPS and limited - area forecast model

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Research Report No. 2003-15
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Abstract

The GPS Networks of Germany and Switzerland, operated by the GeoForschungsZentrum and Swiss Federal Office of Topography, provide Zenith Total Delay (ZTD) measurement from more than 100 permanent GPS sites.
Integrated Water Vapour (IWV) is extracted and compared to IWV derived from a non-hydrostatic mesoscale model - Local Model (LM), used for operational numerical weather forecast in Germany and Switzerland. For the period April to December 2001 GPS IWV is compared against IWV fields from LM. Special attention is paid to the difference between GPS and model data in the day-to-night behaviour.

Contents

1. Ground - based GPS networks

a. GPS network in Germany

In 1999 the GeoForschungsZentrum (GFZ), Potsdam initiated the establishment of the German ground - based GPS network within the ”GPS Atmosphere Sounding (GASP)” project. This network consists of 83 GPS sites, from Germany and the neighbouring countries (figure 0.1), processed by GFZ in Near - Real Time (NRT) mode. The NRT data analysis is based on hourly retrieved data. The software used is the EPOS.P.V2 package developed at GFZ. The implemented technique uses a 12 hour sliding window where the result for the latest hour forms the NRT product. To allow an orbit relaxation in addition to the German network some global IGS sites are used to stabilise the orbit parameter improvement. The station coordinates are fixed after their coordinates are determined with mm-accuracy.

b. Automated GPS network of Switzerland

The ground based GPS network of Switzerland (AGNES) was completed in 2001 and consists of 29 permanent receivers sites processed by the Swiss Federal Office of Topography (Brockmann et al. 2002). The location of the GPS sites is presented in figure 0.2. The AGNES spatial density is about 50 km providing hourly data of Zenith Total Delay. The processing is done using the Bernese Normal Equation Stacking software with a 10° elevation cut - off and in Post Processed mode. For verification purposes 11 sites have been selected with appropriate model-to-station height difference.

Figure 0.1: The GPS network processed by GFZ. German radiosonde stations (red squares) are ploted in addition.

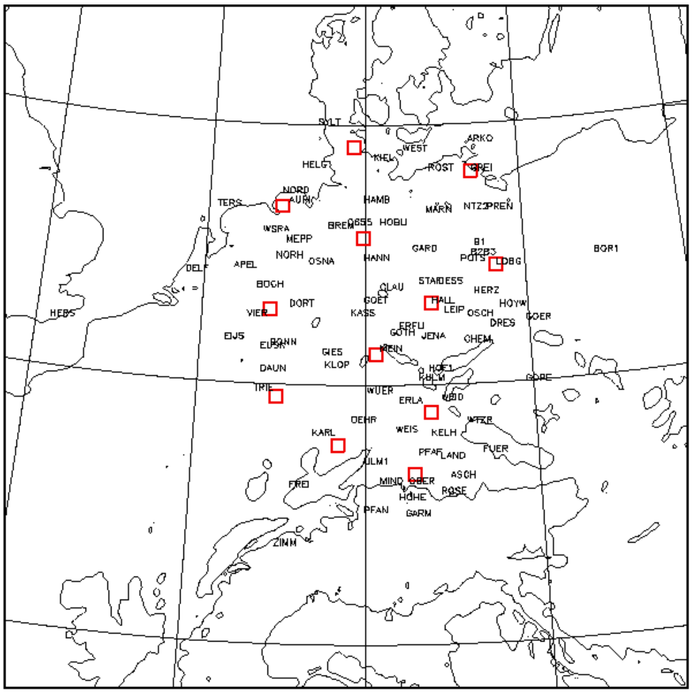
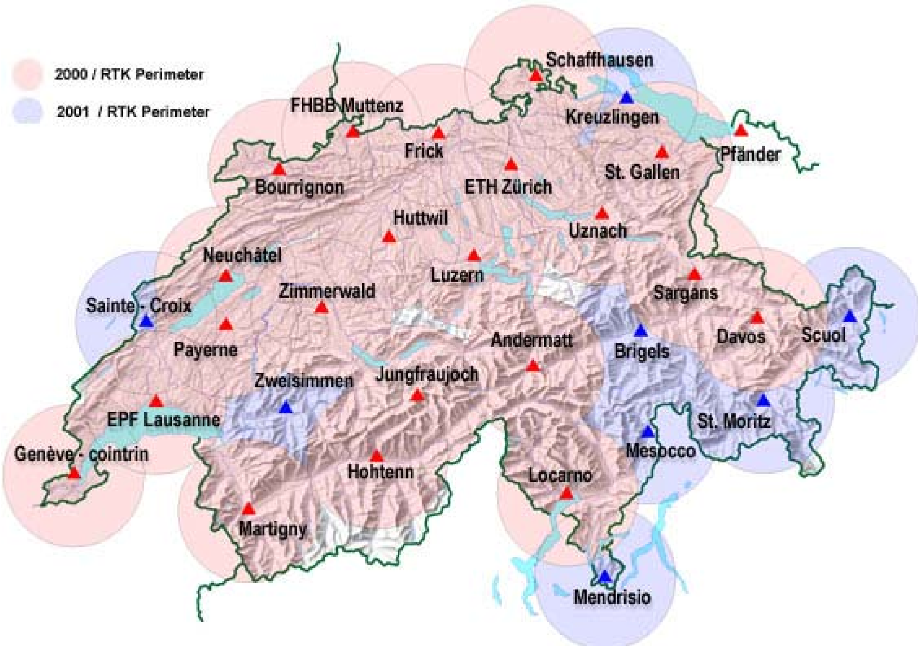


Figure 0.2: The automated GPS network of Switzerland (AGNES).



2. Mesoscale limited area forecast model

The limited area nonhydrostatic mesoscale model implemented in the operational NWP in Germany and Switzerland is a joint development within the Consortium for Small - Scale Modelling (COSMO).

a. Model configuration at German Weather Service - DWD

The Local Model (LM) is in operational weather prediction at DWD since December 1999. The LM is nested in the GME global model and has horizontal resolution of 7 km with 35 vertical levels. The domain is centred in Germany and has 325x325 points in 2D. The data assimilation scheme is Newtonian relaxation - nudging (Schraff 1997).

b. Model configuration at MeteoSwiss

The Alpine Model (aLMo) is the Swiss implementation of the nonhydrostatic fully compressible Local Model. It has been in operational use at MeteoSwiss since April 2001. Horizontal resolution of aLMo is 7 km or 1/16° with 45 hybrid vertical levels. The nudging data assimilation has been in operational use since November 2001. The domain is centred in Switzerland and covers a substantial part of Europe and the Mediterranean sea (figure 0.3). The operational forecasts and analysis run on a high performance NEC SX - 5 machine using 12 processors.

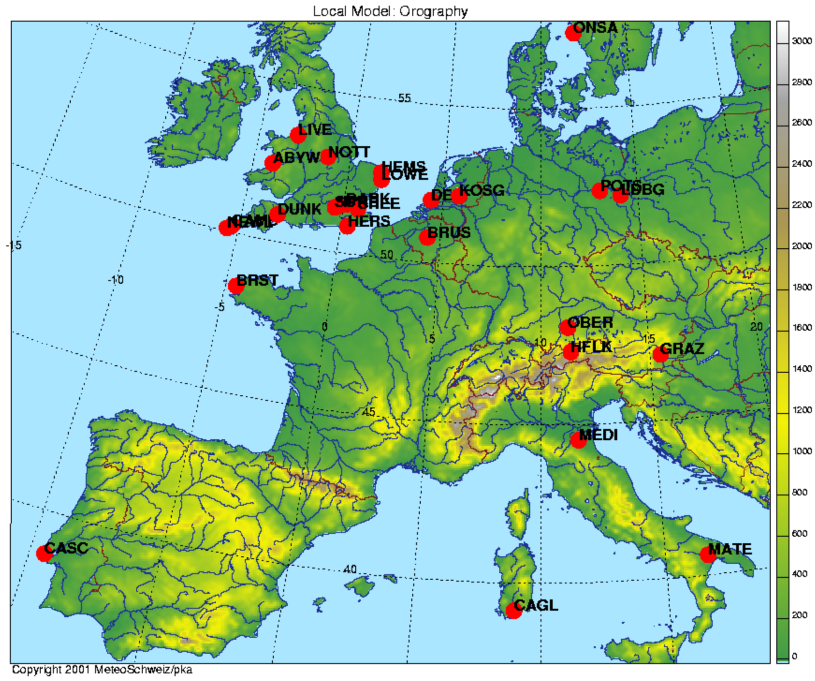
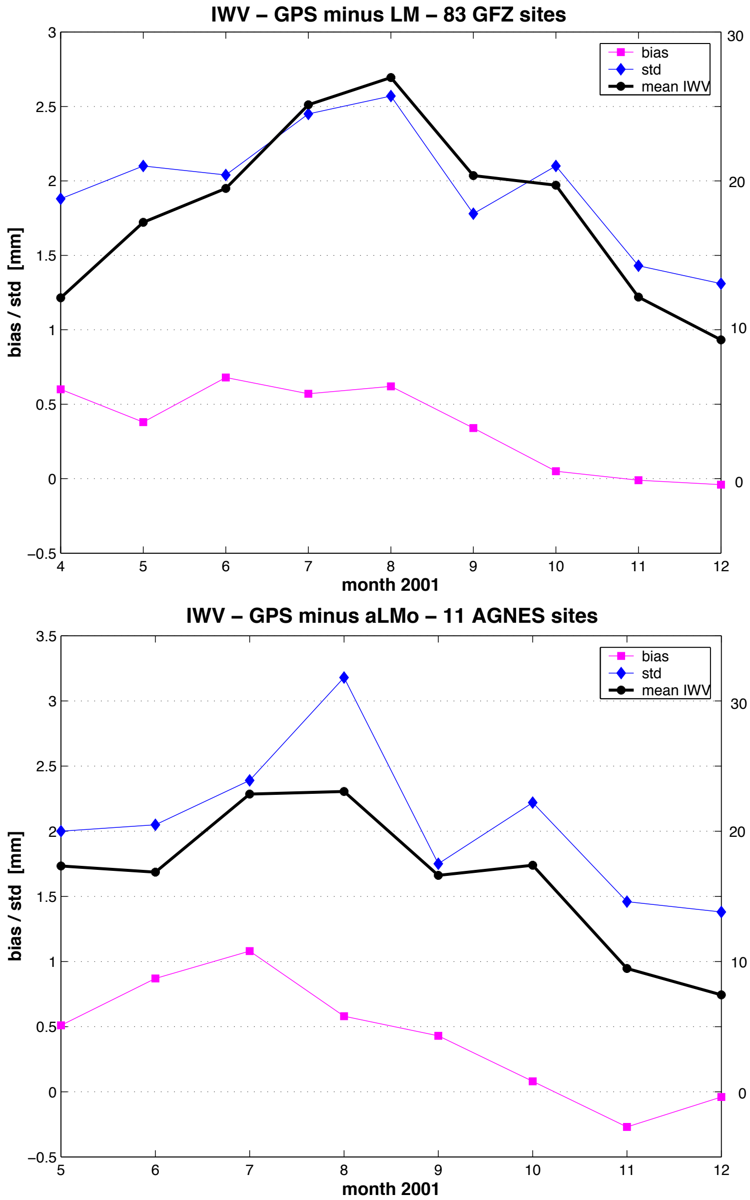


Figure 0.3: Domain covered by the Swiss configuration of the Local Model - aLMo.

3. IWV monitoring in Germany and Switzerland

The model monitoring using GPS derived Integrated Water Vapour (IWV) has been conducted in parallel in Germany and Switzerland. The IWV is extracted from Zenith Total Delay data following Bevis et al. (1992). The IWV from GPS is compared to the IWV from the model analyses for the period April - December 2001. The results presented in figure 0.4 show consistency of the bias and standard deviation for Germany (figure 0.4 a) and Switzerland (figure 0.4 b). The bias (GPS minus LM) is positive in the summer months (up to 1.07 mm) and decreases in the winter. The standard deviation variation follows the seasonal variation of the mean GPS IWV (thick black line). The ratio of the std to the mean



a.

b.

Figure 0.4: IWV bias (pink line) standard deviation (blue line) and monthly mean (black line) for: a) Germany April to December 2001 and b) Switzerland May to December 2001.

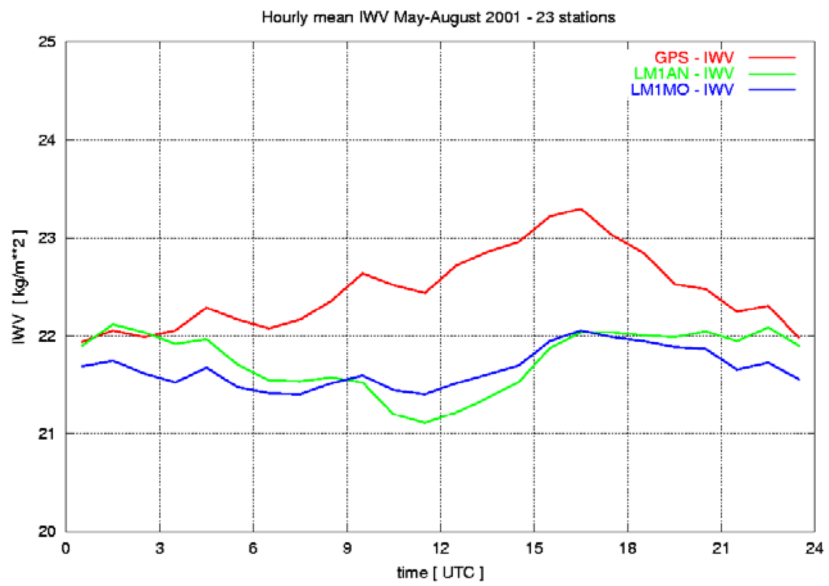


Figure 0.5: Diurnal IWV cycle from GPS (red line), LM analysis (green line) and LM forecast (blue line) in the period May to August 2001.

observation is larger during winter, suggesting larger relative errors in situations with low water vapour amounts.

The diurnal cycle of IWV from LM and GPS has been investigated in DWD for the period May to August 2001. The comparison can be seen in figure 0.5. The GPS IWV is systematically higher than the model and describes a different diurnal cycle. The GPS (red line) observes an increase of IWV after 6 UTC, with a maximum at around 16 and a decreases after 18 UTC. LM analysis run tends to be opposite with a small decrease of IWV during the morning and a minimum around 12 UTC. The LM forecast run (blue line), has a smaller diurnal variation with a minimum at 12 UTC which is not as well pronounced as in the LM analysis. The underestimation of IWV in the hours between 6 and 21 UTC can be a reason for the reported systematic monthly bias in the summer 2001.

4. Conclusions

The monitoring of IWV amount from the limited area forecast model, used for operational Numerical Weather Prediction in Germany and Switzerland, has been performed using the ground - based GPS data from GZF and AGNES networks. The results give similar model performance for Germany and Switzerland. The model tends to underestimate the water vapour content of the atmosphere, and this tendency is very well pronounced in the summer months June to September. The diurnal cycle of the model was investigated in the summer months of 2001. In the hours between 6 and 21 UTC the model analysis and forecast are systematically underestimating the IWV. This is a possible reason for the negative monthly bias. Thus a possible improvement in the diurnal cycle of the model can be expected through efficient assimilation of GPS data.

References

Bevis, M., S. Businger, T.A. Herring, C. Rocken, R.A. Anthes, and R.H. Ware, 1992: GPS Meteorology: Remote sensing of atmospheric water vapor using the Global Positioning System. *J. Geophys. Res.,* **97,** 15 787-15 801.

Brockmann E., G. Guerova, M. Troller, 2002: Swiss Activities in combining GPS with Meteorology. Mitteilung des Bundesamtes für Kartographie und Geodäsie, J.A. Torres and H. Hornik Eds., EUREF Publ. Vol. 23, Frankfurt, Germany 95-99.

Schraff, Ch., 1997: Mesoscale data assimilation and prediction of low stratus in the Alpine region. Meteor. Atmos. Phys. 64, 21-50.

3. Verification of the aLpine Model with the GPS data in the period 2001-2003. G. Guerova, Ch. Mätzler and N. Kämpfer, to be submitted to Meteorol. Atmos. Phys.

Verification of the aLpine Model with the GPS data in the period 2001-2003.

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Abstract

The importance of GPS as a monitoring tool in operational Numerical Weather Prediction has grown in the last decade. The validation of the nonhydrostatic mesoscale aLpine Model (aLMo) of MeteoSwiss for a period of 30 months is reported. Data from 14 sites of the GPS Network of Switzerland - AGNES are compared against the aLMo Integrated Water Vapour (IWV) field. The monthly bias and standard deviation exhibit strong seasonal dependence with a pronounced dry bias of the model during the warm months, May to October 2002. The diurnal IWV cycle in 2001 gives good model performance between 0 and 9 UTC and underestimation of IWV by up to 1.5 kg/m^2 for the rest of the day. In 2002 the diurnal cycle shows a systematic dry bias in the model. The precipitation verification for summer 2002 gives a strong model overestimation of light precipitation amounts (below 0.1 mm/6h). It is expected that a strong correlation between the dry IWV bias and significant precipitation overestimation exist in this summer period. The results demonstrate the usefulness of GPS data for model monitoring.

1. Introduction

Water vapour plays a key role in the hydrological cycle and atmospheric radiation. It is actively participating in the processes of precipitation formation, energy transfer and atmospheric stability. In addition water vapour has a short life time in the atmosphere of about one week and significant spatial and temporal variation, which affect both climate and Numerical Weather Prediction. This makes the observations a challenging task. Traditionally observations of water vapour are made through balloon-borne soundings. The radiosonde network provides a world wide coverage but its poor temporal resolution, typical two soundings a day, is not sufficient enough to study water vapour variations at different temporal and spatial scales. From the existing satellite observations the extraction of water vapour is still a challenging work over the vegetation covered surfaces of the Earth. This is however not the case for the ground - based Global Positioning System (GPS). The advantage of GPS is that it operates in all weather conditions, provides low temporal resolution data (every hour or less) and has dense spatial coverage, more than 300 receivers are operating only in Europe. It is inexpensive, easy to operate and its potential is expected to increase with the new European project GALILEO (the European Satellite Navigation System) in operational service from 2008.

In Europe two projects, funded by EU, have been dedicated to the use of GPS in mesoscale meteorology. The first of them, the MAGIC project (Haase et al. 2002), studied the variability of the GPS derived water vapour measurements in the western Mediterranean area. The second, COST Action 716 (Elgered 2001), initiated in 1999, has the objective to explore the application of GPS data in operational NWP in Europe. Within this Action the task of Working Group Three was to validate the data and to perform assimilation experiments (Elgered et al. 2003). The Swiss contribution to COST 716 is a collaboration between Swiss Federal Office of Topography (Swisstopo), Federal Office of Meteorology and Climatology (MeteoSwiss) and the Institute of Applied Physics, University of Bern (IAP, UniBe). The first model validation was performed using the measurements from the Automated GPS Network of Switzerland (AGNES) processed by

Swisstopo. The operational NWP system of MeteoSwiss the hydrostatic Swiss Model and the Swiss version-aLpine Model (aLMo) of the nonhydrostatic Local Model (LM) have been compared against the GPS measurements from six sites in the period November 2000 to March 2001 (Guerova et al., 2003a).

Further work on monitoring the IWV field of NWP models was completed by Yang et al. (1998), Kopken (2001), Haase et al. (2002), Tomassini et al. (2002). Haase et al. (2002) performed a NWP model (HIRLAM) validation for a period larger than two years. The results show a seasonal dependence of the model bias and standard deviation. Tomassini et al. (2002) reported a dry bias in the LM model and a dry bias in diurnal cycle in the day time hours.

The objective of this study is to validate the water vapour field of the operational NWP system of MeteoSwiss, using the GPS Network of Switzerland (AGNES). In section 2 a description of the data sets is given. The verification of aLMo with GPS data from AGNES for the period January 2001 - June 2003 is presented in section 3. A summary and conclusions can be found in section 4.

2. Datasets used

a. Global Positioning System (GPS) data

AGNES, the ground-based GPS network of Switzerland, is operated by the Swiss Federal Office of Topography (Swisstopo). It is primarily used for navigation and surveying purposes in post processing and real time mode. The network has been completed in 2001 and has 30 permanent receivers providing a spacing of 50 km (Brockmann et al. 2001). For estimation of hourly Zenith Total Delay (ZTD) the Bernese 4.2 software package (Rothacher and Marvart 1996) with Niell mapping function and 10° minimum elevation angle is used. In this study the data from twenty AGNES sites are compared to the aLMo. The site locations are represented by white dots in figure 1. The GPS IWV is retrieved from the Zenith Total Delay (ZTD) following the standard extraction procedure described in Bevis et al. (1992) and Emardson et al. (1998). The meteorological data, surface temperature and pressure, are obtained from the surface observation network of MeteoSwiss (ANETZ).

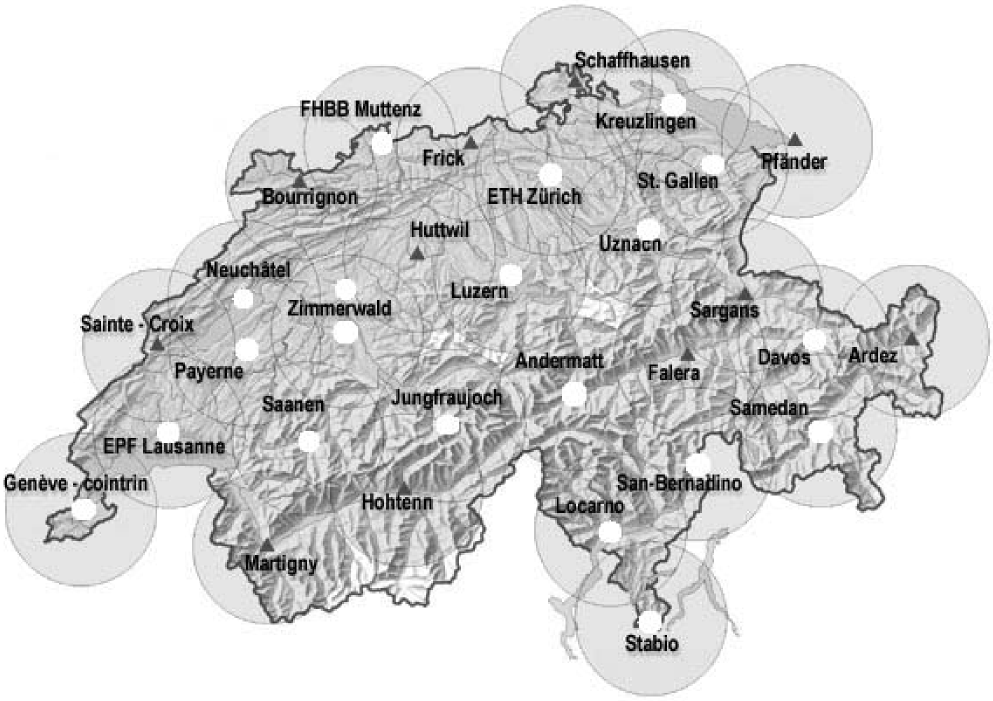


Figure 1: Automated GPS Network of Switzerland - AGNES. The sites used for verification are marked with white dots.

b. Numerical Weather Prediction (NWP) data

At the Federal Office of Meteorology and Climatology (MeteoSwiss) the nonhydrostatic COSMO model (COnsortium of Small scale MOdelling Doms and Schaettler 2001), is in operational NWP since 1 April 2001 with a preoperational test from September 2000 to March 2001. The Swiss implementation of the model-aLMo has a horizontal grid of 7 x 7 km (1/16°), 45 vertical levels from the surface up to 20 hPa in a generalized terrain-following co-ordinate system. The aLMo analyses are obtained via interpolation of driving model analyses - German Global Model (GME). The model prognostic variables are : temperature, perturbation pressure, horizontal and vertical wind velocity, water vapour, cloud water and air density. The aLMo IWV is computed as in equation 1. For each GPS site the grid point selection is based on smallest height difference. For the first fourteen sites in table 1 the height difference is less than or about 50 m and they are selected for the validation. For the remaining six sites the height difference is larger than 50 m and they are given for completeness.

c. Radiosonde data

There is one radiosonde sounding site in Switzerland located at Payerne (Swiss Plateau region). A balloon sounding (sonde type SRS 400, MeteoLabor, Switzerland) is performed twice a day (00 and 12 UTC) measuring temperature, pressure, humidity and wind profiles.

A fast response VIZ ACCU-LOK carbon hygristor is used to measure relative humidity. During the radiosonde preflight procedure, the lock-in humidity resistance is introduced in the data acquisition software and the sensor. The operating range extends from 0 to 100 % relative humidity (RH), and from - 60 to +40 °C, with an accuracy of 2 % RH (rms) (Richner 1999).

The radiosonde IWV amount is calculated using:

$$IWV = \int_{h_0}^{h_{top}} \rho_{wv}(h)dh \tag{1}$$

where ρ_{wv} is water vapour density, h is height in meters, and IWV is in kg/m^2.

Table 1: Station name, height above sea level (asl.) of: the GPS sites, the aLMo grid point, and the difference of GPS and aLMo.

GPS site	GPS height [m] asl.	aLMo height [m] asl.	GPS - aLMo difference [m]
1. Payerne (PAYE)	498	495	3
2. Lausanne (EPFL)	409	404	5
3. St.Gallen (STGA)	707	711	-4
4. Zimmerwald (ZIMM)	906	908	-2
5. Saanen (SAAN)	1368	1379	-11
6. Luzern (LUZE)	493	503	-10
7. Geneve (GENE)	419	432	-13
8. Zurich (ETHZ)	547	536	11
9. Muttenz (FHBB)	329	315	14
10. Neuchatel (NEUC)	454	431	23
11. Stabio (STAB)	366	397	-31
12. Andermat (ANDE)	2317	2360	-43
13. Bern (EXWI)	577	624	-47
14. Kreuzlingen (KREU)	483	430	53
15. San-Bernadino (SANB)	1653	1841	-188
16. Davos (DAVO)	1598	1785	-187
17. Uznach (UZNA)	428	682	-254
18. Locarno (LOMO)	388	685	-300
19. Samedan (SAME)	1711	2217	-506
20. Jungfraujoch (JUJO)	3584	3599	-15

3. Results

a. Intercomparison of GPS and radiosonde data for Payerne

The radiosonde IWV data is compared to the GPS data from the collocated site PAYE. In figure 2 are plotted the results for 00 and 12 UTC in 2001, 2002 and 2003. The bias is computed separately for 00 and 12 UTC soundings. At 12 UTC the radiosonde has less IWV compared to the GPS by 1.45 and 0.89 kg/m^2 in 2002 and 2003, respectively. At 00 UTC of the same period the agreement between the two measurements is good. On the contrary in 2001 the mid-day sounding has much better agreement with GPS than the mid-night one. The 00 UTC sounding has on average 1 kg/m^2 more IWV than the GPS derived one. One possible reason for the differences in the day-night biases in 2001 and 2002-2003 can be the change in GPS data processing introduced in mid September 2001. In addition the radiosonde observations at 12 UTC are corrected for the impact of the solar heating, and this correction is possibly influencing the estimation of relative humidity. However, this does not explain the differences between 2001 and 2002-2003. Note that the number of intercomparisons is less than 400 per year, which is possibly influencing the statistics.

The further validation of the GPS derived IWV will be performed with independent measurements from the Microwave Radiometer TROWARA, operated at Institute of Applied Physics, University of Bern, and the sunphotometar network of MeteoSwiss - CHARM. Special attention will be devoted to the day-night bias of the GPS derived IWV.

b. Monthly statistic from verification of aLMo forecast using GPS data

The model bias and standard deviation (see appendix) are calculated on monthly bases for the forecast hours from 0 to +23h, i.e. first day forecast. The results presented in figure 3 are averaged over 14 stations (model grid points) in the period from January 2001 to June 2003. Noted that the monthly mean GPS IWV is to be multiplied by ten. A clear

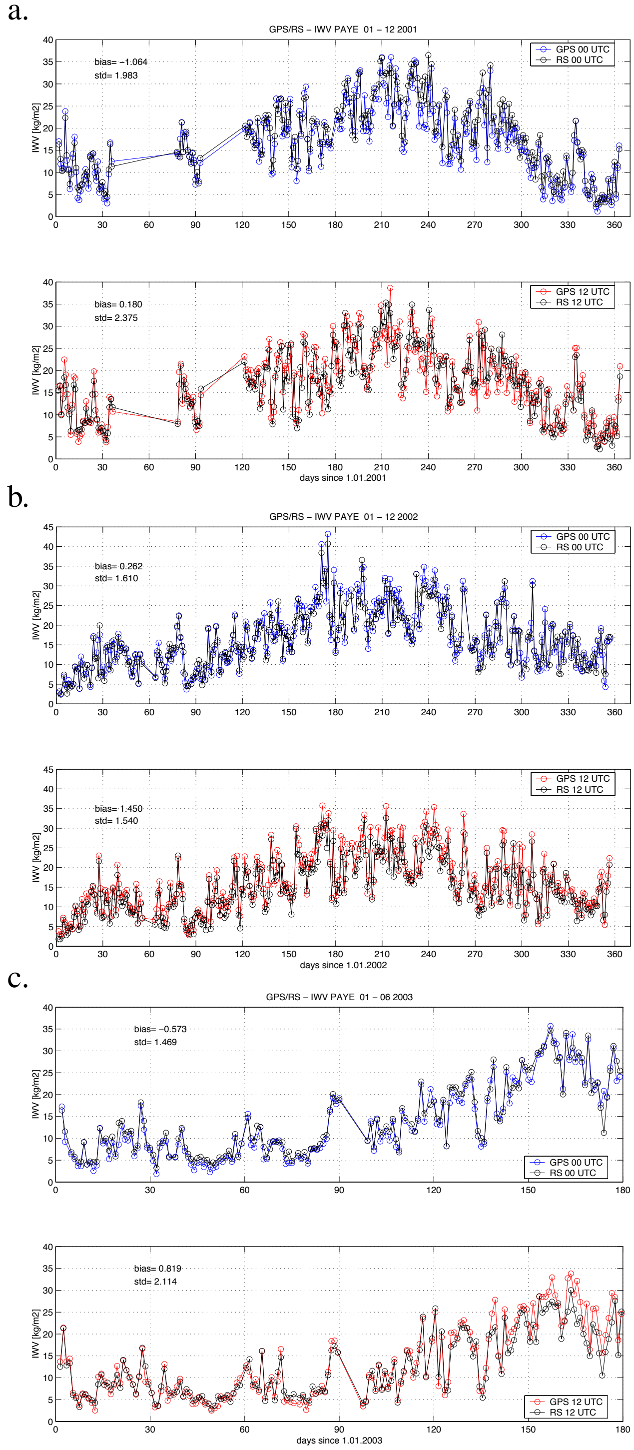


Figure 2: Validation of GPS IWV with the radiosonde station Payerne. a. For 2001 at 00 UTC (first plot) and 12 UTC (second plot), b. the same as a. but for 2002, c. the same as a. but for first six months of 2003.

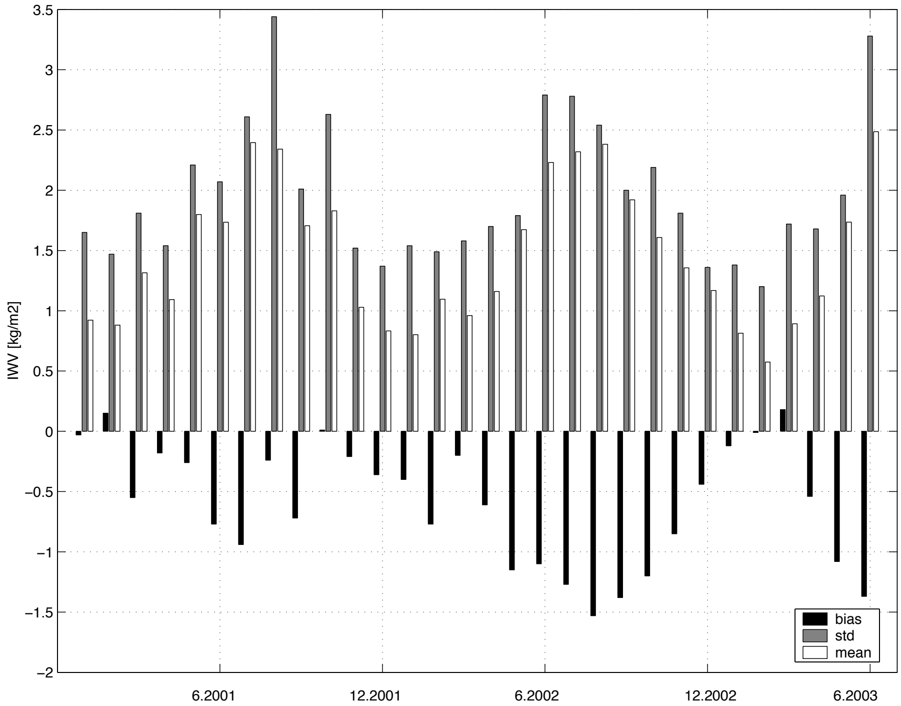


Figure 3: Monthly IWV model bias and standard deviation in the period January 2001 to June 2003 averaged over 14 Swiss sites. Note that the monthly mean IWV from GPS is to be multiplied by ten.

seasonal dependence of both the bias and the standard deviation (std) is seen. Generally, the bias is significant in the warm months June to September as is very well pronounced in 2002. In the period December to March the model bias rarely exceeds -0.5 kg/m^2. The model tends to underestimate the IWV amount reported by the GPS measurements i.e. the model exhibits a dry bias. This result is consistent with model verification with the German Network reported in Tomassini et al. (2002). Some differences are seen when the year 2001 and 2002 are compared. In 2002 the dry model bias is well below -1 kg/m^2 and the std ranges from 1.5 to 2.8 kg/m^2 in the period May to October. In 2001 the dry bias in the model is less pronounced and varies between -0.4 and -0.9 kg/m^2. The monthly mean IWV in summer 2001 and 2002 are in the same range, which does not explain the difference in the bias. A possible reason could be the already mentioned change in the GPS processing in September 2001. A further investigation will be however necessary to make more accurate conclusions.

In addition it is interesting to investigate the site dependent bias and std. In figure 4 to 7 the bias and std histograms for 20 GPS sites are plotted. The interpretation of the results will start with the sites PAYE (first plot in figure 4), EPFL (second plot in figure 4), STGA (third plot in figure 4) and ZIMM (fourth plot in figure 4), which are at the same height as the model orography (see table 1).

For the site PAYE the overall dry bias in aLMo is seen only in the summer time of 2002. During the cold months the model forecast is successfully predicting the water vapour content of the atmosphere and the bias is small, in the range $\pm$ 0.2 to $\pm$ 0.5 kg/m^2. This result is possibly due to the collocated radiosonde measurements assimilated in the model and providing a good initial state for the forecast. The model is performing very well for the site EPFL located some 60 km south from PAYE. There the typical dry bias is identified only in the three summer months of 2002. For the remaining two sites STGA and ZIMM the model dry bias is present during the entire period under investigation. It is to be noted that the altitude of the sites is about 200 and 400 m above the average Swiss plateau height (about 500 m), and this can be a reason for the persistent dry bias.

For the remaining 10 sites a pronounced dry bias is well detected in the summer months of 2002. A bias in the range of 1 to 1.8 kg/m^2 is well seen for EXWI (first plot in figure 6), FHBB (third plot in figure 5), GENE (first plot in figure 5) and LUZE (sixth plot in figure 4). Note that for the two alpine sites SAAN (at 1368 m asl.) and ANDE (at 2317 m asl.) the IWV monthly bias in June, July and August of 2002 is exceeding 2 kg/m^2. The same is true for the site STAB located in southern Switzerland. The bias reported from these three sites is contributing substantially to the overall bias seen in summer 2002. The GPS IWV derived from the site JUJO is continuously underestimating the model IWV. This site is often measuring negative IWV due to uncorrected antenna phase centre model (Guerova et al., 2003).

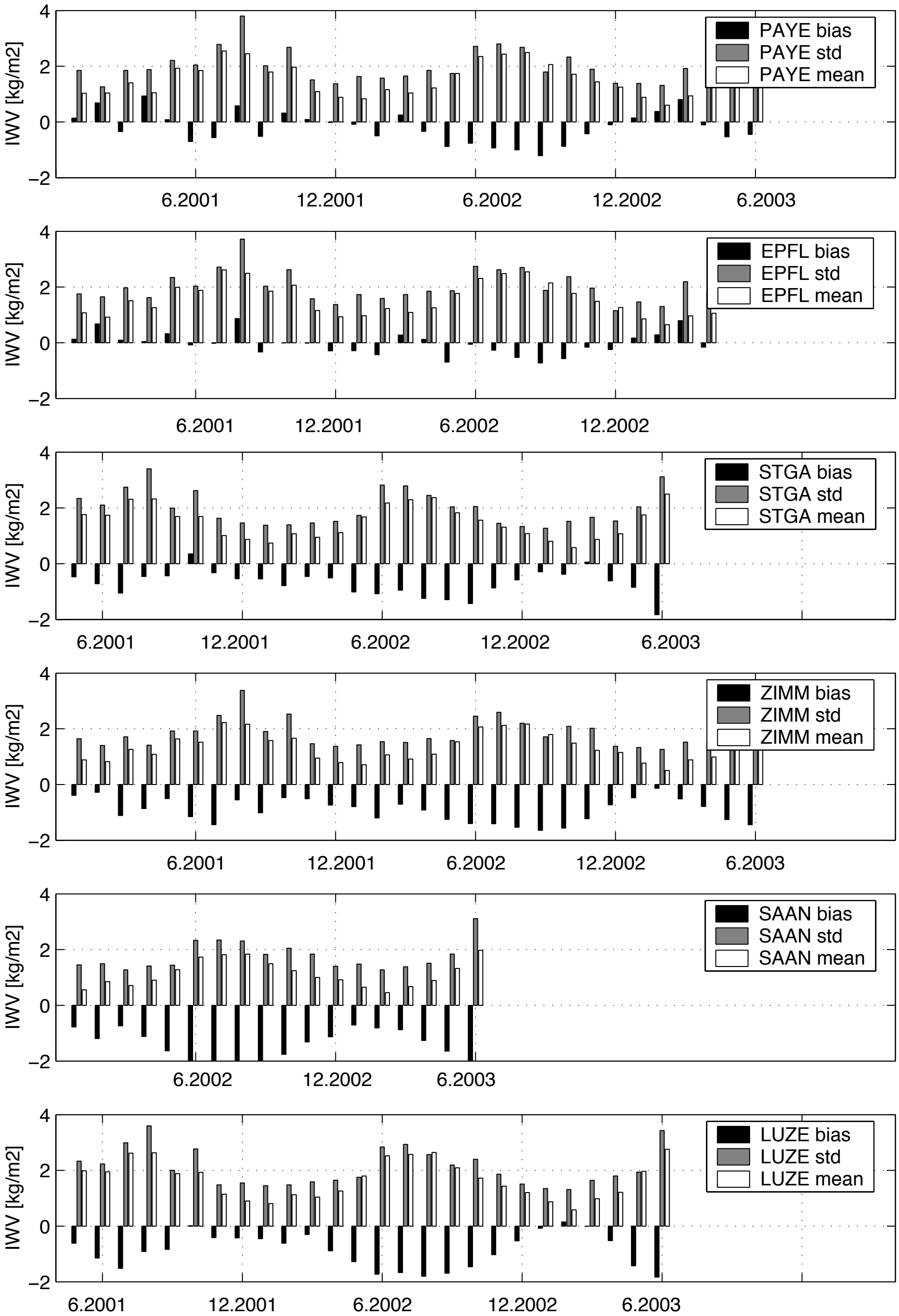


Figure 4: IWV bias, standard deviation and GPS monthly mean for: PAYE, EPFL, STGA, ZIMM, SAAN and LUZE. Note that the monthly mean IWV from GPS is to be multiplied by ten.

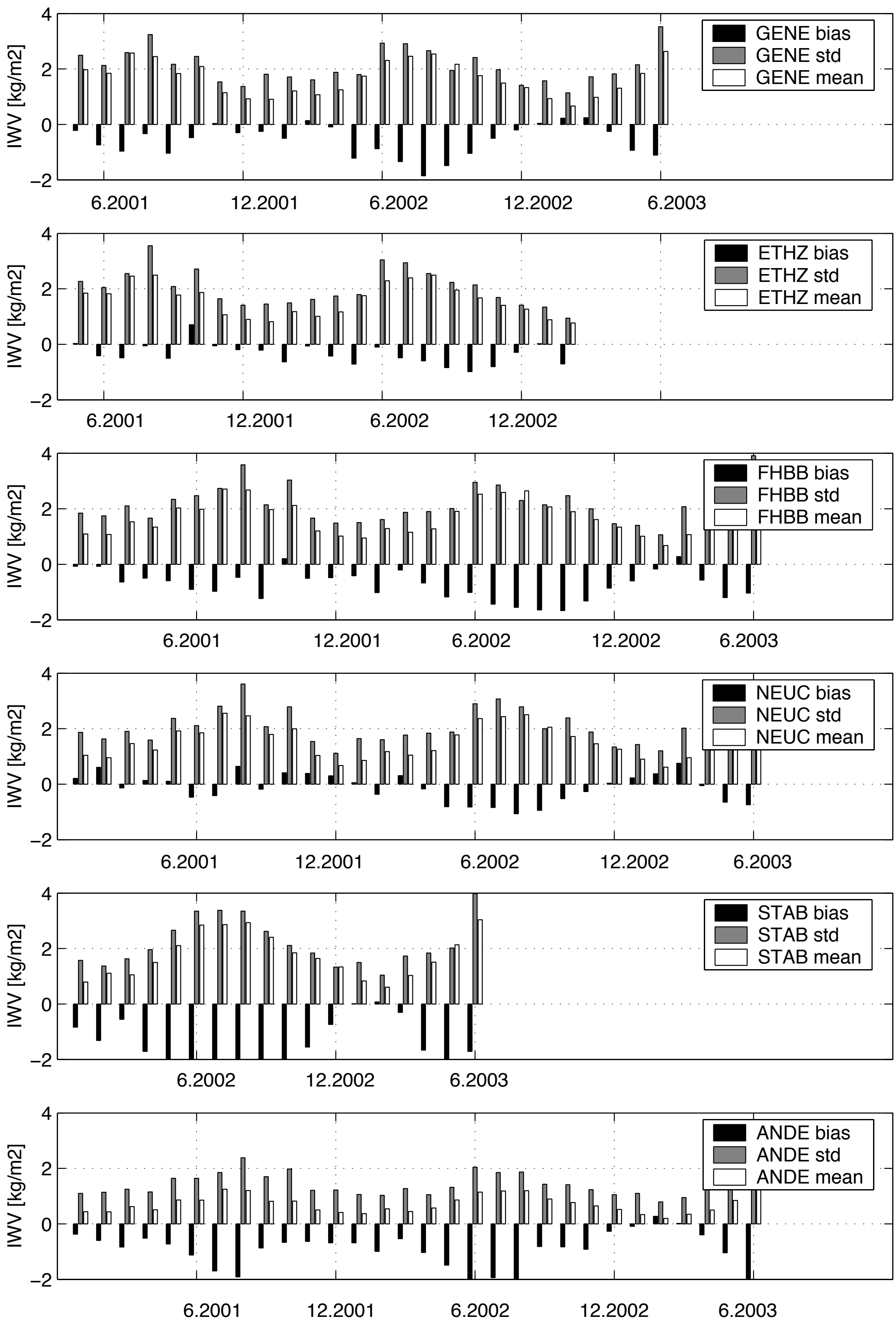


Figure 5: IWV bias, standard deviation and GPS monthly mean for: GENE, ETHZ, FHBB, NEUC, STAB and ANDE. Note that the monthly mean IWV from GPS is to be multiplied by ten.

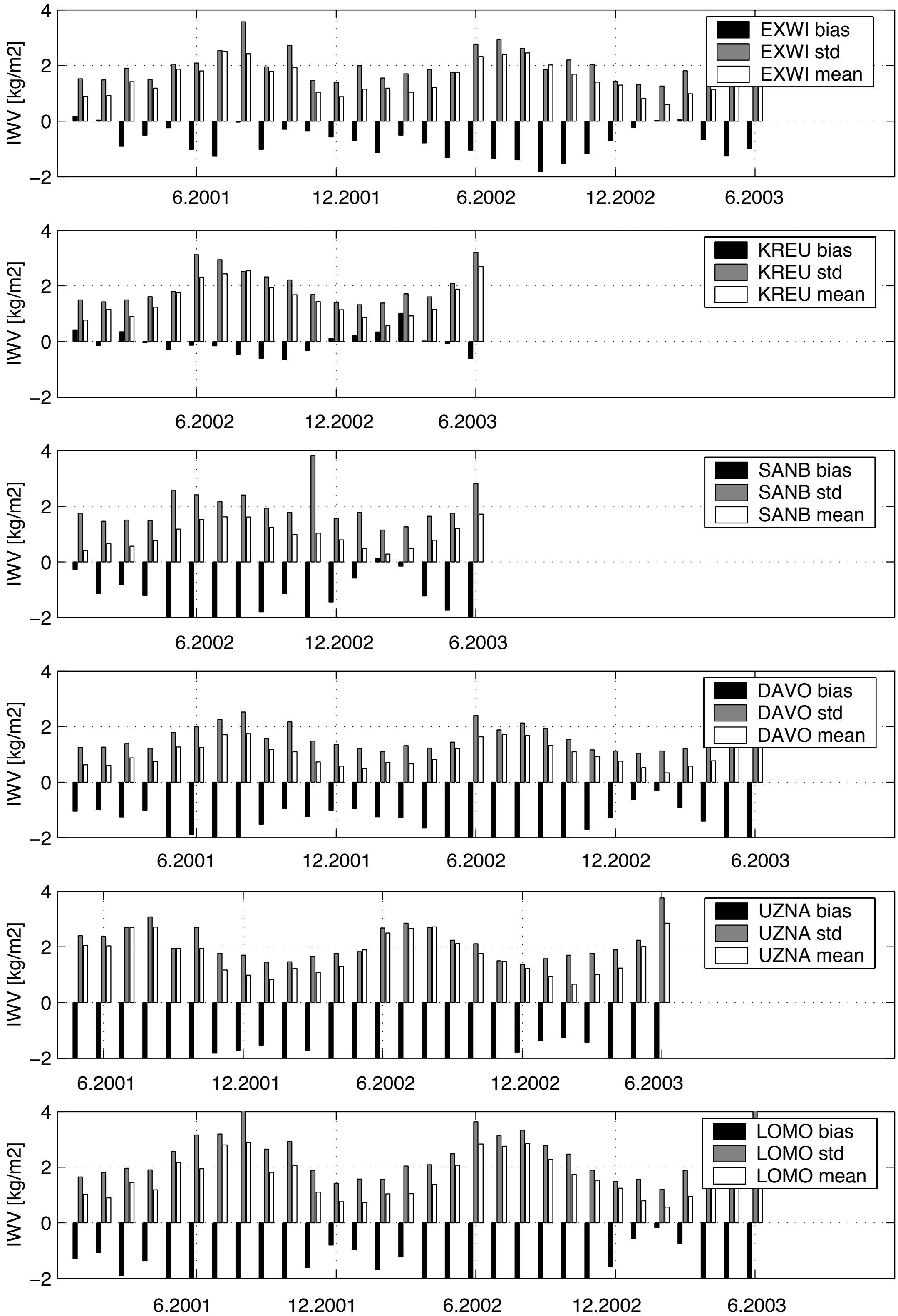


Figure 6: IWV bias, standard deviation and GPS monthly mean for: EXWI, KREU, SANB, DAVO, UZNA and LOMO. Note that the monthly mean IWV from GPS is to be multiplied by ten.

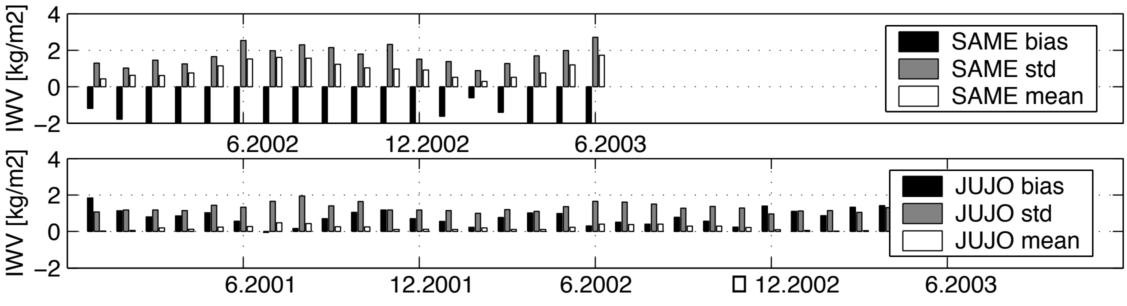


Figure 7: IWV bias, standard deviation and GPS monthly mean for: SAME and JUJO. Note that the monthly mean IWV from GPS is to be multiplied by ten.

c. Diurnal cycle of IWV and precipitation

The diurnal variations of atmospheric water vapour affect atmospheric long wave radiation and atmospheric absorption of solar radiation (Dai et al., 2002). It is also related to many other processes such as atmospheric stability, diurnal variation of moist convection and precipitation, surface wind convergence and evapotranspiration. The diurnal IWV cycle from GPS and aLMo are investigated in this section of the manuscript. Attention is paid to the link between IWV and precipitation variations.

The diurnal water vapour cycle has been investigated for the summer months, from May to October, of 2001 and 2002. The comparison is plotted in figure 8 and figure 9, respectively. The diurnal cycle of IWV in 2001 presents a good agreement between GPS and aLMo in the hours between mid-night to 9 UTC and a dry bias of the model in the range 0.5 to 1.5 kg/m^2 for the rest of the time. At 12 UTC in July, August and September the dry bias of the forecast is reaching 2 kg/m^2. This amount is about 1 kg/m^2 larger than the one reported by Tomassini et al. (2002) and by Guerova and Tomassini (2003b). Precipitation verification in summer 2001 (June to August) gives the maxima of precipitation in the mean about 3-6 hours too early. High precipitation amounts (10 mm/6h) are underestimated for grid points below 800 m asl. (by 30%) and slightly overestimated (10%) above. The rare very high amounts (30 mm/6h, observed in 0.2% of all cases) are again overestimated over all height regions (by more than 50%).

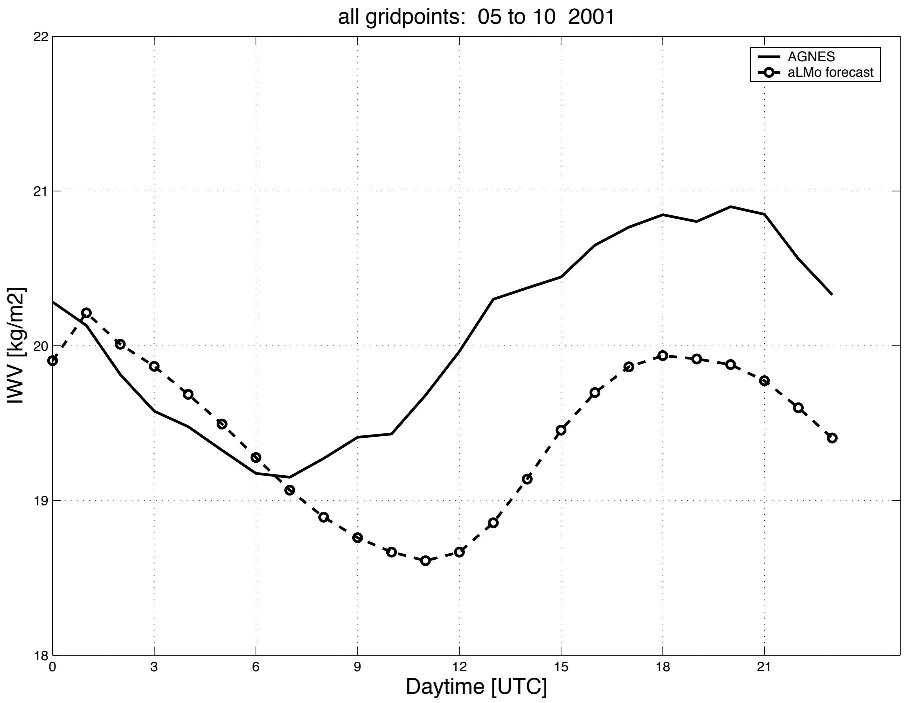


Figure 8: Diurnal cycle of IWV from aLMo forecast (dash dotted line) and GPS (solid line) in the period May - October 2001. A dry bias of the range 1 to 1.5 kg/m^2 is seen in the hours between 10 and 23.

The diurnal cycle in 2002 clearly demonstrates the model (dashed line) underestimation of IWV amount measured by GPS (solid line). For the period May to October (see figure 9a to 9f) a systematic IWV underestimation in the range 2.0 to 2.8 kg/m^2 is found. From precipitation verification in summer 2002 (June, July and August) done at MeteoSwiss, using the ANETZ synop observations, the following summary is given: precipitation amounts are overestimated: for grid points below 800 m asl., by $\sim$ 50 - 60 % for light precipitation amounts (0.1 mm/6h threshold) and by $\sim$ 10% for high precipitation amounts (larger than 10mm/6h). For grid points below 800 m, the daily maxima are forecasted too early and are too pronounced, the evening maxima (at 16 UTC) 2-3 hours too early and the second maxima during the night (at 02 UTC) 4 hours too early. From the precipitation and IWV verification it can be concluded that a possible coupling exists in 2002 i.e. too less water vapour and too much light precipitation. Thus it is a important to further investigate the water vapour cycle of the model as it is with relevance in the future assimilation of GPS derived IWV in aLMo. The future aLMo validation work will include intercomparison with model analysis.

4. Summary and conclusion

Monitoring IWV forecast of the aLpine Model, the operational NWP model of MeteoSwiss, has been performed over two and half years, from 2001 to 2003, using the GPS measurements. The ground - based GPS data from 30 permanent Swiss sites is processed by Swiss Federal Office of Topography in post processed and near real time mode. In this study the post processed data have been used. 20 GPS sites have been selected based on availability of surface meteorological observations. The model monthly bias and standard deviation for 14 sites exhibit a seasonal dependence with pronounced dry bias in the summer 2002. The diurnal IWV cycle in aLMo exhibits underestimation of the IWV in the day time hours of 2001 and over the entire day in 2002. The strong dry bias, reaching 2.8 kg/m^2, seen in the model forecast in 2002 is possibly coupled with the reported overestimation up to 50% of the light precipitation events. The results of the diurnal cycle monitoring are of relevance for the planned future operational assimilation of GPS derived IWV in aLMo. The reason for the fast water vapour transformation to liquid water and then precipitation is possibly a model deficiency on parameterization level or inadequate vertical distribution of water vapour content, i.e. too much at the condensation level height and too little in the boundary layer.
The future work of monitoring aLMo with GPS derived IWV will also consider the model analysis field.

Acknowledgement. This work is supported by the Swiss Federal Office of Education and Science under Grant C97.0027. We would like to thank Swiss Federal Office of Topography for providing the post processed GPS data and MeteoSwiss for the aLMo

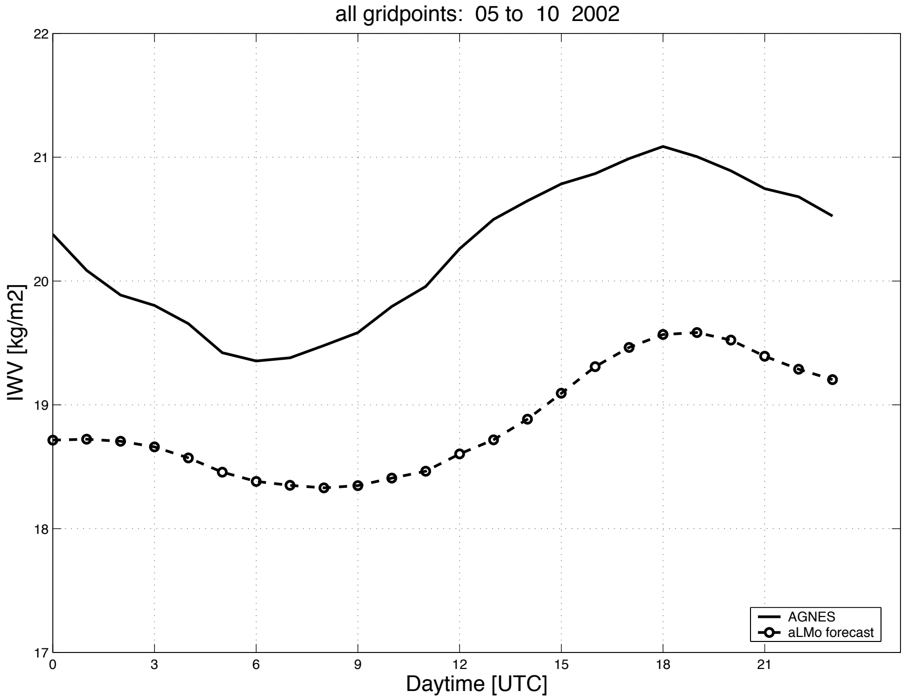
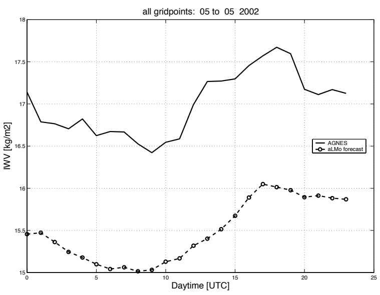
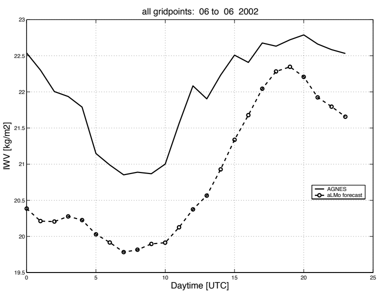


Figure 9: Diurnal cycle from aLMo forecast (dash dotted line) and GPS (solid line) in the period May October 2002. The model exhibits a constant dry bias of 1.5 kg/m^2, which correlates well with precipitation overestimation.

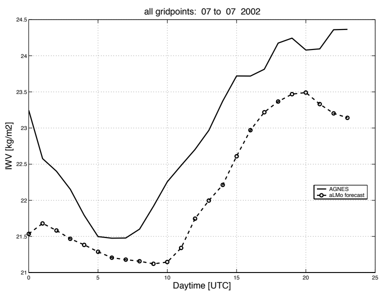
a.



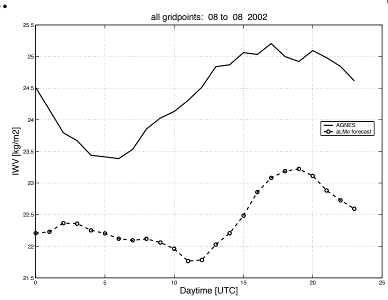
b.



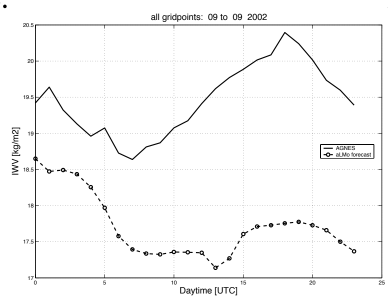
c.



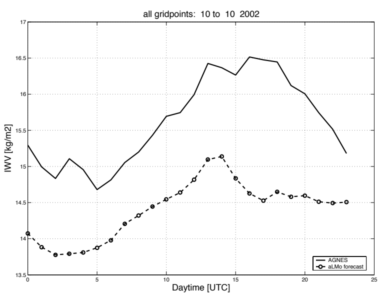
d.



e.



f.



data.

Appendix : Definition of statistics

For computation of the bias and standard deviation the following definitions are used:

$$bias = \frac{1}{N}\sum_{i=1}^{N}(IWV_{im} - IWV_{io}) \tag{2}$$

$$rms = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(IWV_{im} - IWV_{io})^2} \tag{3}$$

$$std = \sqrt{rms^2 - bias^2} \tag{4}$$

where IWV_{im} and IWV_{io} are model and observation IWV values, respectively, at a given time and location. N is number of cases.

References

Bevis, M., S. Businger, T.A. Herring, C. Rocken, R.A. Anthes, and R.H. Ware, 1992: GPS Meteorology: Remote sensing of atmospheric water vapor using the Global Positioning System. *J. Geophys. Res.,* **97,** 15 787-15 801.

Brockmann E, Guerova G, Troller M (2002) Swiss Activities in combining GPS with Meteorology. Mitteilung des Bundesamtes für Kartographie und Geodäsie, J.A. Torres and H. Hornik Eds., EUREF Publ. Vol. 23, Frankfurt, Germany 95-99.

Dai, A., J. Wang, R. H. Ware, and T. Van Hove, 2002: Diurnal variation in water vapor over North America and its implications for sampling errors in radiosonde humidity. *J.*

Geophys. Res., **107(D10),** 10.

Doms, G., and U. Schaettler, 2001: Consortium for Small-Scale Modelling (COSMO). Newsletter Consortium for small-scale modeling, 1, G. Doms and U. Schaettler, Eds., 114 pp. [Available from Deutscher Wetterdienst, P.O.Box 100465, 63004 Offenbach, Germany.]

Elgered G., 2001: An overview of COST Action 716: Exploitation of ground-based GPS for climate and numerical weather prediction applications. *Phys Chem Earth (A),* **26: 6-8,** 399-404.

Elgered G., H.-P. Plag, H. van der Marel, S. Barlag, and J. Nash, 2003: Ground-Based GPS for Climate and Numerical Weather Prediction Applications. *The EGGS,* **4,** 22-24. Available online at: www.the-eggs.org/data/eggs_4.pdf

Emardson, T. R., G. Elgered, and J. Johanson, 1998: Three months of continuous monitoring of atmospheric water vapor with a network of Global Positioning System receivers. *J. Geophys. Res.,* **103,** 1807-1820.

Guerova G., E. Brockmann, J. Quiby, F. Schubiger, Ch. Matzler, 2003: Validation of NWP mesoscale models with Swiss GPS Network AGNES. *J. Appl. Meteorol.* **42,** 1, 141-150.

Guerova G., Tomassini M., 2003b: Monitoring IWV from GPS and limited - area forecast model. *Research Report* **03-14,** Institute of Applied Physics, University of Bern, Switzerland.

Haase J., M. Ge, H. Vedel, and E. Calais, 2002: Accuracy and variability of GPS Tropospheric Delay Measurements of Water Vapour in the Western Mediterranean. *Bull.*

Am. Meteor. Soc. submitted Oct 2002.

Kopken C., 2001: Validation of integrated water vapour from numerical models using ground-based GPS, SSM/I, and water vapour radiometer measurements. *J. Appl. Meteor.,* **40,** 1105-1117.

Rothacher, M., and L. Mervart, 1996: Bernese GPS Software Version 4.0. Astronomical Institute University of Bern.

Richner, H., 1999: Grundlagen aerologischer Messungen speziell mittels der Schweizer Sonde SRS 400. *V*eroeffentlichungen der SMA-MeteoSchweiz **61,** 137. [Available from SMA-MeteoSchweiz, Kraehbuehlstrasse 58, CH-8044, Zuerich, Switzerland.]

Tomassini M., G. Gendt, G. Dick, M. Ramatschi, and Ch. Schraff, 2002: Monitoring of integrated Water Vapour from ground-based GPS observations and their assimilation in a limited area model. *Phys. Chem. Earth* **27,** 341-346.

Vedel H., X.Y. Huang, J.Haase, M. Ge, E. Calais, 2003: Impact of GPS zenith tropospheric delay data on the precipitation forecasts in Mediterranean France and Spain. *Geophys. Res. Lett.* submitted February 2003.

Yang, S., B. H. Sass, G. Elgered, J. M. Johansson, and T. R. Emardson, 1999: A comparison of the precipitable water vapor estimates by an NWP simulation and GPS observations. *J.Appl. Meteor.,* **38,** 941-956.

Chapter 3

Part II: Assimilation experiments

1. **GPS observing system experiment with the Local Model. Report from the COST 716 Short Term Scientific Mission. G. Guerova ,*Research Report 03-16*, University of Bern, Switzerland**

GPS observing system experiment with the Local Model. Report from the COST 716 Short Term Scientific Mission.

Guergana Guerova

Research Report No. 2003-16
September 2003

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Abstract

This report covers the main activities carried out during the COST 716 Short Term Scientific Mission to the Deutscher Wetterdienst in April 2001. The objective of this mission was to check and improve the GPS assimilation subroutines in the Local Model (LM). In addition an impact experiment has been computed for a frontal passage on April 3, 2001. The results present a successful correction of the model Integrated Water Vapour field at 06 UTC and a minor impact at 12, 18 and 21 UTC. No marked impact on temperature, cloud cover and precipitation fields is reported. From the LM monitoring with the real-time GPS observations a problem of radiosonde observation was identified.

Contents

1. Short Term Scientific Mission at Deutscher Wetterdienst (DWD)

The Short Term Scientific Mission (STSM) involved Guergana Guerova, of the University of Bern, Switzerland visiting the Deutscher Wetterdienst (DWD), Offenbach Germany for one month. The visit was approved by the Management Comity of COST Action 716 ”Exploitation of ground based GPS for climate and numerical weather prediction application”. The aim of this STSM is related to the application of GPS in operational Numerical Weather Prediction in Switzerland. The visit was conducted in April 2001. The main work undertaken is summarised below.

a. Nudging of GPS observations

The assimilation system of the Local Model (LM) of DWD employs the Newtonian relaxation - nudging concept (Schraff 1997). The model's prognostic variables are relaxed towards a prescribed value within a fixed time window. The relaxation in LM is performed towards direct observations. The nudging equation for the specific humidity - q and for a single observation has the following form:

$$\frac{\partial}{\partial t} q(t) = Q(q) + G_q.W_q.[q_{obs} - q_{mod}], \qquad (0.1)$$

where Q denotes the model physics and dynamics, q_{obs} and q_{mod} are the observed and the model specific humidity, $G_q = 6.10^{-4}s^{-1}$ is the coefficient defining the relaxation time, and $W_q = W_q(x).W_q(t)$ consists of spatial and temporal weights and of a quality factor. The second term in equation (1) is the nudging term and the part $[q_{obs} - q_{mod}]$ is for the observation increment. For the horizontal spreading of the observation increments the following weight function is used:

$$W_q(x) = (1 + x/s)e^{-x/s}, \tag{0.2}$$

where x is the distance between the model grid point and the observation and s is a correlation length. The temporal weight function $W_q(t)$ equals one at the observation time and decreases linearly to zero at 1.5 hours before and 0.5 hours after the observation time, i.e. a 2 hour asymmetric time window is used. The observation density is also taken into account to set the value of W_q.

In the nudging scheme a direct assimilation of an integrated quantity is not possible. Thus, an indirect assimilation procedure based on Kuo et al. (1993) was developed at DWD (figure 0.1). The GPS Zenith Total Delay (ZTD) observation is treated initially similar to a surface observation. Temperature and pressure from the model are interpolated to the height of the GPS station for the extraction of Integrated Water Vapour (IWV) information from ZTD. The model IWV is computed as a height integral of water vapour density:

$$IWV = \frac{1}{\rho_w} \int_{h_0}^{h_{top}} \rho_{wv}(h)dh \tag{0.3}$$

where ρ_{wv} is water vapour density, *h* is height in meters and ρ_w is density of liquid water and IWV is in kg/m^2. The model initial specific humidity profile is then modified by the ratio (K in figure 0.1) of the IWV observation (IWV_gps figure 0.1) to the IWV model (IWV_lm figure 0.1). All model layers above the GPS station height and below 500 hPa (about 5.5 km) are corrected. When a relative humidity value exceeds 100 % the level is set to saturation.

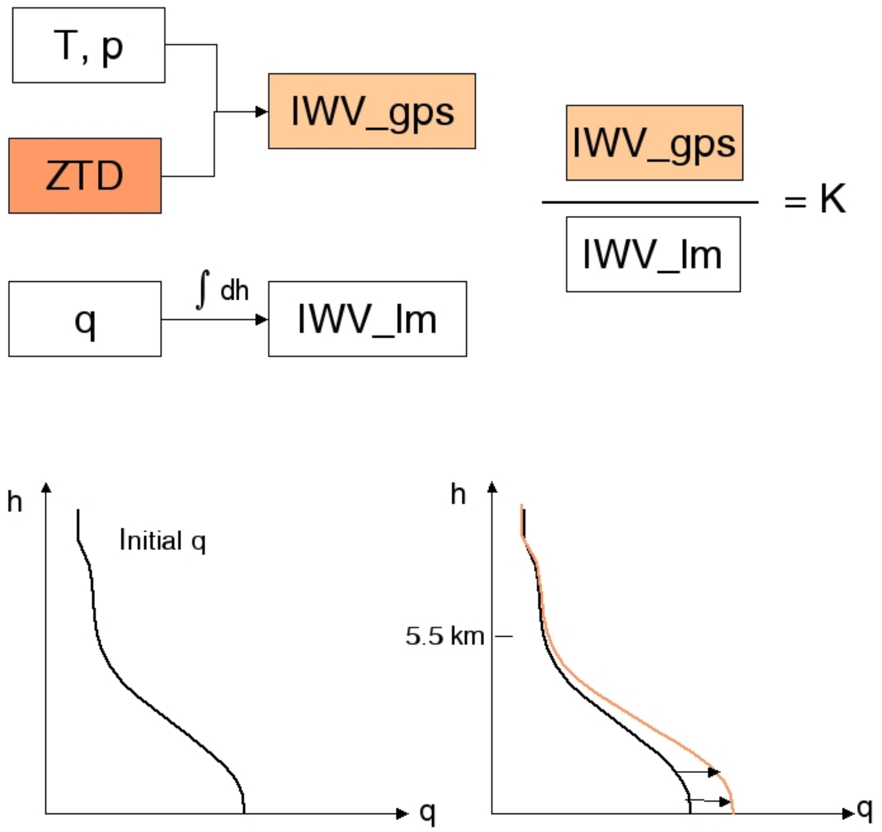


Figure 0.1: Nudging of GPS derived IWV employed in LM (after Kuo et al., 1993).

b. Checking the GPS related subroutines

The data assimilation concept of the LM has a complicated structure involving interactions between different modules. The part of the LM code dedicated to the assimilation of GPS data was developed at DWD in co-operation with the GeoforschungsZentrum (GFZ) within the German project: "GPS Atmospheric Sounding (GASP)". In order to assimilate GPS data, two new subroutines were written and a significant number of modifications in about ten existing model routines were required. A subroutine for reading the data in COST 716 format was a starting point for introducing the GPS observation in the nudging process. The GPS-related subroutines were checked.

c. Modifications introduced in the assimilation code

Changes were introduced in the code in order to check the input data and to produce output for control and statistical purposes. It was also decided to introduce in the code the minimum threshold of 2 kg/m^2 for the assimilation of GPS IWV. Very low IWV amounts were found to give an incorrect GPS humidity profile retrieval in some particular weather situations (e.g. strong humidity gradient on winter nights, well depicted by the model, were excessively smoothed by low GPS IWV values).

2. Set up of impact experiment with GPS real - time data

The data selected for the experiment are from 40 stations of the German network processed in near real time by the GeoforschungsZentrum (GFZ) in Potsdam, Germany. These data are also available since February 2001 within the near real time campaign agreed in COST 716. The day chosen for impact experiment is 3 April 2001. As seen from figure 0.2, during this day a cold front is crossing Germany.

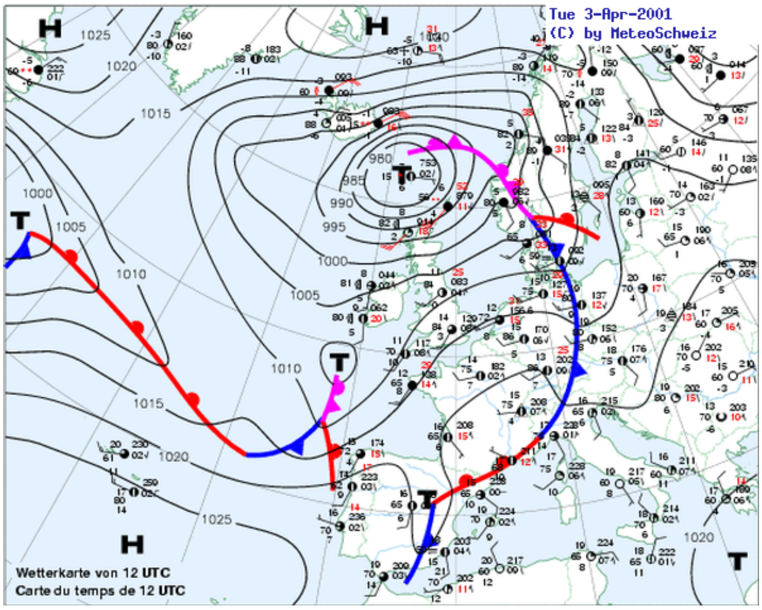


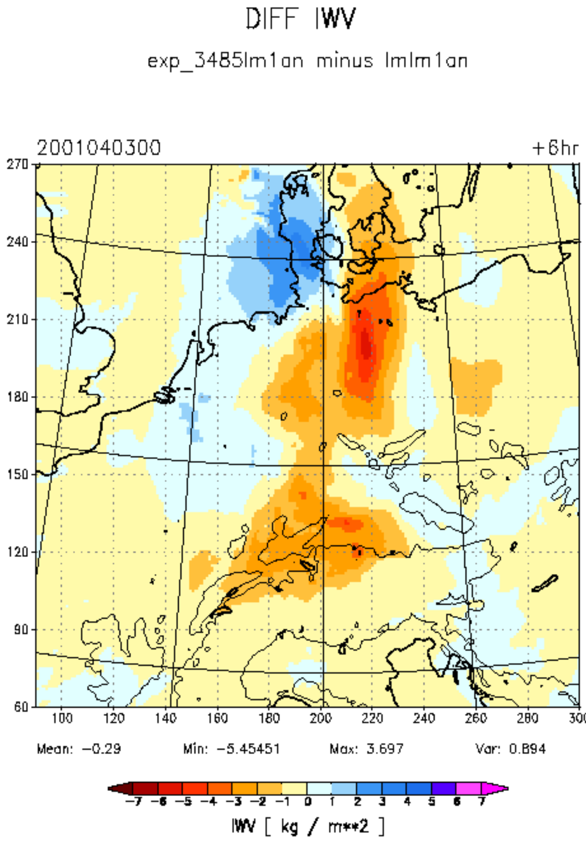
Figure 0.2: Surface synop chart at 12 UTC April 3. Note that a cold weather front is crossing Germany.

3. Results

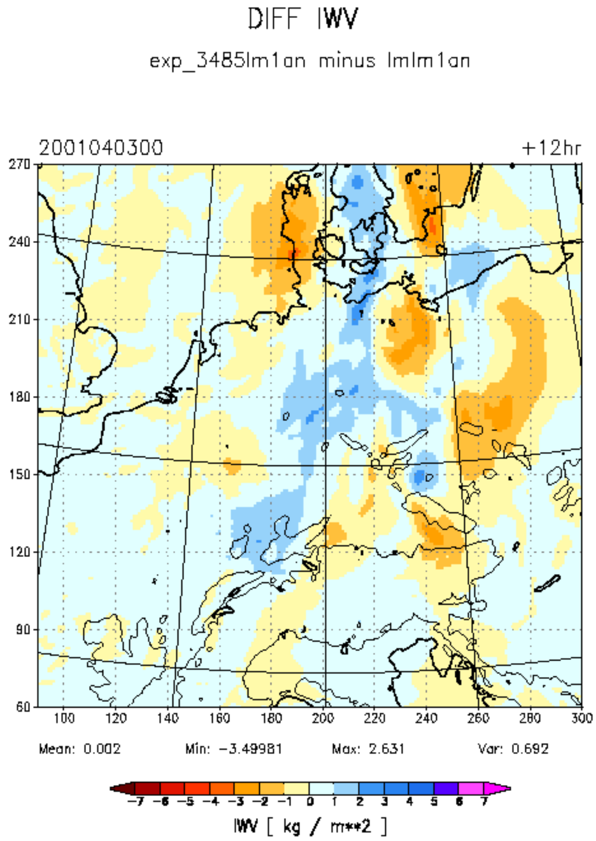
a. Impact experiment on April 3, 2001

A continuous GPS assimilation was run between 00 and 21 UTC on April 3, 2001. The model was fed with hourly GPS observations. On average 32 out of the 40 selected stations were assimilated.

After 6 hours of continuous nudging of the GPS data some relevant phase differences between the experiment with GPS and the operational LM run without GPS (reference analysis) were to be seen, as shown in figure 0.3a. From this IWV difference field (GPS minus reference) at 06 UTC it is clearly seen that the frontal edge is located too far eastwards with respect to the gps run. The corrected location of the frontal line resulted in a substantial decrease in IWV of the order



a.

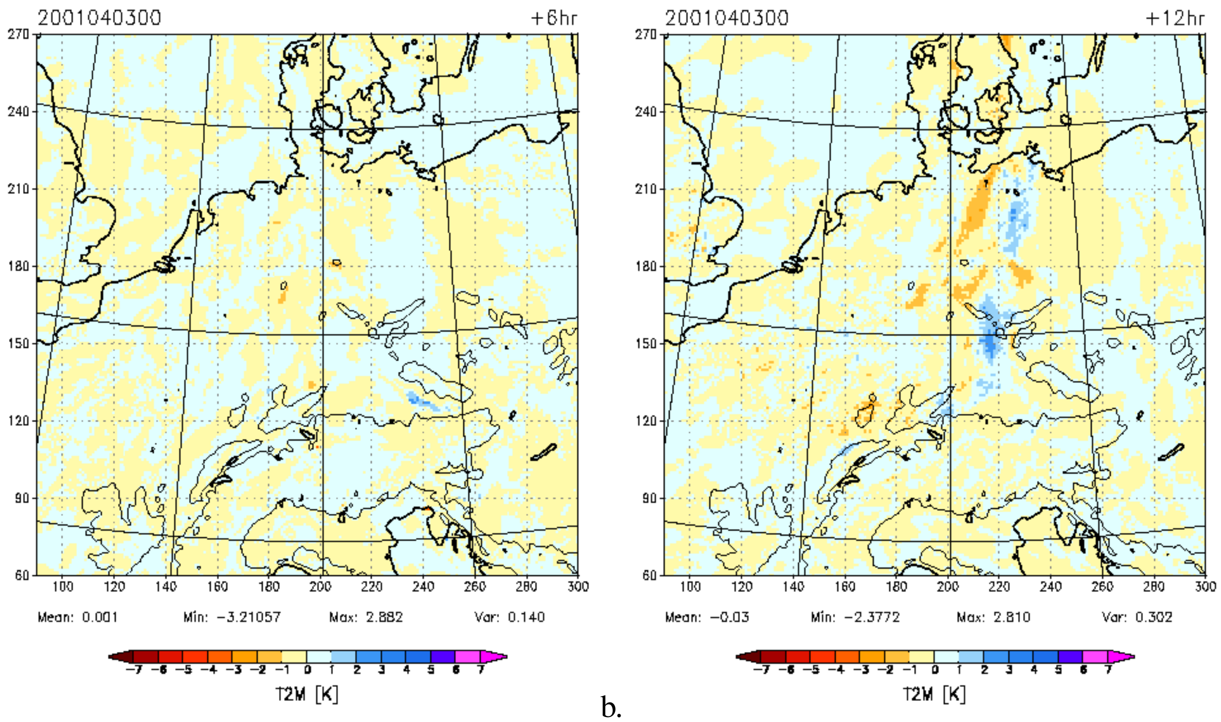


b.

Figure 0.3: IWV difference over Germany on April 3 2001 at a. 06 UTC and b. 12 UTC. Note the frontal zone shift at 06 UTC.

of 3 to 4 kg/m^2 in the GPS experiment. Over Northern Germany this correction reaches the maximum value of 5.5 kg/m^2, i.e. some 20% of the maximum IWV amount. The overall difference for the entire LM domain is -0.29 kg/m^2. On the left side of the frontal line the GPS assimilation resulted in an increase in the IWV value in the range of 1 to 3 kg/m^2. This phase shift demonstrates a tendency in the model to speed up the cyclone passage.

At 12 UTC the mean difference is vary small (figure 0.3b). This can be explained by the availability at this time of radiosonde observations which offer a good spa-



a. b.

Figure 0.4: Temperature difference over Germany on April 3 2001 at a. 06 UTC and b. 12 UTC.

tial coverage over Germany.

The impact of GPS data on the 2m temperature field is presented in the difference plot in figure 0.4. At 6 UTC the 2m temperature difference does not present a typical pattern and is in the range $\pm$ 1 K. A more pronounced difference pattern is seen at 12 UTC (figure 0.4b). Over central and eastern Germany the differences can be as high as 2.8 K and as low as -2.3 K. The reason is possibly the accumulated impact of the GPS data assimilation. Thus it is concluded that the overall impact on the 2m temperature is small.

The precipitation fields from the LM reference and GPS runs have been investigated in addition, and only minor differences can be seen. In comparison with the radar and synop precipitation observations, the LM overestimates the precipitation amount over Germany.

b. Real - time monitoring of LM

The monitoring of the operational LM analysis with the real -time GPS data is done on a daily basis at DWD. One interesting case was found on 24 April 2001 at 00 UTC. In figure 0.5 the LM IWV field is plotted as a background colour map. The circles show the position of the GPS stations and their colour the measured IWV value. A visual inspection of the LM field gives a relatively homogeneous IWV distribution over central and eastern Germany with values in the range of 10 to 15 kg/m^2. On the boundary between Germany and the Netherlands a local IWV maximum of more than 20 kg/m^2 is to be seen (in green and orange colours). The nearby GPS site reports at the same time an IWV of 10 kg/m^2. The reason for this discrepancy was identified to be the assimilation of an incorrect radiosonde observation. The problem arose by assimilation of an incorrect single level temperature observation from a nearby radiosonde station. This incorrect observation (temperature 10 degrees higher than the model) was at a height of 3 km and went through the model quality control, resulting in almost doubling of model water vapour. The spatial radius of influence of this observation can be well seen. This case was identified in the early morning of April 24 and at mid day the corrected 00 UTC analysis has been available. Thus it is to be concluded that the model verification with the real-time GPS derived IWV is valuable for quality control of the standard meteorological observations.

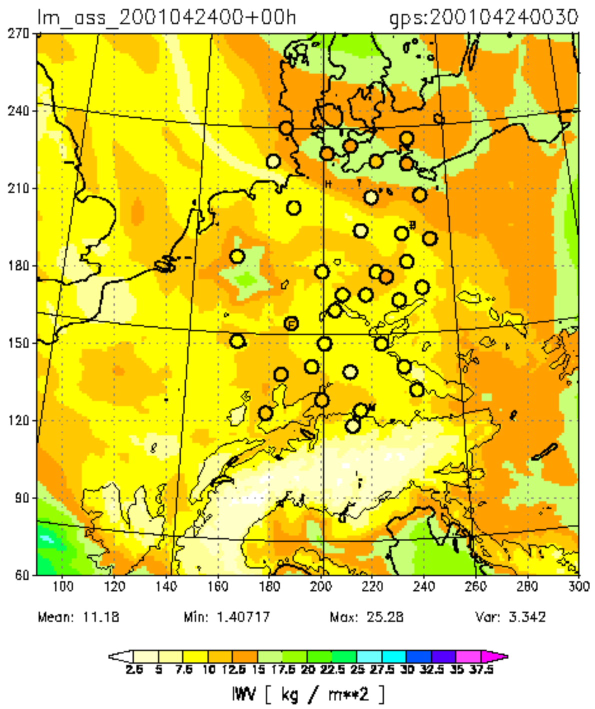


Figure 0.5: LM IWV field (colour map) and the GPS observations (circles). A false IWV maximum at the boundary between Germany and the Netherlands.

4. Conclusions

The work completed during the COST 716 Short Term Scientific Mission at DWD was a starting point for assimilation experiments with the Local Model using the real-time GPS data. From the assimilation experiment conducted it can be concluded that the Local Model is sensitive to the assimilation of GPS derived water vapour and this sensitivity is demonstrated in a correction of up to 20 % in the model IWV field during a cold front passage. The impact on 2m temperature and precipitation is relatively small. The monitoring of the operational LM analysis at 00 UTC on the 24 April resulted in the identification of an incorrect radiosonde observation.

5. Planned future work

The work initiated during the mission was a starting point for the introduction of GPS data and subsequent experiments in Switzerland. It provided an excellent opportunity for exchange of knowledge and experience on modelling and data assimilation. A number of discussions on the efficient GPS assimilation took place with M. Tomassini, Ch. Schraff and W. Wergen. The GPS observations, their quality and possible problems in the nudging process have also been considered. It was also valuable with respect to exchange of information on the Local Model verification done in both Germany and Switzerland.

The work continued with implementation of the GPS routines in MeteoSwiss version of LM. Assimilation experiments using the Swiss GPS network (AGNES) were conducted for two week periods in 2001 and 2002 with the Swiss implementation of the Local Model - aLMo. The verification of the results from the analysis and forecast GPS impact experiments covered: precipitation, 2m temperature, humidity and cloud cover fields. The results obtained from four impact experiments are summarised in Guerova et al. (2002 and 2003).

References

Guerova, G., J.-M. Bettems, E. Brockmann, and Ch. Matzler, 2002. Assimilation of the GPS-derived Integrated Water Vapour (IWV) in the MeteoSwiss Numerical Weather Prediction model - a first experiment. *Phys. Chem. Earth.,* in press.

Guerova G., Bettems J.-M., Brockmann E., and Ch. Matzler, 2003. Assimilation of COST 716 Near Real Time GPS data in the nonhydrostatic limited area model used at MeteoSwiss. *Meteorol. Atmos. Phys.,* submitted August 2003.

Kuo Y., Y. Guo, and E. Westwater, 1993. Assimilation of Precipitable Water Vapour into a Mesoscale Numerical Model, *Mont. Weath. Rev.*, **121,** 1215 - 1238.

Schraff Ch., 1997: Mesoscale data assimilation and prediction of low stratus in the Alpine region. *Meteor. Atmos. Phys.,* **64,** 21-50.

2. Assimilation of the GPS-derived Integrated Water Vapour (IWV) in the MeteoSwiss Numerical Weather Prediction model - a first experiment. G. Guerova, J.-M. Bettems, E. Brockmann, and Ch. Mätzler, *Phys. Chem. Earth.,* 2002 in press.

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Assimilation of the GPS-derived Integrated Water Vapour (IWV) in the MeteoSwiss Numerical Weather Prediction model - a first experiment

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Abstract. A high resolution (7 km) limited area model called aLpine Model (aLMo) is used for operational Numerical Weather Prediction (NWP) at MeteoSwiss. A continuous data assimilation scheme based on the nudging technique produces the initial conditions for the forecast. Since November 2001 all standard meteorological observations have been routinely assimilated. The goal of this study is to evaluate the benefit of introducing GPS-derived Integrated Water Vapour (IWV) in this scheme. In this first observing system experiment, data provided for COST action 716 are used. A two week period in mid September 2001 was selected, characterized by an advective weather regime and intense precipitation events. On average observations from 80 European GPS sites are assimilated by the model. Results presented here are based on the aLMo assimilation cycle only, the impact on the forecast has not been evaluated. This experiment shows a tendency for GPS data to increase the model IWV amounts in the day-time, and shows a substantial impact of GPS in the southern part of the model domain. The negative bias of the model IWV daily cycle is mainly corrected by assimilating GPS data. An improvement of the daily precipitation cycle over Switzerland for the grid points below 800 m is also observed in the GPS run. The bias precipitation score confirms the better model performance when the GPS data are assimilated. This experiment has also revealed a weakness in the way the IWV is assimilated. In presence of highly inhomogeneous humidity fields an isotropic influence of the IWV increments can be detrimental. The first GPS assimilation results are considered encouraging but need to be consolidated. New assimilation experiments will be performed to investigate the GPS data impact for different weather regimes.

1. Introduction

Atmospheric water vapour belongs to the most important weather forming components of the troposphere. However, due to its high temporal and spatial variability it is also one of the least known and hence all instruments providing insight into the variability of water vapour are considered essential in Numerical Weather Prediction (NWP).
In the last years it was expected that the satellite-borne in-

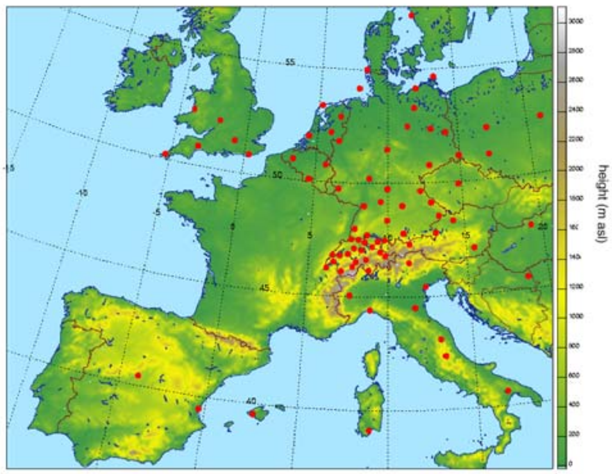

Figure 1. Location of GPS sites(red dots) assimilated over the aLMo domain.

struments like SSM/I (Special Sensor Microwave/Imager) and AMSU (Advanced Microwave Sounding Unit) would deliver water vapour information with the high temporal and spatial resolution needed for the NWP models. The success of satellite based instruments in retrieving information over ocean surfaces, has resulted in routine assimilation of satellite radiances in global NWP models. But it is also true that satellite retrievals of tropospheric water vapour over vegetation covered areas pose problems and remain a research topic. This opens the way for another source of water vapour retrieval, namely the ground-based GPS (Global Positioning System).
In the last decade a number of validation studies have shown the quality of GPS-derived Integrated Water Vapor (IWV) compared with radiosondes (Ohtani and Naito 2000), microwave radiometers (Emardson et al. 1998, Liou et al. 2001) and also VLBI (Very Long Baseline Interferometer) (Niell et al. 2001). Moreover, the validation of NWP models with GPS - IWV have been reported in several publications (Yang et al. 1999, Koepken 2001, Guerova et al. 2002). It is now accepted that GPS has a clear potential for verifying NWP model performance.

Within the European COST Action 716 ”Exploitation of ground based GPS for climate and numerical weather prediction application”, GPS data from northern, western, central and southern Europe have been collected and are available for research studies. A part of COST 716 is the Near Real Time Campaign (http://www.knmi.nl/samenw/cost716/), which started in March 2001 and proved that GPS Zenith Total Delay (ZTD) estimates could be available within a time window of 90 min, as required for operational weather forecasting. At present the assimilation of GPS in NWP systems has been considered by a number of European Meteorological Offices, one of which is the Federal Office of Meteorology and Climatology in Switzerland (MeteoSwiss).
This paper presents the first assimilation experiment with the operational NWP system of MeteoSwiss, the Alpine Model (aLMo). In section 2 a description of the aLMo data assimilation scheme is given. The experimental set up is presented in section 3. The results from the assimilation experiment are discussed in section 4. Summary and conclusions can be found in section 5.

2. Alpine Model: assimilation of the GPS retrieved IWV

ALMo is a nonhydrostatic limited area mesoscale model used for operational NWP at MeteoSwiss since 1st of April 2001. The model domain extends from 35.11°N, -9.33°E to 57.03°N, 23.42°E and is covered by a mesh of 385 by 325 points with a horizontal resolution of about 7 km; it covers most of western Europe (see figure 1). A generalised terrain-following vertical coordinate system has been used, with 45 levels from the surface up to 20 hPa (Doms et al. 1999, 2001). ALMo is the Swiss configuration of the COSMO (COnsortium for Small-Scale MOdelling) model developed by the National Weather Services of Switzerland, Italy and Greece under the lead of the German Weather Service (DWD).
At MeteoSwiss two 48-hour forecasts are performed daily (at 00 and 12 UTC) with initial conditions obtained from a continuous data assimilation cycle. This assimilation cycle is based on a Newtonian relaxation technique, the nudging of model fields towards direct observations (Schraff, 1997). This scheme has been tested in the period April - November 2001 and has been integrated into the operational environment.
The ZTD derived from GPS measurements is assimilated in aLMo in four steps. First, ZTD is converted into Integrated Water Vapour following Bevis et al. (1992) using the model temperature and surface pressure. Second, GPS IWV is compared with aLMo IWV and an IWV ratio (GPS versus aLMo) is calculated. Third, using this ratio the model specific humidity profile is shifted from the surface up to 500 hPa (Kuo et al. 1993). Fourth, the model specific humidity increments are spread laterally using an autoregressive horizontal weight function with a typical scale of 70 km.

3. Experimental set up

The GPS data provided by the Near Real Time Campaign have been used for this first observing system experiment. Data were processed by five Processing Centers, namely: GFZ (Potsdam, Germany, http://www.gfz-potsdam.de/), GOP (Pency, Czech Republic), IEEC (Barcelona, Spain, http://www.ieec.fcr.es/), ASI (Matera, Italy, http://www.asi.it/) and LPT (Wabern, Switzerland, http://www.swisstopo.ch/). The data provided by LPT are from post-processed solutions. The post-processed GPS solutions are obtained using precise satellite orbits while the near-real time data are calculated with predicted orbits. The time resolution of the data varies from 15 to 60 min. As seen from figure 1 the data density is very good over Germany and Switzerland; observations are also available in Italy, UK and Spain but no data are available in France. This is a real drawback of the data set used, because French data could bring up-wind information, which is essential for the forecast in Switzerland.

As discussed in section 2, MeteoSwiss calculates two daily aLMo forecasts and a continuous data assimilation cycle (analysis) where the model is continuously forced towards actual observations in order to produce the best possible state of the atmosphere. The experiment described in this paper only considers the assimilation mode. Follow-up experiments will also consider the forecast mode.

The assimilation period from 9 to 23 September 2001 was selected. It was characterized by intense atmospheric circulation, front passages and cyclogenesis in the Gulf of Genoa. All standard meteorological observations are assimilated (synop, buoys, temp, aircraft wind and temperature), but no satellite data are used. A reference analysis is calculated with this observation set and a GPS analysis is obtained by adding GPS derived IWV information to this set.

In this experiment aLMo is nested in the ECMWF global model. The boundary conditions for the aLMo assimilation cycle are obtained from the ECMWF 4D - var assimilation cycle. The same boundary conditions are used for both GPS and reference runs.

4. Results of the assimilation experiment

4.1. *Case study: September 9th 2001*

Figure 2 shows the IWV differences for the 9th September 2001 at 6, 12 and 18 UTC. From the 6 UTC plot (figure 2a) it can be seen that IWV in northern Italy and in the Gulf of Genoa has been decreased by assimilating GPS (blue color). However, six hours later, at 12 UTC, a strong increase is seen over the sea with a maximum value of + 23 mm. This "wet patch" further intensifies and reaches a maximum of + 33 mm in the 18 UTC plot; its shape displays a south-eastern elongation.

The 850 hPa wind field (figure 3) shows a cyclone in the Baltic sea region (the upper right corner in figure 3) and a

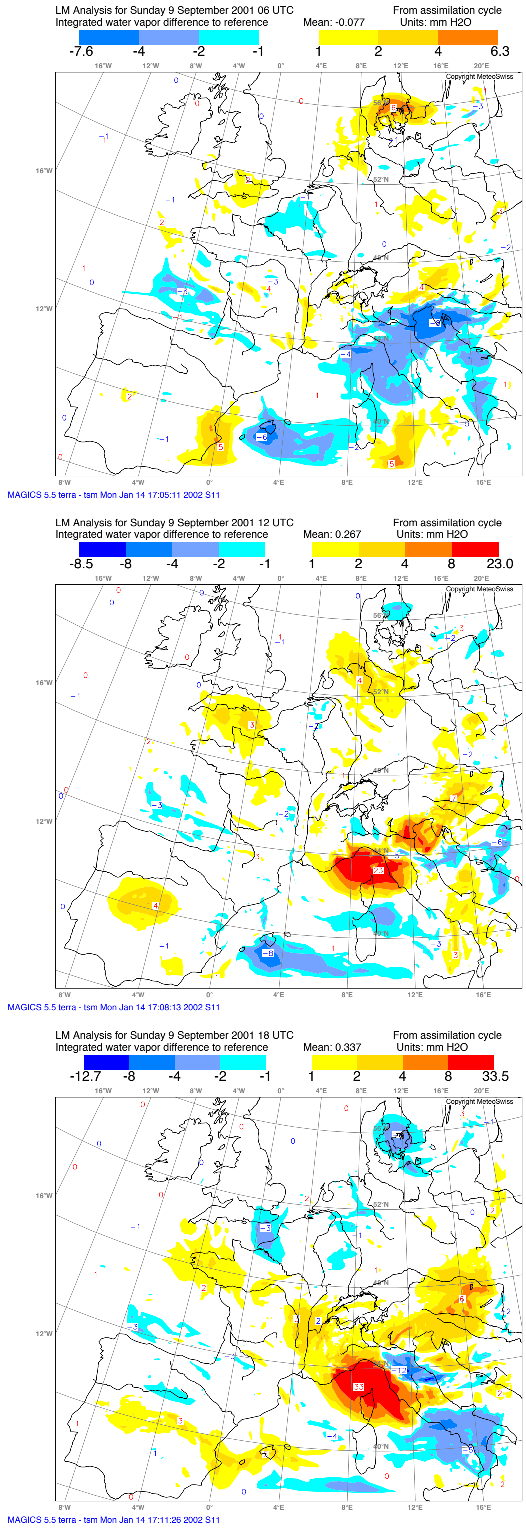

Figure 2. Analyzed IWV differences (GPS minus reference run) on 9th September 2001 a) at 6 UTC b)at 12 UTC c) at 18 UTC.

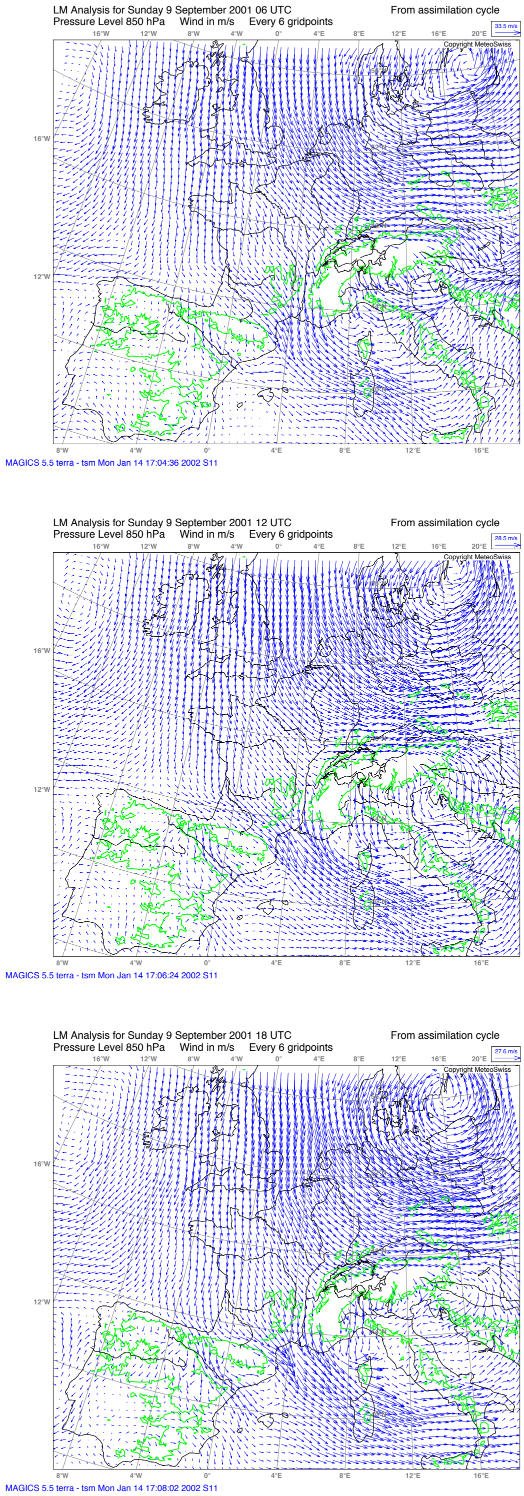

Figure 3. Analyzed wind speed and direction at 850 hPa on 9th September 2001 in GPS experiment a) at 6 UTC b) at 12 UTC c) at 18 UTC.

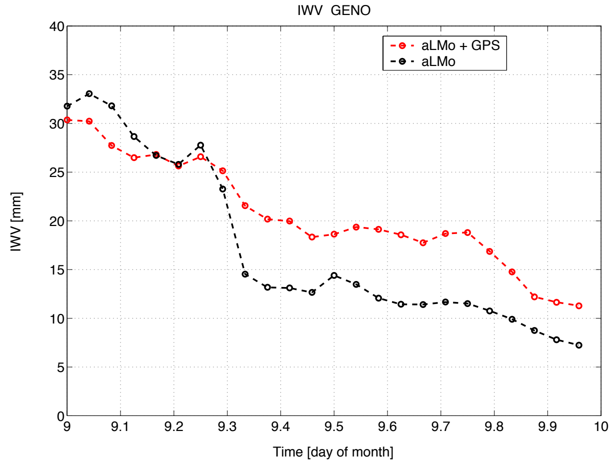

Figure 4. IWV at the GPS site Genoa (GENO) on September 9th 2001. Black dashed line for the reference run versus red dashed line for the GPS experiment.

strong wind channeling between the Pyrenees and the Alps. In the region of Genoa the wind is light with an intensification about mid-day (figure 3b). This is the reason for the further advection of the IWV patch in southeast direction reported at 18 UTC. On the other hand, the predominantly light wind observed throughout the day explains why the generated wet patch remains in the Gulf for a significant amount of time. Only at about 0 UTC on September 10th will the patch vanish.

Note, that the closest GPS site assimilated in the model is Genoa (GENO). The IWV at the grid point Genoa for the GPS experiment (red dashed line) and the reference run (black dashed line) are plotted in figure 4. The trend shows a gradual decline of IWV for the GPS experiment, starting from a value of 30 mm at 0 UTC and ending to a value slightly higher than 10 mm at 23 UTC. In contrast, the IWV from the reference run registers a sharp drop from 23 to 15 mm between 7 and 8 UTC. The IWV differences at Genoa are in the range from +4 to +7.5 mm between 8 and 19 UTC. These values are much more realistic than the ones obtained over the sea in the Gulf.

The weather situation during this day has been examined in order to identify the possible reason for the substantial discrepancy between the two model runs over the Gulf of Genoa. As already mentioned, a cyclone centered in the Baltic Sea was moving eastward. A cold front associated with this cyclone induced a shallow cyclogenesis in the Gulf of Genoa. This can be proven from the standard 0 UTC surface pressure maps for the 9th and 10th of September. The shallow cyclogenesis in the region of Genoa is a known typical phenomenon for this time of the year, namely late sum-

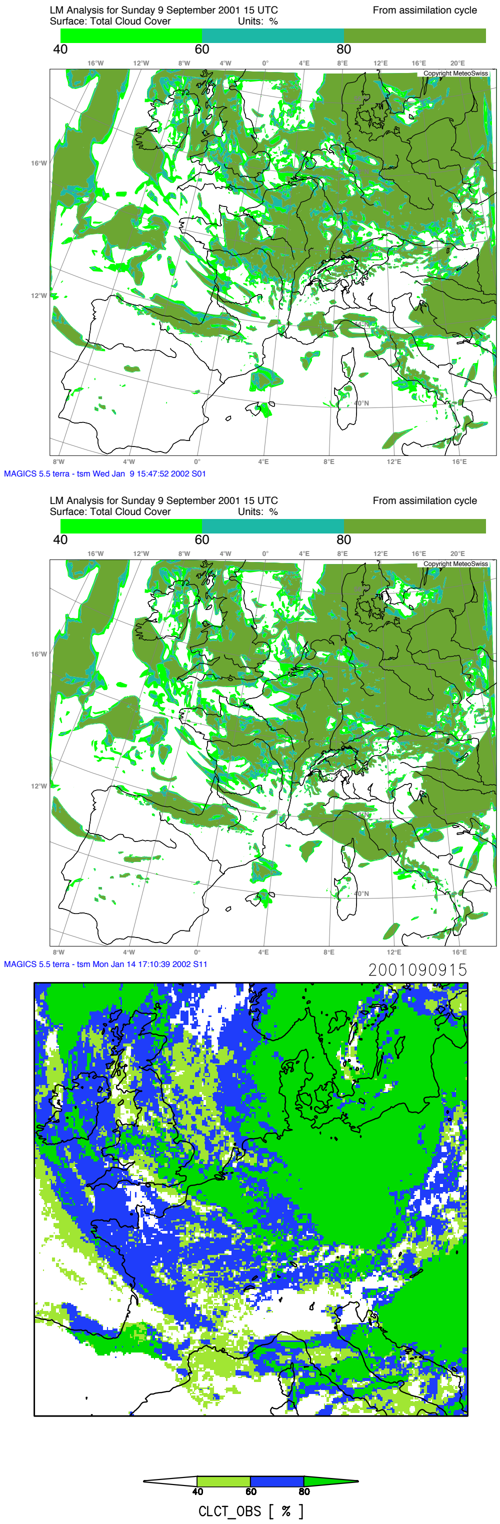

Figure 5. Analyzes and observed total cloud cover at 15 UTC on 9th September 2001 from: a) the reference run b) the GPS run c) the satellite observations.

mer, when external air reaches the Mediterranean through the gaps between mountains i.e. Rhone valley. This produces large temperature and water vapour gradients due to cold air advection (west of Genoa) and subsequent blocking by the Alps of the warm and humid air in northern Italy. This inhomogeneity of the IWV field was not taken into account when the GPS increments were spread over a significantly large area by the nudging scheme. As a consequence the assimilation of the correct IWV information at the observation grid point Genoa (as discussed above) results in artificial "pumping" of water vapour in a large neighborhood.
Despite, these exaggerated IWV differences in the Gulf of Genoa, the visual verification of the total cloud cover with satellite observations (figure 5c) shows that a more realistic picture has been obtained in the GPS experiment (figure 5). The observed cloud cover pattern over the sea is better represented in the GPS run (figure 5b). This is consistent with the work of Crewell (2002) which shows that the German version of aLMo systematically underestimates the cloud liquid water content compared with observations from a water vapour radiometer. So in this case, GPS assimilation has a positive impact on the total cloud cover field of aLMo.
This case study is important in several aspects. First, it can be concluded that the radius of influence of GPS observations has to be decreased in order to obtain a better representaty of the spatial variation of the humidity field. Second, it is an indication that the spread of observation increments over the sea has to be treated with caution. One could mention here that additional GPS information such as gradients and slant paths could be used to tune the model horizontal structure function and improve the spreading of GPS increments. Third, as the weather circulation in the Mediterranean sea is known to be very special, it could be beneficial to have more GPS sites in the coastal areas. More generally, coastal GPS sites are of special importance due to the substantial difference between evaporation regimes of coastal and inland areas.

4.2. *Verification for Switzerland*

Verification over Switzerland has been done with the operational tools of MeteoSwiss. Figure 6 presents the daily cycle of the IWV for the period 9 to 23 September for 9 GPS sites below 800 m collocated with the model grid points. The grid points selected have an average height difference of +10 m to the GPS antenna height. As expected, the results from the GPS run (red dashed line) compare well with the observations (black solid line) and a similar tendency of the IWV variation can be seen. In contrast, the reference run (black dashed line) is predominantly underestimating the IWV amounts. A negative bias of 0.61 mm (reference run versus observations) is measured. This bias is consis-

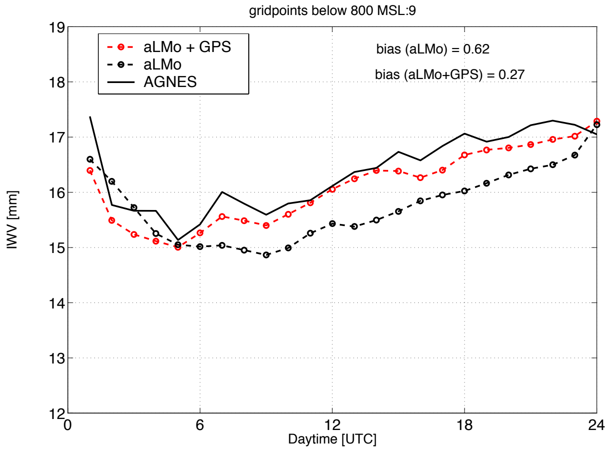

Figure 6. Daily IWV cycle for 9 grid points below 800 m msl. collocated with the GPS sites in Switzerland: GPS observations (black solid line), reference run (black dashed line) and GPS experiment run (red dashed line).

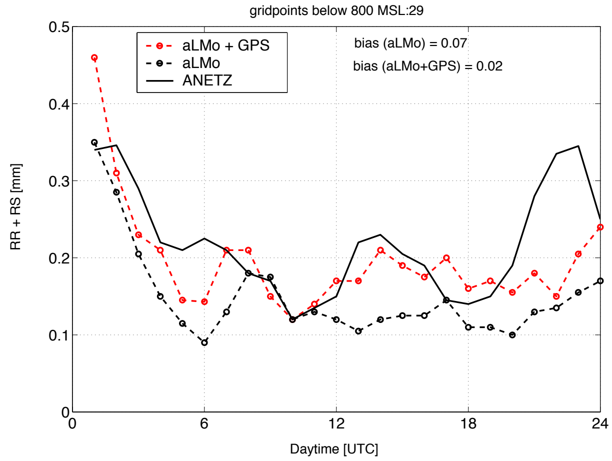

Figure 7. Daily precipitation cycle for 29 grid points below 800 m msl. collocated with ANETZ stations: ANETZ observations (black solid line), reference run (black dashed line) and GPS experiment run (red dashed line).

tent with the IWV bias observed in the operational model verification over Switzerland for the period of May to October 2001. A similar systematic negative IWV bias is also reported from the model verification at DWD (Tomassini, 2002). As can be seen in Figure 6 this bias is significantly reduced by GPS data.

Figure 7 shows the daily precipitation cycle for 29 grid points collocated with observing stations of the Swiss automatic surface stations network (ANETZ) below 800 m. It can be seen that the reference run tends to underestimate the overall precipitation amount reported, while the GPS run (red dashed line) improves the precipitation picture, especially in the afternoon hours between 12 and 17 UTC. This improvement of the precipitation is very likely connected to the already discussed improvements of the IWV daily cycle.

The bias score for the 6 hour accumulated precipitation verified against ANETZ stations below 800 m is displayed in table 1. Three precipitation thresholds have been defined, namely 0.1, 2 and 10 mm. A bias score below 100 is to be interpreted as underestimation and above 100 as overestimation of the frequency of precipitation amount larger than the corresponding threshold. A perfect analysis will produce a bias score of 100. The bottom line in table 1 gives the average score for all 6 hour periods between 6 and 24 hour. The first score for a 0.1 mm threshold shows that GPS assimilation results in overestimation of the low precipitation events, while the reference run shows a slightly better score but with a tendency for underestimation of low precipitation cases. For the 2 mm threshold, the GPS run performs much better than the reference run. For the 10 mm threshold, i.e. heavy rain, the scores from both the GPS experiment and the reference are relatively poor; however, due to the limited number of heavy rain events, this score is statistically not very significant (easily biased if a single precipitation event is missed).

5. Conclusions

Assimilation of water vapour in numerical weather prediction models has been a prime objective of the last decade. As the radiosondes network is not dense enough to provide sufficient information about the atmospheric humidity, this information has been retrieved from SSM/I and AMSU satellites over the ocean. However, the land surfaces of the Earth remain a challenge for satellites due to their strong and inhomogeneous microwave signal. That is why the ground based GPS-derived IWV has attracted interest and support in Europe through the COST Action 716.

The GPS-derived IWV from about 80 sites in Europe, provided within the Near Real Time Campaign of COST 716, has been used for this first observing system experiment with the operational NWP model of MeteoSwiss. A two week period in September 2001, characterized by advective weather regime and intense precipitation events, has been chosen.

The results from this experiment show a significant modification of the IWV field in the southern part of the model domain up to 30% relative change. By visual inspection of the overall daily impact one observes a tendency of GPS to increase the IWV in the day-time.

The verification of aLMo over Switzerland reveals a clear positive impact of GPS on the IWV daily cycle and on the

Table 1. Bias precipitation score for the grid points below 800 m collocated with ANETZ for period 8 to 23 September 2001.

BIAS	GPS Assimilated			GPS NOT Assimilated		
threshold [mm/6h] at:	0.1	2.0	10.0	0.1	2.0	10.0
0h .. 6h	84.8	89.3	240.0	102.9	69.9	110.1
6h .. 12h	101.4	106.2	100.0	84.8	92.3	33.3
12h .. 18h	140.8	113.3	66.7	111.2	76.0	50.0
18h .. 24h	105.4	66.7	27.3	89.2	58.3	9.1
6h-intervals 6h .. 24h	113.4	92.4	47.1	93.5	73.3	20.6

precipitation. The negative IWV bias produced in the reference run is mainly corrected by the GPS assimilation. The daily cycle of precipitation has been improved in the hours between 12 and 17 UTC, which is probably due to the correction of the negative bias in the IWV. In addition the bias precipitation scores give promising results for the GPS run.
A detailed investigation of IWV differences on September 9th 2001 shows a substantial increase in the Gulf of Genoa when the GPS data are assimilated. This has a positive effect on cloud cover, but the amount of introduced water is exaggerated. This could be traced back to inadequate spreading of humidity increments: this case was characterized by strong inhomogeneities in the IWV field, produced by the advection of cold air west of Genoa and the blocking of warm and humid air in northern Italy, inhomogeneities which were not taken into account by the large symmetric influence of IWV increments. In this case information from GPS-derived IWV gradients as well as slant path estimates will be beneficial in correctly shaping the model structure function.
The verification of IWV and precipitation reported in this paper gives encouraging first results. The future GPS assimilation work will include investigation for different weather regimes. As the GPS assimilation tends to put more water in the atmosphere it is necessary to investigate whether this is beneficial for different weather regimes such as low stratus cases or summer high. In addition the spread of the observation increments will be decreased in order to avoid extreme cases in case of highly inhomogeneous humidity fields. Based on the results of these new experiments, usage of GPS in the operational NWP environment of MeteoSwiss will be considered.

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References

Bevis, M., Businger,S., Herring,T.A., Rocken, C., Anthes, R.A., Ware, R.H., 1992. GPS Meteorology: Remote sensing of atmospheric water vapor using the Global Positioning System. J. Geophys. Res. 97, 15787-15801.

Crewell, S., 2002. Bodengebundene Fernerkundung der bewoelkten Atmosphaere und deren Nutzung zur Evaluierung dynamischer Atmosphaerenmodelle. Kumulative Habilitationsschrift. pp.49 [Available from Meteorological Institute, Auf dem Huegel 20, D-53121 Bonn, Germany.]

Doms, G., Schaettler, U., 1999. The nonhydrostatic limited-area model LM (Local-Modell) of DWD, Part I: Scientific Documentation. Deutscher Wetterdienst LM F90 1.35. pp.172 [Available from Deutscher Wetterdienst, P.O.Box 100465, 63004 Offenbach, Germany.]

Doms, G., Schaettler, U., 2001. Consortium for Small-Scale Modelling (COSMO). Newsletter Consortium for small-scale modeling, 1, G. Doms and U. Schaettler, Eds., pp.114 [Available from Deutscher Wetterdienst, P.O.Box 100465, 63004 Offenbach, Germany.]

Emardson, T. R., Elgered, G., Johanson, J., 1998. Three months of continuous monitoring of atmospheric water vapor with a network of Global Positioning System receivers. J. Geophys. Res. 103, 1807-1820.

Guerova, G., Brockmann, E., Quiby, J., Schubiger, F., Matzler, Ch., 2002. Validation of NWP mesoscale models with Swiss GPS Network AGNES. J. Appl. Meteorol. in press.

Koepken, Ch., 2001. Validation of Integrated Water Vapor from numerical models using ground-based GPS, SSM/I, and water vapour radiometers measurements. J. Appl. Meteorol. 40, 1105-1117.

Kuo, Y. -H., Guo, Y.-R., Westwater, E.R., 1993. Assimilation of precipitable water measurements into a mesoscale numerical model. Mon.Wea. Rev. 121, 1215 - 1238.
Liou, Y.-A., Teng, Y.-T., Van Hove, T., Liljegren, J., 2001. Comparison of precipitable water observations in the near tropics by GPS, microwave radiometer, and radiosondes. J. Appl. Meteorol. 4, 5-15.
Niell, A. E., Coster, A.J., Solheim, F.S., Mendes, V.B., Toor, P.C., Langley, R.B., Upham, C.A., 2001. Comparison of measurements of atmospheric wet delay by radiosonde, water vapour radiometer, GPS, and VLBI. J. Atmos. Oceanic Technol. 18, 830-850.
Ohtani, R., Naito, I., 2000. Comparisons of GPS-derived precipitable water vapors with radiosonde observations in Japan. J. Geophys. Res. 105, 26 917-26 929.
Schraff, Ch., 1997. Mesoscale data assimilation and prediction of low stratus in the Alpine region. Meteor. Atmos. Phys. 64, 21-50.
M. Tomassini, Gendt G., Dick G., Ramatschi M., Schraff Ch., 2002. Monitoring of integrated water vapour from ground-based GPS observations and their assimilation in a limited area model. Phyis. Chem. Earth 27, 341-346.
Yang, X., B.H. Sass, G. Elgered, J.M. Johansson, and T.R. Emardson 1999. A comparison of precipitable water vapour estimates by an NWP simulation and GPS observations. J. Appl. Meteorol. 38, 941-956.

3. Assimilation of COST 716 Near Real Time GPS data in the nonhydrostatic limited area model used at MeteoSwiss. G. Guerova, J.-M. Bettems, E. Brockmann, and Ch. Mätzler, *Meteorol. Atmos. Phys.*, submitted Aug. 2003.

Submitted to: *Meteorology and Atmospheric Physics*, August 2003.

Assimilation of COST 716 Near Real Time GPS data in the nonhydrostatic limited area model used at MeteoSwiss

G. Guerova, J.-M. Bettems, E. Brockmann and Ch. Mätzler

Abstract. Application of the GPS derived water vapour into Numerical Weather Prediction (NWP) models is one of the focuses of the COST Action 716. For this purpose the GPS data covering Europe have been collected within the Near - Real Time (NRT) demonstration project and provided for Observing System Experiments (OSE). For the experiments presented in this manuscript the operational NWP system of MeteoSwiss is used. The limited area nonhydrostatic aLpine Model (aLMo) of MeteoSwiss covers most of western Europe, has a horizontal resolution of 7 km, 45 layers in the vertical, and use a data assimilation scheme based on the Newtonian relaxation (nudging) method. In total 17 days analyses and two 30 hours daily forecasts have been computed, with 100 GPS sites assimilated for three selected periods in autumn 2001, winter and summer 2002. The NRT data quality has been compared with the Post - Processed data. Agreement within 3 mm level Zenith Total Delay bias and 8 mm standard deviation was found, corresponding to an Integrated Water Vapour (IWV) bias below 0.5 kg/m^2. Most of the NRT data over aLMo domain are available within prescribed 1 h 45 time window. In the nudging process the NRT data are successfully used by the model to correct the IWV deficiencies present in the reference analysis; stronger forcing with a shorter time scale could be however recommended. Comparing the GPS derived IWV with radiosonde observations, a dry radiosonde bias has been found over northern Italy. The GPS IWV impact on aLMo is large in June 2002, moderate in September 2001 and minor in January 2002 Observing System Experiment (OSE). January OSE is inconclusive due to inconsistent use of the humidity correction scheme. In June OSE a substantial IWV impact is seen up to the end of the forecast. Over Switzerland the dry bias in the reference analysis has been successfully corrected and the 2m temperature and dew point have been slightly improved over the whole aLMo domain. The subjective verification of precipitation against radar data in autumn 2001 and summer 2002 gives mixed results. In the forecast the impact is limited to the first six hours and to strong precipitation events. A missing precipitation pattern has been recovered via GPS assimilation in June 20 2002 forecast. A negative impact on precipitation analysis on June 23 has been observed. The future operational use of GPS will depend on data availability; european GPS networks belong mainly to the geodetic community. A further increase of GPS network density in southern Europe is welcome. The GPS derived gradient and Slant Path estimates could possibly improve efficiency of IWV assimilation via the nudging technique.

1. Introduction

The last decade brought in operational Numerical Weather Prediction (NWP) a new generation of nonhydrostatic meso - γ scale models. They run with a horizontal resolution below 10 km (mesh size) and are aimed to better resolve storm - scale phenomena, complex topography and to provide reliable short range forecast up to 2 or 3 days.

For the needs of high resolution NWP models a further extension of the existing Meteorological Observing System will be necessary. In particular, Bettems (2002) reported that additional information about local structures in the humidity field will be needed. Some promising candidates are the weather radar and lidar networks. In the last decade it was expected that satellite - borne instruments like Special Sensor Microwave/Imager (SSM/I) and Advanced Microwave Sounding Unit (AMSU) would deliver water vapour information with the high temporal and spatial resolution needed for the NWP models. However, the satellite retrievals are often limited to the ocean regions and the footprint of about 50 km is too coarse for high - resolution mesoscale models; due to the frequency employed the satellite instruments are also disturbed by rain. MODIS, the Moderate Resolution Imaging Spectroradiometer, has a spatial resolution of 1 km but a poor temporal resolution, i.e. daily averaged water vapour products. Another source of water vapour information are the ground - based networks of Global Positioning System (GPS) receivers, currently operated for geophysical purposes. With improvements of the GPS accuracy, i.e. improved mapping functions and antenna phase centre models (Haase et al., 2002), it is possible to obtain reliable information of the atmospheric signal delay in the zenith direction (ZTD). In 1992 Mike Bevis (Bevis et al., 1992) proposed to use the ground-based GPS for retrieving the water vapour content of the atmosphere. In the following years several publications investigated the accuracy of GPS in comparison with the conventional sources of water vapour information like ,radiosondes and water vapour radiometers, and in comparison with unconventional ones like sunphotometer, sunspectrometer and VLBI (Very Long Baseline Interferometer). The findings, as summarised in Haase et al. (2002), confirm the accuracy of GPS derived Integrated Water Vapour (IWV) in the range of 1 kg/m^2, i.e. the same level of accuracy as the conventional observations.
The validation of mesoscale NWP models using GPS is presented in Cucurull et al. (2000), Kopken (2001), Haase et al. (2002), Tomassini et al. (2002) and Guerova et al. (2003). Tomassini et al. (2002) studied the diurnal IWV cycle from GPS and LM over Germany in summer 2000. They found a systematic IWV underestimation, higher than 1 kg/m^2, in the model analysis for the hours between 06 and 18 UTC. The HIRLAM model has been validated for the western Mediterranean area (Haase et al., 2002). An IWV bias of 0.5 kg/m^2 and standard deviation of 3 kg/m^2 is reported as well as a latitude dependence of the standard deviation. The validation studies agree that a dense GPS network provides a valuable additional information for NWP models.
Assimilation experiments with GPS IWV are reported in several publications: Kuo et al. (1996), Guo et al. (2000), Smith et al. (2000), De Pondeca and Zou (2001), Vedel et al. (2002), Falvey and Beavan (2002), Tomassini et al. (2002), Gutman et al. (2003) and Nakamura et al. (2003). The GPS impact is mainly evaluated by analysing the model precipitation skills. The results point towards an overall neutral impact when assimilating GPS. However, during active weather phases the GPS is reported to have a positive influence on the location of the front boundaries, and a continuous improvement of precipitation forecast skills has been obtained in a five year assimilation period in the USA (Gutman et al., 2003). Falvey and Beavan (2002) and Tomassini et al. (2002) use a nudging scheme, which makes their results of particular interest for the study presented here. Falvey and Beavan (2002) report that continuous GPS assimilation improved the upwind total rainfall to 1 % significance level only. They also discuss one case where the humidity profile adjustment deteriorated the precipitation structure; the reason was the proportional moisture removal from all model levels based on the GPS observation. In Tomassini et al. (2002) a mixed impact on precipitation analysis is reported for a severe weather case.
In Europe the work on possible application of ground - based GPS in operational meteorology was started with the MAGIC project. An extensive overview about MAGIC is given in Haase et al. (2002). In 1999 the COST Action 716 "Exploitation of ground based GPS for climate and numerical weather prediction application" followed (Elgered, 2001). The Swiss contribution to COST 716 was established as a collaboration between three Institutes namely, the Swiss Federal Office of Topography (Swisstopo), the Federal Office of Meteorology and Climatology (MeteoSwiss) and the Institute of Applied Physics at the University of Bern (Brockmann et al. 2002). The first goal in evaluating the potential of GPS for meteorological purposes, was the verification of the operational NWP models against GPS data from the Automated GPS Network of Switzerland (AGNES), reported in Guerova et al. (2003a). The second goal, evaluating the impact of GPS data in the NWP system of MeteoSwiss, was initiated in 2001. A first GPS assimilation experiment was calculated for two weeks of September 2001. The precipitation verification over Switzerland shows improvements of the scores as well as an improved diurnal precipitation cycle. In addition we found out that the typical horizontal scale for spreading of the observation increments was too large, particularly in presence of strong water vapour gradients; to avoid this problem the corresponding model parameter was modified. The results obtained in this first experiment (Guerova et al., 2003b) have been considered encouraging, and three new Observing System Experiments (OSE) have been calculated in 2002.
This manuscript reports the results of those three OSEs. In section 2 the mesoscale model of MeteoSwiss is described. The COST 716 Near - Real Time (NRT) demon-

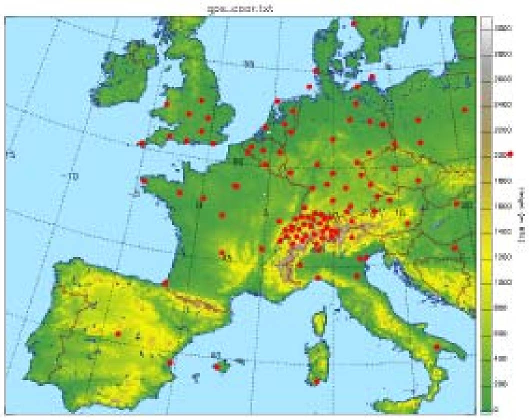


Figure 1. ALMo domain and the location of the European GPS sites (red dots) used in our experiments. The colour scale presents the orography and the thin red line the country boundaries.

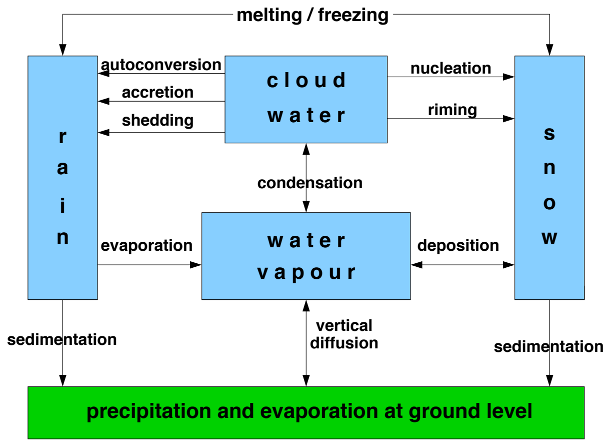


Figure 2. Hydrological cycle and microphysical processes implemented in aLMo. Four types of hygrometeors are considered namely: water vapour, cloud water, rain and snow. Note that no ice phase was implemented.

stration project is outlined in section 3. Section 4 reports the OSE set - up. The results are discussed in section 5 and summarised in section 6.

2. The operational NWP system at MeteoSwiss

2.1. *The aLpine Model - on overview*

Since April 2001 a nonhydrostatic mesoscale model named aLpine Model (aLMo) is used for operational NWP at MeteoSwiss. ALMo is the Swiss configuration of the COSMO (COnsortium for Small-Scale MOdelling) limited area model (Doms et al. 2001) developed by the National Weather Services of Switzerland, Italy, Poland and Greece under the lead of the National Weather Service of Germany (DWD). The Swiss implementation of the model has a horizontal resolution of about 7 km, and the domain extends from 35.11 N -9.33 E to 57.03 N 23.42 E (figure 1), covering most of western Europe. A terrain following vertical coordinate system is used, with 45 vertical layers and about 100 m vertical resolution in the lowest 2 km of the atmosphere (Bettems, 2002), and a top level at 20 hPa. A filtered orography was introduced to produce more realistic precipitation fields. Lateral boundary conditions are assimilated following Davies (1976). The aLMo prognostic variables are: horizontal and vertical Cartesian wind components, temperature, perturbation pressure, specific humidity and cloud water content.

The aLMo parameterization schemes take into account a variety of physical processes like: grid-scale clouds and precipitation, subgrid-scale clouds, moist convection, radiation, vertical diffusion, boundary layer and soil processes. The subgrid-scale cloudiness is a combination of cloudiness due to convective processes and cloudiness described as an empirical function depending on relative humidity and height. The grid scale clouds are described via cloud water saturation adjustment. For precipitation formation a Kessler type bulk parameterization scheme is used, and four categories of water substances are considered, namely: water vapour, cloud water, rain and snow. The aLMo hydrological cycle and microphysical processes are presented in figure 2. As seen from figure 2 the cloud ice phase is neglected, assuming a fast transformation from cloud water to snow. A cloud ice scheme has been developed (Doms, 2002) but was not yet tested at the time of the experiments.

2.2. *The data assimilation scheme*

The aLMo data assimilation is based on Newtonian relaxation (or nudging) scheme (Schraff, 1997); the model's prognostic variables are relaxed towards prescribed value within a fixed time window. In aLMo the relaxation is performed towards direct observations. For example, the prognostic equation for the specific humidity - q and for a single observation has the following form:

$$\frac{\partial}{\partial t}q(t) = Q(q, u, v, ...t) + G_q.W_q.[q_{obs} - q_{mod}], \quad (1)$$

where Q denotes the model physics and dynamics, q_{obs} and q_{mod} are the observed and the model specific humidity, $G_q = 6.10^{-4}s^{-1}$ is the coefficient defining the relaxation scale and W_q consists of spatial and temporal weights and of a quality factor. The second term in equation (1) is the nudging term and the part $[q_{obs} - q_{mod}]$ is called the observation increment. For the horizontal spreading of the observation increments an autoregressive weight function is used:

$$W_q(x) = (1 + x/s)e^{-x/s}, \qquad (2)$$

where x is the distance between the model grid point and the observation and s is a correlation scale factor. The temporal weight function $W_q(t)$ equals one at the observation time and decreases linearly to zero at 1.5 hours before and 0.5 hours after the observation time, i.e. a 2 hour asymmetric saw tooth shaped time window is used. The observation density is also taken into account to set the value of W_q. The observation increments are computed once every 6 time steps i.e. once every 240s.

In the nudging scheme a direct assimilation of GPS derived IWV is not possible as no prognostic variable of this type is available in the model equations. Thus, an indirect assimilation procedure based on Kuo et al. (1993) has been developed at DWD (Tomassini et al., 2002). This procedure is briefly summarised here. First, the Zenith Total Delay (ZTD) from GPS is converted into IWV following Bevis et al. (1992) using the model temperature and surface pressure. Second, IWV ratio between the observation and the model is calculated. Third, using this ratio the model specific humidity profile is scaled from surface to the 500 hPa level. Specific humidity is set to saturation at any level where the specific humidity exceeds its saturation value due to the scaling. The humidity increments are spread laterally using a correlation scale factor of 35 km (s in equation 2). Only GPS stations with a difference between station height and model orography larger than -100 m have been assimilated. For GPS stations above the model orography, the model level closest to the GPS height has been used as initial level in the profile scaling. This condition about the height of the station is particularly important for the Alpine areas in Switzerland, France, Austria and Italy. Due to this condition about 20 GPS stations have not been assimilated, eight of them from the Swiss GPS network.

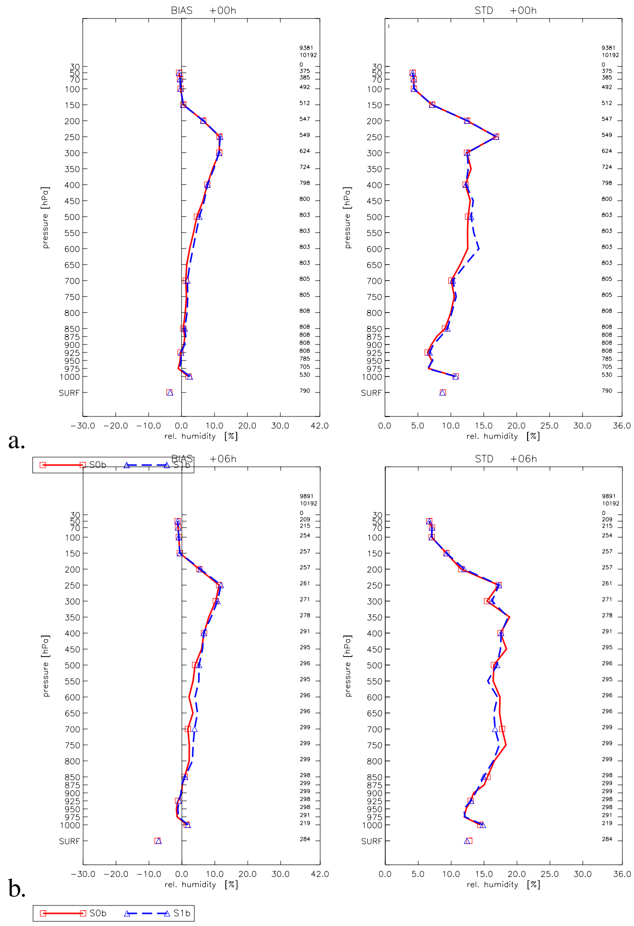


Figure 3. Upper - air verification (aLMo minus TEMP) of relative humidity bias (left) and std (right) for September, January and June OSEs. The blue dashed line presents the GPS forecast and the red line the reference forecast at: a. +00h and b. +06h. A minor bias increase at +06h is obtained when assimilating GPS, but std is slightly improved.

3. GPS Near - Real Time Demonstration Project

The Near - Real Time (NRT) demonstration experiment started in May 2001 as a main activity in Working Group 2 of the COST Action 716 (COST-716, 2002). The objective of this experiment was to develop a dense NRT GPS network covering Europe and providing ZTD estimates suited for operational NWP, i.e. with data delivery within 1 h 45 min after the observation time. Seven regional processing centres are contributing to the NRT project, delivering hourly ZTD files from about 250 stations in a predefined COST format (COST-716, 2001a) to the ftp server of the UK Met Office. An extensive overview about the NRT project is available in Van der Marel et al. (2003).

The assimilation experiments reported in this manuscript use data from about 100 GPS stations, processed by three processing centres; LPT (Swisstopo, Wabern, Switzerland), GOP (Geodetic Observatory Pecny, Czech Republic) and GFZ (GeoForschungsZentrum, Potsdam, Germany). The selection of processing centres is based on optimal domain coverage, data quality and availability. For the period May 2001 - December 2002 the three centres delivered more then 90 % of the data within the selected time window of 1 h 45 min (Van der Marel et al., 2003). The data provided by LPT and GOP have been processed using the Bernese Normal Equation Stacking Software with a time window of 7 and 12 hours, respectively, 30 s sampling rate and elevation cut-off angle of 10°. The GFZ data have been processed with Precise Point Positioning Software - (EPOS) with data sampling of 120 s and elevation cut-off 7°. Hourly observations are reported by LPT and GOP, at H + 30', and two observations per hour are reported by GFZ, at H + 15' and H + 45'. As seen in figure 1 the overall GPS coverage over Switzerland and north of Switzerland is pretty good, but is poor in the southern part of the aLMo domain.

4. The Observing System Experiment Design

All assimilation experiments reported here have been performed by nesting aLMo in the ECMWF global model, the boundary conditions being obtained from the main ECMWF 4D - VAR assimilation cycle with a 6 hour update frequency. All standard meteorological observations are assimilated (SYNOP, BUOY, TEMP, aircraft wind and temperature), but no satellite data are used. Two daily 30 hour forecasts starting at 00 and 12 UTC have been calculated without (reference experiment) and with GPS data assimilation (GPS experiment). Initial conditions for these forecasts were obtained from the corresponding aLMo assimilation cycle. In the forecast runs the observations are still assimilated during the first two hours.

Three weather regimes have been selected for these OSE, namely: an advective period in September 2001, a winter low stratus case in January 2002 and a summer convection period in June 2002. During the five days period from 9 to 13 September 2001 the weather was driven by a cyclone located over the Baltic Sea and a cold front moving slowly eastward, passing over Switzerland on September 9 and initiating cyclogenesis in the the Gulf of Genoa in the night of September 10. The five days period between 10 and 14 of January 2002 is characterised by low stratus over the Swiss Plateau and Southern Bavaria, induced by an anticyclone with weak pressure gradients located over Hungary - a typical winter situation. The third experiment, from the 18 to the 24 of June 2002, was a very active period with intense precipitation events and front passages. One should note, that the French GPS stations have only been available for this June OSE.

A comprehensive verification of the three Observing System Experiments has been performed. The vertical structure and the near - surface parameters have been verified for the entire model domain. The precipitation and cloud cover observations were collected for the western and central part of the domain. The diurnal IWV cycle and ZTD are studied over Switzerland.

5. Experimental results

5.1. *Upper-air and near-surface verification*

The vertical structure of the model atmosphere has been verified against 28 radiosonde stations (TEMP) regularly distributed over aLMo domain, using the operational package of MeteoSwiss. Bias and standard deviation (std) for temperature, relative humidity, wind direction, wind speed and the geopotential are calculated for the forecast times: +00, +06, +12, +18, +24 and +30h. The temperature, wind and geopotential (bias and std) do not significantly differ between the reference and GPS forecast. In figure 3, the bias and standard deviation (aLMo - TEMP) of the relative humidity are plotted for forecast times at +00h and +06h, for the 17 days period. A small increase of the bias of the order of 3 to 4 % is observed in the GPS experiment for the layers above 800 hPa; the assimilation of GPS data resulted in a global increase of the model humidity content. This is specially pronounced over northern Italy (Milan and Udine radiosondes) where the positive humidity bias reaches 10 - 12 % in June 2002 OSE. This bias is not limited only to the first +06h forecast, but is also present up to +30h forecast. This is a sign of a systematic underestimation in the radiosonde humidity profiles. Studies in Japan (Ohtani and Naito, 2000) and western Mediterranean (Haase et al., 2002) report a dry radiosonde bias in mid day observations.

Near-surface parameters have been verified against about 1000 surface stations from the SYNOP network; the pressure (PS), dry bulb temperature (T_2M) and dew point temperature (TD_2M) at 2m have been considered. Table 1 summarises the bias and the std of the reference and the GPS analyses for the three OSE periods. Overall T_2M and TD_2M biases are moderately improved in September and June OSEs and degraded in January OSE; impact of GPS on the standard deviation shows the same trend, but with a much smaller magnitude. Note that in the September OSE the bias of all parameters is reduced in comparison with the June and January OSEs. The reason is an overall good skill of the model for this September period, which is further confirmed by the precipitation verification.

In the September OSE, the improvement of the 2m temperature bias and of the dew point temperature bias is 7 % and 13 %, respectively. In the January OSE, assimilating GPS degrade model performance, with a 7 % degradation of TD_2M and a 17 % degradation for T_2M. We believe the reason for this negative impact is related to the absence of the cloud ice scheme and the associated adjustments of the TEMP humidity in the assimilation cycle, which will be further commented in section 5.b. The surface verification of the June OSE presents a positive impact of the GPS data on the model performance. The dew point temperature bias is improved by about 0.1 K, or about 14 %, and the 2m dry bulb temperature is improved by about 25 %. This is a positive signal in favour of GPS observations.

Table 1. aLMo minus SYNOP in September, January and June OSEs.

	Sept. ref	Sept. GPS	Jan. ref	Jan. GPS	June ref	June GPS
PS bias [Pa]	-146.2	-146.9	-153.0	-153.1	-152.3	-152.9
PS std [Pa]	2563.0	2563.0	2710.0	2710.0	2423.0	2423.0
TD 2M bias [K]	-0.68	-0.60	-0.78	-0.84	-0.82	-0.72
TD 2M std [K]	2.29	2.26	2.96	2.94	2.73	2.69
T 2M bias [K]	0.15	0.14	-0.32	-0.39	0.27	0.21
T 2M std [K]	2.29	2.26	2.47	2.49	2.55	2.52

Table 2. January 2002 OSE aLMo versus ANETZ cloud cover.

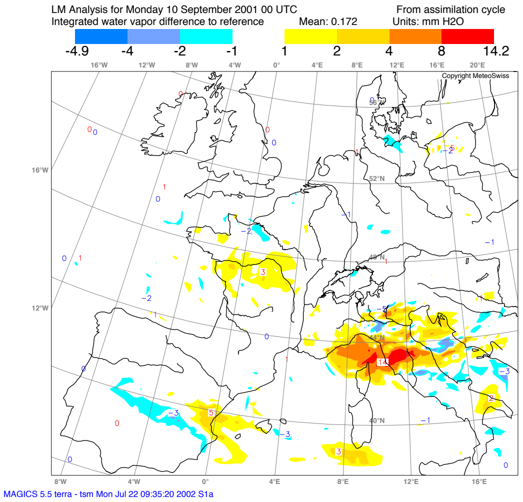
CLC [octa]	0	1	2	3	4	5	6	7	8	TOTAL
ANETZ :	367	78	52	61	30	21	26	40	346	1021
aLMo ref. analysis :	445	106	38	24	23	16	23	33	313	1021
aLMo GPS analysis :	440	115	57	34	22	25	28	41	259	1021
ANETZ :	465	92	57	66	34	27	32	50	444	1267
aLMo ref. forecast :	640	146	58	41	36	33	38	43	232	1267
aLMo GPS forecast :	674	128	60	49	44	26	36	42	208	1267

5.2. *Precipitation and cloud cover verification*

To provide an overview of the GPS impact on the model humidity field, the IWV differences (GPS minus reference) are plotted in figure 4 for the September 10, 2001, January 14, 2002 and June 20, 2002 cases. In the September 2001 case (figure 4 a) a moderate impact is observed when assimilating GPS, with an average difference at analysis time of ± 20 % for an average IWV amount of 20 kg/m^2. This impact has completely vanished in the +12h forecast. Most of IWV modifications are over northern Italy and over the Gulf of Genoa (see Guerova et al., 2003b for a full analysis of this period). As seen in figure 4 b, the IWV differences for the January case are small. The average IWV difference between the GPS and the reference experiment is in the range of ± 10 % for an average IWV amount of 10 kg/m^2. Unlike the other two experiments, the June 2002 period is of prime interest in terms of GPS impact on the model humidity field. During this period (figure 4 c) the GPS assimilation resulted in significant modifications of the aLMo IWV field over the entire model domain, with an average impact of ± 30 % at analysis time for an average IWV amount of 32 kg/m^2. Moreover, both the 00 and 12 UTC forecasts exhibit substantial IWV differences, in order of ± 20 %, up to the end of the forecast (+30h). Note that the plots presented in figure 4 are 00 UTC analysis, which means that the radiosondes humidity profiles have also been available at this time; in this respect the GPS contribution in June OSE is substantial. This is possibly a consequence of the GPS network density and high temporal availability which allows better representation of water vapour structure during periods of active weather.

To further investigate the GPS impact on the model skills, the precipitation data have been examined. The radar composite covering Germany, France, Belgium and Netherlands has been available through M. Tomassini (DWD). Additionally, the Swiss radar composite and the surface precipitation from the ANETZ network are used. ANETZ is the Swiss automatic surface stations network. To get better evaluation of timing and structure of precipitation patterns, the six hour instead of 24 hour accumulated precipitation is used.

For the September 10, 2001 case, a weak impact on the precipitation field is seen in the first six forecast hours. Figure 5 shows the precipitation plots from the reference and GPS forecast. Due to lack of radar data for this date the verification is done against the ANETZ data. The observations give a slight advantage for the GPS forecast (figure 5 b) in terms of reduction of precipitation intensity and better correspondence for precipitation free regions. Note, that the predicted maximum precipitation is 34 $mm/6h$ in the GPS experiment and 37 $mm/6h$ in the reference experiment, significantly overestimating the measured value of 6.2 $mm/6h$. In this respect the GPS data seem to have a potential to push the model towards more realistic forecast, but they are not able to compensate for the model deficiencies probably responsible for this massive overestimation. This case is one of the few cases during the September OSE where some differences in the precipitation patterns



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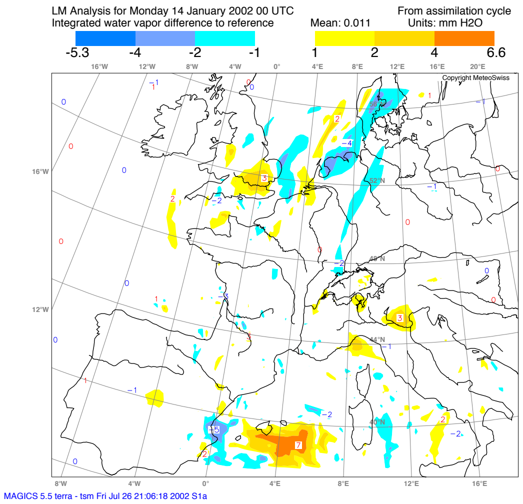

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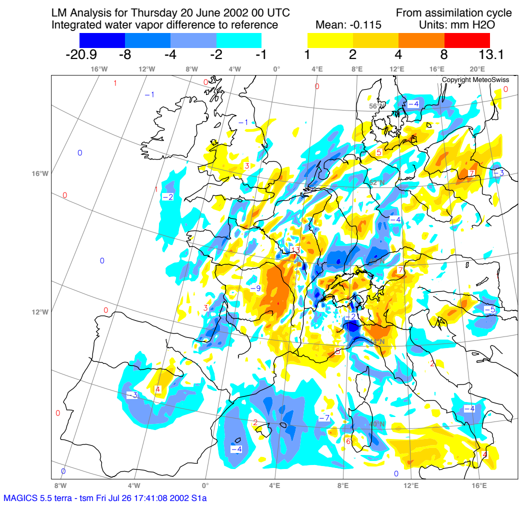
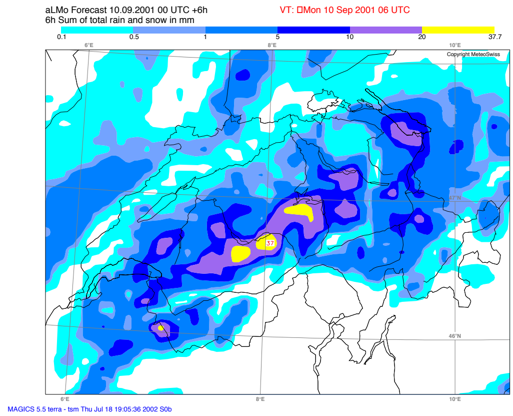


c.

Figure 4. Plot of the IWV difference between GPS and reference experiment at 00 UTC analysis time on: a. 10 September 2001, b. 14 January 2002 and c. 20 June 2002. Note that the major IWV modefications are for the June 2002 case.

a.



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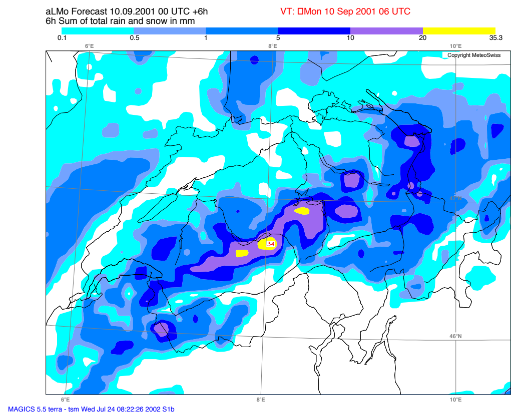

Figure 5. Accumulated six precipitation forecast on 10 September 2001 00 UTC to 06 UTC over Switzerland: a. reference forecast and b. GPS forecast. The contour line defines the Swiss boundary and the main rivers and lakes. Note the differences in the precipitation patterns in the GPS and the reference experiment over the Jura mountain.

could be recognised over the entire aLMo domain. In addition the daily precipitation statistic for Switzerland does not show significant differences between the forecasts with and without GPS. This weak impact could be related to the lack of upwind GPS sites in this experiment (French stations are only assimilated in the June 2002 experiment).

During the June 2002 OSE period, intense precipitation events (above $20mm/6h$) are reported on the 20 - 21 and 23 - 24 June. Two interesting cases can be singled out: one with a positive impact on the forecast and one with negative impact on the analysis. The first case is the 00 UTC forecast on 20 June 2002 and is presented in figure 6. The intense precipitation event seen in the GPS experiment (upper left corner of figure 6 b) is not observed in the reference experiment (figure 6 a). In comparison the radar data (figure 6c) shows intense precipitation over the Jura mountain i.e. Northwest of Switzerland. From figure 4 c, one can see that a moisture deficiency of up to

8 kg/m^2 was present at 00 UTC west of Switzerland in the reference run (the intense orange patch). The predominant south - westerly flow in the hours between 00 and 06 UTC advected this additional moisture towards Switzerland, which resulted in the reported precipitation improvement. In this case the GPS data provide important information at the right time and place and improve the forecast.

The second case, this time with a negative impact on the aLMo analysis, has been seen in the night of 23 - 24 June in the hours between 18 and 06 UTC. The model precipitation from the reference and GPS analyses are plotted in figure 7 a and 7 b and the radar data are in figure 7 c. The GPS assimilation resulted in a substantial increase of large - scale precipitation amount in southern Switzerland with a maximum higher than 200 $mm/6h$, tripling the reference value. Over southern Switzerland the radar data is certainly in better agreement with the reference than with the GPS experiment. The explanation of this case could be traced to the too fast advection of humidity structures towards Switzerland in aLMo, by the predominant south-westerly air flow, provoking a continuous feeding of the model with water vapour through assimilation of the Italian GPS site Torino. A detailed study of the IWV amount on 23 and 24 June 2002 indicates a peak value of 55 kg/m^2 in northern Italy and 45 kg/m^2 in Switzerland (figure 9a), an extremely high water vapour content rarely observed at these latitudes. The specific humidity profiles from Torino show that moisture was substantially increased in the lower 2 to 2.5 km in the model GPS analysis.

A summary of the findings from the qualitative intercomparison between aLMo precipitation and the radar data gives an impact limited to the early forecast hours (up to +6h), which is consistent with the findings reported by Gutman et al. (2003).

In the January OSE the focus was on forecast of low stratus cloud cover. Table 2 shows the total cloud cover as analysed and predicted by aLMo with and without GPS, and the corresponding observations from the ANETZ network. The cloud cover is measured in octa from: clear sky condition - 0 octa to complete cloud cover - 8 octas. The model tends to overestimate clear sky conditions and underestimates the fully overcast situations; this is a known deficiency of aLMo, which fails to correctly simulate stratus situations over the Swiss Plateau. Assimilation of the GPS data strengthen this tendency, in both the analysis and the forecast. Visual comparisons with the METEOSAT cloud cover confirms that assimilating GPS retrieved water vapour has a negative impact on the analysis of the low level stratus over the Swiss Plateau and southern Germany. A possible explanation for this negative impact is the absence of prognostic cloud ice scheme and the use of raw GPS derived IWV (Ch. Schraff, personal communication). At temperature below $0°C$ clouds usually form and exist at saturation over ice; however, in absence of cloud ice scheme, the clouds can only form at saturation over water, i.e. at higher values of specific humidity. So, to get the correct cloud amount, the observed humidity should be increased; this adjustment is taken into account for radiosonde observations but not for the GPS observations. For a winter period this adjustment is important and it should have been introduced in the January OSE.

5.3. *Diurnal IWV cycle and ZTD verification for Switzerland*

The diurnal cycle of water vapour is an important part of the model verification. The diurnal IWV cycle for nine Swiss GPS stations at altitude below 800 m is plotted in figure 8 for the analysis and the forecast. The plot 8 a presents the June 2002 OSE reference and GPS analyses (black and red lines), and the IWV extracted from the Near - Real Time (blue line) and the Post - Processed (PP) GPS data (green line). The reference analysis tends to underestimate the water vapour in the atmosphere when compared with both NRT and PP GPS observations. The bias (aLMo reference / NRT) is in order of -0.64 kg/m^2. On the other side the GPS analysis is overestimating the IWV and the bias is 0.34 kg/m^2. The standard deviation has been reduced from 0.87 kg/m^2 in reference to 0.48 kg/m^2 in the GPS experiment. A visual investigation of the GPS analysis and the NRT observation show satisfactory agreement, except for the early morning hours; however, one should note that NRT observations were missing in the early morning of June 24. A day by day evaluation of the diurnal cycle shows substantial differences between the reference and GPS analysis. On June 21, 22 and 24 the reference model bias, compared to the NRT data, is -2.0, -3.8 and -2.5 kg/m^2 respectively, i.e. the model underestimates substantially the water vapour content. On the other side on June 18 and 19 the reference model bias is positive 2.6 and 1.5 kg/m^2. The figure 8 a is rather difficult to interpret as it covers only one week with rapid changes in the atmospheric conditions. The diurnal cycle of the 00 UTC forecast (figure 8 b) shows a clear underestimation of the water vapour in aLMo in the second part of the day; a slight correction of this error is observed when starting from the gps analysis.

In order to investigate the efficiency of the assimilation scheme and the accuracy of the NRT GPS data, the IWV and ZTD for the GPS sites Payerne (PAYE) are plotted in figure 9. In the panel, one sees that the IWV differences between the reference and GPS experiment are up to 7 - 8 kg/m^2 and that most of the large errors are corrected. However, it is also seen that the assimilation of GPS does not always drive the model to the observed value: for example at 07 UTC on June 18 the difference between model and observation remains in the range of 3 kg/m^2 and the

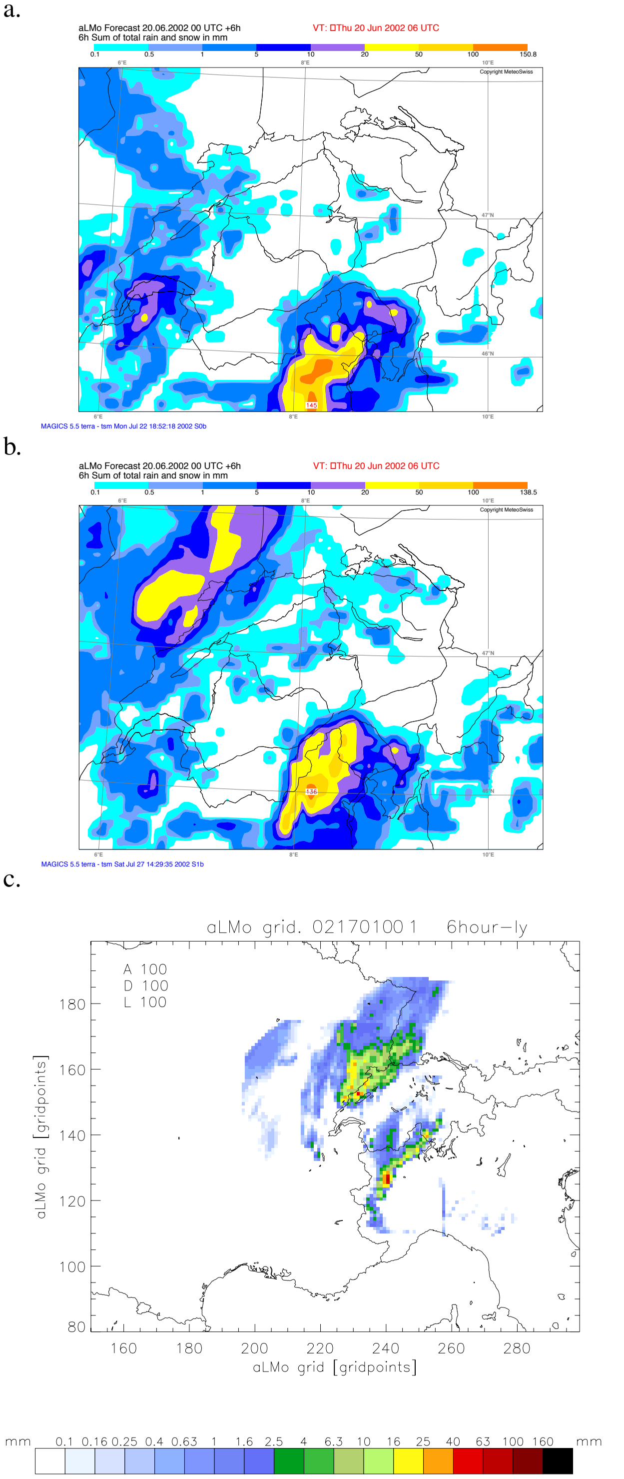

Figure 6. Six hour accumulated precipitation 00 to 06 UTC on 20 June 2002 from: a. reference forecast, b. GPS forecast and c. radar observation. The forecasted intense precipitation over Jura region (i.e. north-western Switzerland) in the GPS experiment is confirmed in the radar plot.

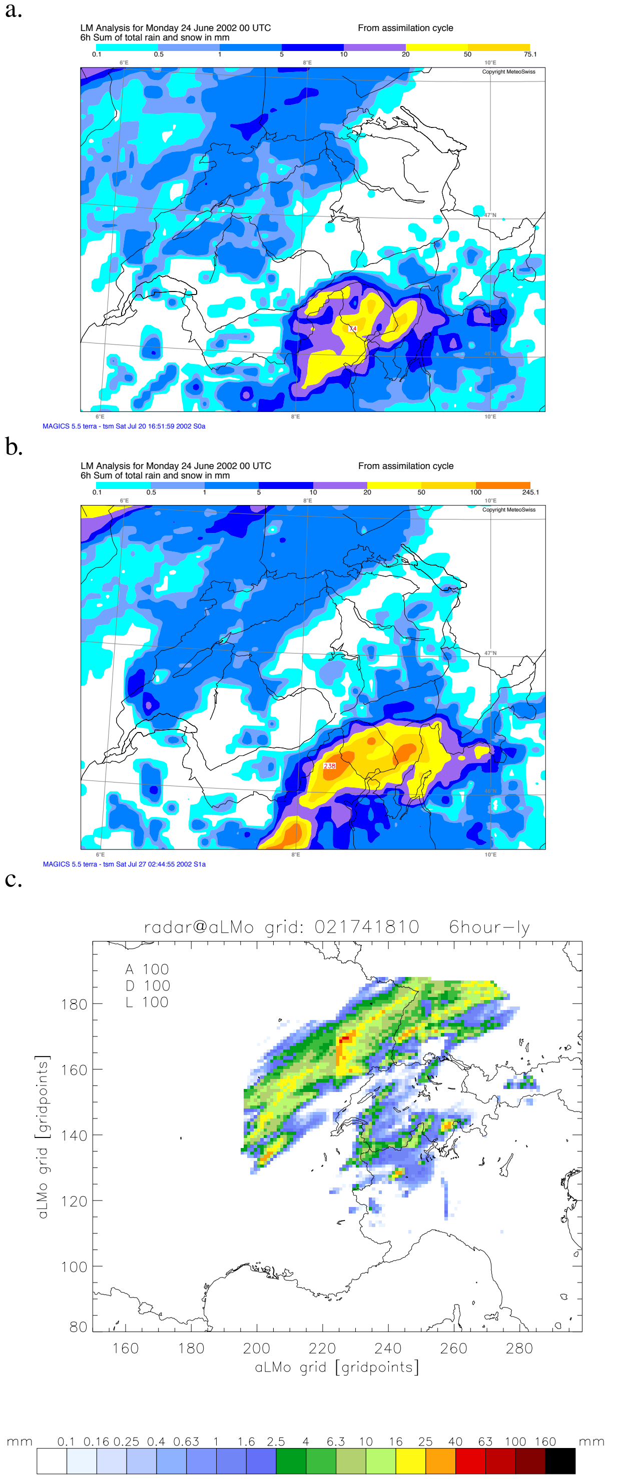

Figure 7. Figure 7: Six hour accumulated precipitation 18 to 24 UTC on 23 June 2002 from: a. reference analysis, b. GPS analysis and c. radar observation. Assimilation of the GPS site Torino resulted in significant overestimation of precipitation over southern Switzerland.

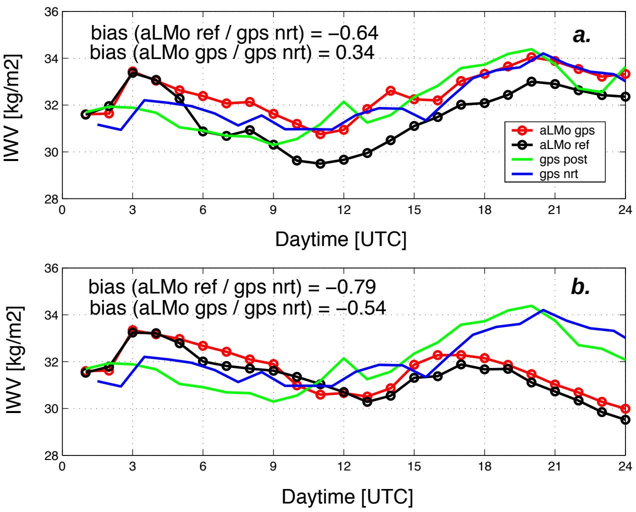

Figure 8. June OSE diurnal IWV cycle for nine Swiss GPS sites below 800 msl. a. The reference analysis - black line , the GPS analysis - red line, Post - Processed GPS green line and NRT GPS - blue line are shown. b. same as a. but for the 00 UTC forecast. Note, the underestimation of the water vapour in the late afternoon hours in the reference and GPS forecast.

minimum of IWV is reached with a three hours delay. A possible explanation is the scale of the nudging term employed in aLMo, which is not optimal for the fast temporal variations of the water vapour; the nudging coefficient (G) used here corresponds to a time scale of about 90 min.
In figure 9 a and 9 b one notes the strong discrepancy between the NRT and PP GPS at midday of June 20. A sharp peak of 35 kg/m^2 is seen in the PP data, which is not well pronounced in the NRT one. This peak has been verified against independent measurements from a sunphotometer, which supports the rapid jump and drop seen in the PP data; this peak is in fact associated with the passage of a cold front. Thus it is to be concluded that NRT processing tends to smooth out the rapid variations of ZTD. This can be explained with the Near - Real Time processing strategy, which incorporates past observations in a 7 hour window to compute the actual ZTD value (processing time window described in section 3). Except for this single observation, a surprisingly good agreement between the two processing schemes is observed. Table 3 displays the bias of the Near - Real Time solution compared with the PP solution for nine Swiss sites, which is in the range 0.4 to 3.7 mm. The averaged ZTD bias is 2.3 mm and the std is in the 8 mm range. This is in agreement with the work reported in Haase et al. (2002) about intercomparison of the MAGIC data set. A ZTD bias of 3 mm corresponds to a IWV bias lower than 0.5 kg/m^2. This result is certainly very encouraging for NWP, as the period under consideration is characterised by rapid changes in atmospheric conditions.

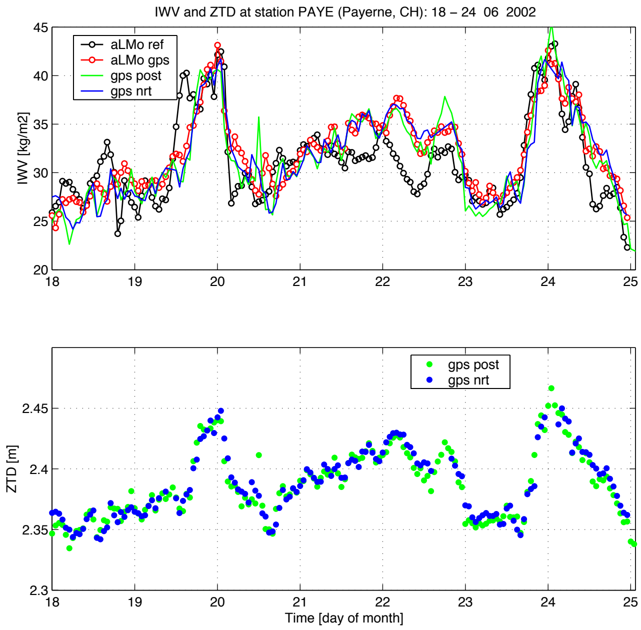

Figure 9. IWV and ZTD for station Payerne in June OSE. a. IWV amount in kg/m^2 from the NRT (blue line) and Post - Processed (green line) GPS data and the aLMo reference (black line) and GPS (red line) analysis. b. ZTD in m at station Payerne from NRT (blue dots) and the Post - Processed (green dots) data. The bias NRT/PP data for station Payerne is 1.8 mm.

Table 3. ZTD (Near - Real Time minus Post - Processed) bias and std in m for the period 18 -24 June 2002.

	ZTD $[m]$	
GPS site:	BIAS NRT/PP	STD NRT/PP
EPFL (Lausane)	0.0028	0.0076
ETHZ (Zurich)	0.0030	0.0081
FHBB (Basel)	0.0004	0.0075
GENE (Geneva)	0.0037	0.0072
LUZE (Luzern)	0.0026	0.0088
NEUC (Neuchatel)	0.0020	0.0087
PAYE (Payerne)	0.0018	0.0078
STGA (St. Gallen)	0.0025	0.0079
UZNA (Uznach)	0.0020	0.0086

6. Conclusions

With the development of high-resolution mesoscale models rose the need of reliable water vapour information with high temporal and spatial resolution. One such source of information are the ground - based networks of Global

Positioning System (GPS) receivers. The focus of the European COST Action 716 was to evaluate the applicability of GPS in operational Numerical Weather Prediction (NWP) through data validation and assimilation experiments. The GPS impact on the operational NWP system of MeteoSwiss, the aLpine Model (aLMo), is reported in this manuscript.
The GPS data from more than 200 European sites have been provided within the Near - Real Time (NRT) demonstration project of COST 716. The quality of NRT data have been validated with the Post Processed (PP) data from Switzerland. It can be concluded that the two data sets have similar quality with few cases of smoothing observed in the NRT data during active weather events. The IWV bias of the NRT data compared with the PP data is less than 0.5 kg/m^2. The data from three COST Processing Centres, namely LPT, GFZ and GOP, are delivered within 1h 45 min observation window in more than 90 % of the cases. The three Centres provide data for 95 % of the GPS sites available in aLMo domain.
Through assimilation experiments with aLMo it was found that the nudging scheme is well able to correct the IWV deficiencies observed in the reference model. A stronger forcing with a shorter time scale could even improve this behaviour in presence of fast meteorological events. The reconstruction of humidity profile is one of the weakest elements of the process; combining GPS with other humidity information or using Slant Path GPS observations could be envisaged to improve this weakness. Comparing radiosonde with GPS, a dry radiosonde bias has been found over Northern Italy. This is consistent with the studies of Ohtani and Naito (2000) and Haase et al. (2002) and seems to be a deficiency in the radiosonde observation during day time.
The impact of GPS assimilation on the aLMo IWV field in winter OSE was weaker than the impact on June and September OSEs. Moreover due to inconsistent usage of humidity correction scheme the results from winter OSE are inconclusive. The strongest GPS impact was obtained in June 2002 OSE, and is visible up to the end of the forecast (+30h). For this period the aLMo reference analysis exhibits a dry bias over Switzerland which is well corrected by assimilating GPS; 2m temperature and dew point temperature analysis have also been improved over the whole domain. However, the impact on the precipitation analysis and forecast is mixed. A missing structure is recovered in the precipitation forecast on June 20 2002. A negative impact on precipitation analysis reported on June 23 is possibly due to model weakness in a special weather situation over northern Italy. The impact on precipitation forecast is limited to the first 6 hours and to intense precipitation events. In our preliminary September 2001 OSE (Guerova et al., 2003b) one case of positive impact on the cloudiness is reported and the precipitation daily cycle of the assimilation cycle was improved.
The use of GPS in NWP has a foreseeable long-term future due to the importance of humidity information for high resolution mesoscale models and the good spatial coverage and temporal availability of these data. The future potential of GPS will be further extended with the new European project - GALILEO (the European Satellite Navigation System) in operational service from 2008. The GPS derived water vapour gradients could help improving the spatial spreading of humidity in active weather regimes and in regions with strong water vapour inhomogeneity. One further improvement could be the retrieval of GPS humidity profiles (tomography), with the limiting factor being the accurate Slant Path estimates. The operational use of GPS in NWP models depends also on future data availability; GPS networks belong mainly to the geodetic community and are not incorporated in the WMO Meteorological Observing System.

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References

Bevis M, Businger M, Herring TA, Rocken C, Anthes RA, Ware RH (1992) GPS Meteorology: Remote sensing of atmospheric water vapor using the Global Positioning System. J Geophys Res 97: 15 787-15 801.
Bettems JM (2002) EUCOS impact study using the limited-area non-hydrostatic NWP model in operational use at Meteoswiss. SMA-MeteoSchweiz Pub. 62. [Available from SMA-MeteoSchweiz, Kraehbuehlstrasse 58, CH-8044, Zuerich, Switzerland.]
Brockmann E, Guerova G, Troller M (2002) Swiss Activities in combining GPS with Meteorology. Mitteilung des Bundesamtes für Kartographie und Geodäsie, J.A. Torres and H. Hornik Eds., EUREF Publ. Vol. 23, Frankfurt, Germany 95-99.
COST - 716 (2001) Format Specification for COST-716 Processed GPS Data, Prepared by: D. Offiler, Met Office, Version 1.0f (http://www.oso.chalmers.se/geo/cost716.html —WG2 — Documents).
COST - 716 (2002) GPS Meteorology - USER REQUIREMENTS, Prepared by S.J.M.Barlag and S. De Haan, KNMI, Version 2.2, (http://www.oso.chalmers.se/geo/cost716.html — WG3 — Documents).
Cucurull L, Navascues B, Ruffini G, Elosegui P, Ruis A, Vila J (2000) The use of GPS to validate NWP systems:

The HIRLAM model. J Atmos Oceanic Technol 17: 773-787.

Davies H (1976) A lateral boundary formulation for multilevel prediction models. Quart J Roy Meteor Soc 102: 405-418.

Doms G, Schaettler U (2001) COSMO Newsletter No 1, 114 pp. [Available from Deutscher Wetterdienst, P.O.Box 100465, 63004 Offenbach, Germany.]

De Pondeca M, Zou X (2001) A case study of the variational assimilation of GPS zenith delay observations into a mesoscale model. J Appl Meteor 40: 1559-1576.

Doms G, (2002) The LM cloud ice scheme. COSMO Newsletter No. 2, G. Doms and U. Schaettler, Eds., 128-136. [Available from Deutscher Wetterdienst, P.O.Box 100465, 63004 Offenbach, Germany.]

Elgered G (2001) An overview of COST Action 716: Exploitation of ground-based GPS for climate and numerical weather prediction applications. Phys Chem Earth (A) 26: 6-8, 399-404.

Falvey M, Beaven J (2002) The impact of GPS precipitable water assimilation on mesoscale model retrievals of orographic rainfall during SALPEX'96. Mon Wea Rev 130: 2874-2888.

Guerova G, Brockmann E, Quiby J, Schubiger F, Matzler Ch (2003a) Validation of NWP mesoscale models with Swiss GPS Network AGNES. J Appl Meteoro 42: 1, 141-150.

Guerova G, Bettems JM, Brockmann E, Matzler Ch (2003b) Assimilation of the GPS-derived Integrated Water Vapour (IWV) in the MeteoSwiss Numerical Weather Prediction model - a first experiment. Phyis Chem Earth in press.

Guo YR, Kuo YH, Dudhia J, Parsons DB, Rocken C (2000) Four-dimensional data assimilation of heterogeneous mesoscale observations for a strong convective case. Mon Wea Rev 128: 619-643.

Gutman SI, Holub K, Sahm SR, Stewart JQ, Smith TL, Benjamin SG, Schwarr BE (2003) Rapid retrieval and assimilation of ground based GPS-Met observations at the NOAA Forecast Systems Laboratory: Impact on weather forecast. Jap Meteor Soc J submitted March 2003.

Haase J, Ge M, Vedel H, Calais E (2002) Accuracy and variability of GPS Tropospheric Delay Measurements of Water Vapour in the Western Mediterranean. Bull Am Meteor Soc submitted Oct 2002.

Kopken C (2001) Validation of integrated water vapour from numerical models using ground-based GPS, SSM/I, and water vapour radiometer measurements. J Appl Meteor 40: 1105-1117.

Kuo YH, Zou X, Guo YR (1996) Variational assimilation of precipitable water using a nonhydrostatic mesoscale adjoint model. Part I: Moisture retrieval and sensitivity experiments. Mon Wea Rev 124: 122-147.

Nakamura H, Koizumi K, Mannoji N, Seko H (2003) Data assimilation of GPS precipitable water vapour to the JMA mesoscale numerical weather prediction model and its impact on rainfall forecast. Jap Meteor Soc J submitted March 2003.

Ohtani R, Naito I (2000) Comparisons of GPS - derived precipitable water vapours with radiosonde observations in Japan. J Geophys Res 105: 26 917-26 929.

Schraff Ch (1997) Mesoscale data assimilation and prediction of low stratus in the Alpine region. Meteor Atmos Phys 64: 21-50.

Tomassini M, Gendt G, Dick G, Ramatschi M, Schraff Ch (2002) Monitoring of integrated Water Vapour from ground-based GPS observations and their assimilation in a limited area model. Phys Chem Earth 27: 341-346.

Van der Marel H, Brockmann E, de Haan S, Dousa J, Johansson J, Gendt G, Kristiansen O, Offiler D, Pacione R, Rius A, Vespe F (2003) COST-716 Near Real-Time Demonstration Project. Jap Meteor Soc J submitted March 2003.

Vedel H, Huang XY, Haase J, Ge M, Calais E (2003) Impact of GPS zenith tropospheric delay data on the precipitation forecasts in Mediterranean France and Spain. Geophys Res Lett submitted February 2003.

Curriculum vitae

Guergana Guerova is born in Elin Pelin Bulgaria on 17 May 1971.

She received the MSc degree in Meteorology (1993 - 1995) from the Dept. of Physics, University of Sofia, Bulgaria. Thesis title: Numerical study of heat and moisture exchange in the morning boundary layer. The MSc thesis subject was boundary layer movements during clear sky, light wind days. A numerical model, based on the fact that when the sun heats the ground, adjacent air warms and rises as a convective thermal, was furter developed and tested for cases of strong temperature inversion.

From 1995 to 1998 she worked as a research scientist at the Dept. "Diffusional Processes and Phase Transitions in the Atmosphere" at the Geophysical Institute, Bulgarian Academy of Science. There she performed simulations of a hailstorm, developed in Colorado on 24 June 1992, using a convective cloud model with a bulk-water parameterization microphysics and different dynamic approaches. In 1997 she joined the team starting a project on acid rain formation in the cumulus clouds, financed through Bulgarian Science Foundation grant. Within this project she studied the formation and growth of the liquid phase in the clouds and was responsible for numerical realisation of a detailed parameterization microphysics.

She attended the Inter-University Program in Water Resource Engineering (1998-2000) at Katholieke University of Leuven, Belgium.

Since March 2000 she has been working on her PhD thesis "Application of GPS derived water vapour for Numerical Weather Prediction in Switzerland" at the Microwave Department, Institute of Applied Physics, University of Bern.