Potential of shipborne GPS atmospheric delay data for prediction of Mediterranean intense weather events

K. Boniface, C. Champollion, J. Chery, Vincent Ducrocq, C. Rocken, E. Doerflinger, P. Collard

Potential of shipborne GPS atmospheric delay data for prediction of Mediterranean intense weather events

K. Boniface[1,*,†], C. Champollion[1], J. Chery[1], V. Ducrocq[2], C. Rocken[3], E. Doerflinger[1] and P. Collard[1]

[1] *Géosciences Montpellier, Université Montpellier II/CNRS, UMR 5243, CC 60, Place E. Bataillon 34095, Montpellier Cedex 5, France*
[2] *CNRM-GAME, Météo-France/CNRS, 42, Avenue G. Coriolis, 31057 Toulouse Cedex, France*
[3] *GPS Solutions, Inc., 1320 Pearl Street, Suite 310, Boulder, Colorado 80302, USA*

**Correspondence to: K. Boniface, Geosciences Montpellier, Université Montpellier II CNRS, UMR 5243, CC 60 Place E. Bataillon 34095 Montpellier Cedex 5, France. E-mail: karen.boniface@ec.gc.ca*

[†] Current address: Environment Canada, Data Assimilation and Satellite Meteorology Research Section, 2121 Transcanada, 1J3 Dorval, QC, Canada.

Received 23 November 2011
Revised 24 March 2012
Accepted 27 April 2012

Abstract

High spatial and temporal variability of mesoscale moisture fields is still a challenge for quantitative precipitation forecast within numerical weather prediction (NWP) models especially over ocean regions where observations are lacking. This study presents the comparison between integrated water vapor over the Mediterranean Sea determined from shipborne GPS, the NWP ALADIN/Météo-France model and MODIS retrieval during a 4-month campaign (autumn 2008).

While moisture prediction of the NWP remains accurate during most of the observation period, there are significant periods with offsets between GPS data and model predictions. We analyze such events and discuss the associated meteorological situation. Copyright © 2012 Royal Meteorological Society

Keywords: GPS; precipitation; mesoscale meteorology

1. Introduction

Most of torrential rainfall events occurring around the Mediterranean coastal mountainous regions are fed by high amounts of humidity coming from the sea. The horizontal distribution of moisture is also a key factor governing the location of the precipitating system. Recent studies have shown that Global Positioning System (GPS) data assimilation (DA) can improve quantitative precipitation forecasts (QPF) (Vedel and Huang, 2004; Cucurull *et al*., 2004) for continental deep convection and upstream conditions well sampled by GPS observations. However, Boniface *et al*. (2009) have shown that even when a large number of GPS stations are assimilated over land, improvement in QPF can be small for Mediterranean coastal heavy precipitation. This neutral impact can be partly explained by the lack of GPS observations sampling the upstream marine moist inflow. Some studies have explored the feasibility of measuring water vapor over the sea with a GPS receiver. In case of a moving GPS platform, the coordinates of the receiving antenna and the tropospheric parameters have to be computed at the same time. The most accurate positioning can be achieved with differential positioning techniques where a kinematic rover (a moving platform) is positioned relative to a fixed site on land. For these techniques to work reliably the reference site(s) should generally be within about 100 km from the rover. Thus, the methods have land and near-shore applications but cannot meet accurate positioning needs in the open ocean or in remote land areas without any reference site infrastructure. For such cases precise point positioning (PPP) (Zumberge *et al*., 1997) methods are commonly employed. Here, the PPP mode is combined with the real-time kinematic technology, which enables high accuracy thanks to ambiguities resolution (Mervart *et al*., 2008), to produce a simultaneous estimation of a new position and tropospheric delay at the antenna.

Fujita *et al*. (2008) reported that shipborne GPS and radiosondes were in good agreement during a 2-month cruise. IWV (integrated water vapor) comparisons have shown a root mean square (RMS) difference of 3 kg m^{-2} during day time. Here, we describe a similar 4-month GPS data acquisition campaign over southeast of France during the VAPIMED (VAPeur d'eau, Pluie intense en MEDiterranée) campaign.

This campaign has been carried out for preparing the upcoming HyMeX (Hydrological cycle in the Mediterranean eXperiment, http://www.hymex.org/) field campaign dedicated to the study of HPEs (high precipitating event) in the Mediterranean region. Two other transects have been recently instrumented with a GPS on board a ship between Marseille and Alger. Another one is being set-up between Roma and Barcelona.

The purpose of this study is twofold. First, we aim to perform a close comparison between GPS-IWV measurements at sea, MODIS IWV retrievals and a high resolution numerical weather prediction (NWP). Second, we want to provide some clues about the meteorological conditions for which GPS shipborne atmospheric delay measurements may improve NWP forecasting. Finally, we discuss the use of such measurements for potential improvement in predictive skills.

2. Experiment and data analysis

The VAPIMED campaign has the scope of characterizing the humidity distribution over the Northwestern Mediterranean coastal Sea. A GPS receiver has been set up on board a commercial ferry shown in Figure 1 (Paglia Orba, SNCM Company). Crossings take place once in the nighttime and the Ferry is docked during daytime alternatively in Marseille and Ajaccio. A Trimble NetRS GPS receiver and its antenna are fixed at about 30 m above sea surface. A supplemental meteorological probe records the surface pressure in the vicinity of the receiver. Data have been collected during a 4-month period (13 September 2008 to 25 January 2009) with a 5-s time sampling. The autumn season has been chosen to observe the highly precipitating quasi-stationary convective systems that developed over the Northwestern Mediterranean coastal regions (Ducrocq *et al*., 2002). Data processing was done with the RTNet software developed by GPS solutions in PPP mode with ambiguity resolution (Rocken *et al*., 2008).

PPP positioning requires accurate Global Navigation Satellite System (GNSS) satellite positions and clocks. For this reason, International GNSS Service (IGS) precise orbits and IGS 30-s clocks are further interpolated to the 5-s GPS receiver sampling epochs. The ship position is estimated together with tropospheric parameters in a fully kinematic mode (100 m s $^{-1}$ constraint on position change). In order to separate vertical ship

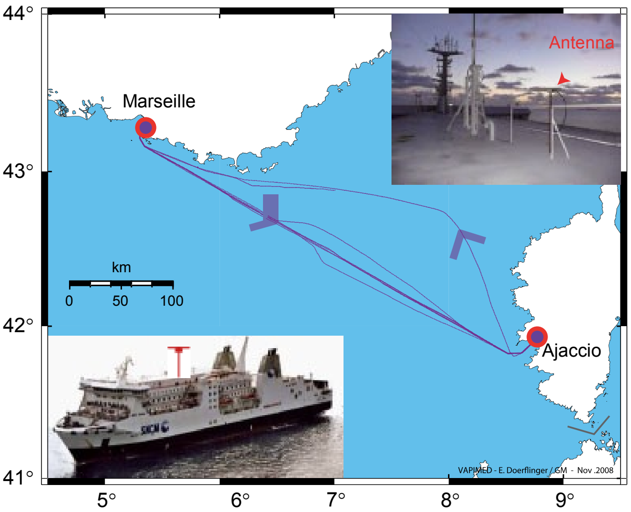

Figure 1. Navigation chart of the Paglia Orba ferry during the VAPIMED campaign. The position of the antenna is shown on both pictures.

positions and the zenithal total delay (ZTD) due to the neutral atmosphere (Bevis *et al*., 1992), we use low elevation observations down to 3° and the global mapping function (Boehm *et al*., 2006). Based on previous validation studies (Fujita *et al*., 2008; Rocken *et al*., 2008) we expect an accuracy in the GPS estimated water vapor from this campaign of 3 kg m $^{-2}$ RMS.

The operational short-range forecast of the NWP ALADIN model is used to compare with the ferry GPS delays over all the 4-month period. At the time of the experiment, ALADIN was running with a 10-km horizontal grid resolution, assimilating observations each 6 h (Bubnova *et al*., 1995) including radiosoundings, screen-level stations, wind profilers, buoys, ships, aircraft and satellite instruments (Yan *et al*., 2008).

ZTD comparisons between GPS estimates and the NWP model evaluations have been carried out when the ferry is on sea or docked in Marseille and Ajaccio Harbors (Figure 2), the associated statistics are summarized in Table I.

The distribution of ZTD differences is similar when the roving GPS is located in the harbors or on sea (Figure 2). Statistics indicate that ZTD measurements have an RMS difference of 16 mm (equivalent IWV ≈ 2.6 kg m $^{-2}$). Therefore, discrepancy between NWP model and GPS measurements above this threshold is substantial and should be considered.

GPS data processing delivers a ZTD measurement calculated above the antenna height. An evaluation of the zenithal hydrostatic delay (ZHD) is done before getting the zenithal wet delay (ZWD) and deducing the final IWV quantity. Several possibilities exist to calculate the ZHD. The Saastamoinen empirical model (1972) has proven to be accurate to a few millimeters exploiting collocated surface pressure data. Another one consists in computing the ZHD by means of pressure and temperature integrations over each layer (Brenot *et al*., 2006). Besides, comparisons have been realized between the surface pressure observations and ALADIN forecast surface pressure to check the validity of both methods and showed a good agreement. We decide to use the latter method to compute the ZHD as it allows a full consistency with the NWP model. The pressure and temperature extracted from the 6 to 12 h ALADIN forecasts issued from 0000 UTC and 1200 UTC analyses are used with a temporal linear interpolation to get continuous GPS-IWV (Figure 3). The advantage of using directly the model variables is the possibility to compute a ZHD everywhere without meteorological surface probes. Finally, the ZWD is deduced by subtracting the ZHD from the ZTD one.

The methodology followed for computing the equivalent delays issued from ALADIN forecasts consists in integrating independently the index of refractivity for the hydrostatic and wet parts of the troposphere. Then, the wet delays extracted from GPS data and ALADIN model outputs need to be converted into an IWV quantity. The conversion is done using Bevis

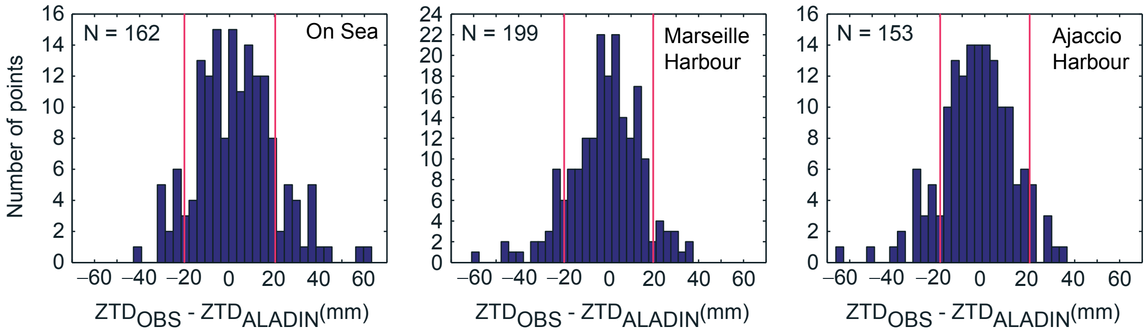

Figure 2. Histogram of the residual distributions of ZTD_{OBS}–ZTD_{ALADIN} on sea (left), at Marseille Harbor (middle) and at Ajaccio Harbor (right). Statistics are computed over the entire VAPIMED campaign.

Table I. Statistics on the differences ZTD_{OBS}–ZTD_{ALADIN} over the entire VAPIMED campaign.

Ship location	RMS difference (mm)	Bias (mm)	Correlation coefficient	Sample
Sea	17.9	3.2	0.939	162
Marseille	15.8	−1.4	0.959	199
Ajaccio	16.3	−3.7	0.932	153

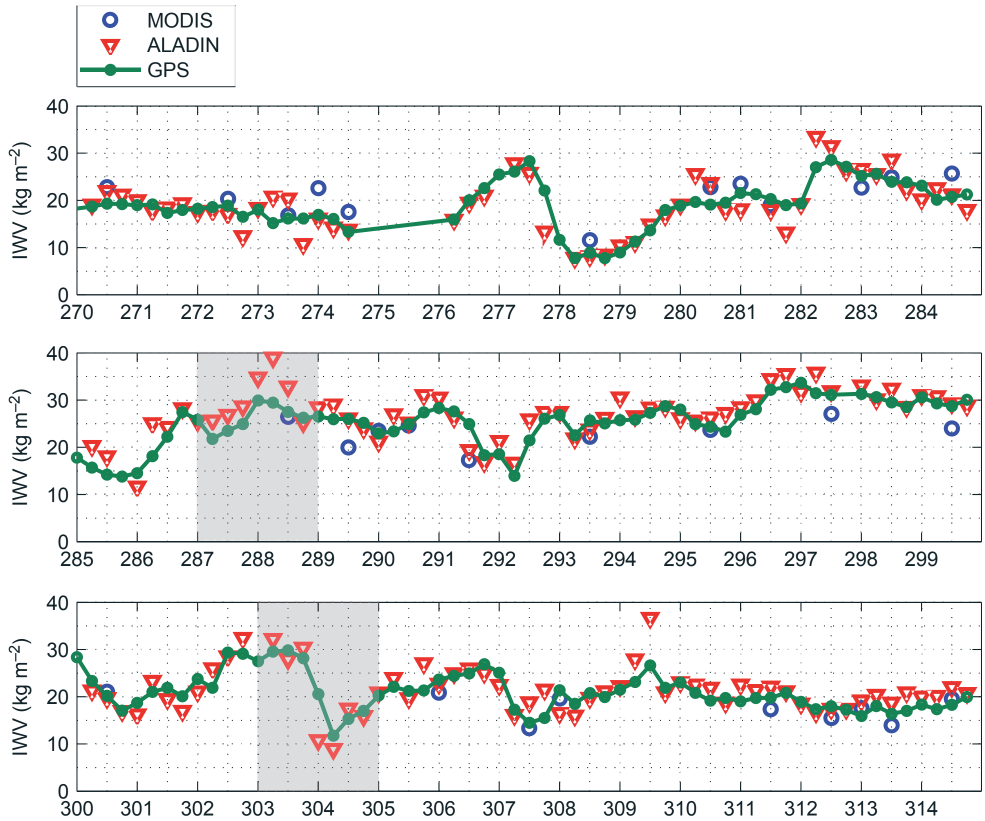

Figure 3. IWV time series between day of year 270 and 315 (26 September 2008 to 10 November 2008) for GPS, ALADIN forecasts and MODIS retrievals. Events around days 288 and 304 highlighted in gray are zoomed in Figure 5.

et al. (1992):

$$IWV_{OBS} = \frac{ZWD_{OBS}}{PI} \text{ and } IWV_{ALADIN} = \frac{ZWD_{ALADIN}}{PI}$$

with a PI factor estimated to about 6.5 according to the specificity of the Mediterranean region (Emardson and Derks., 1999) and depending on surface temperature.

The PI factor was determined using more than 120 000 radiosondes over Europe considering an averaged surface temperature of 275 K with a relative RMS error of 1.14%. This allow us to consider a subsequent accuracy in terms of IWV of less than 1 kg m^{-2} as demonstrated in the study of Brenot *et al.*, (2006). However, such accuracy may be exceeded in case of extreme events with a bias reaching 3 kg m^{-2}.

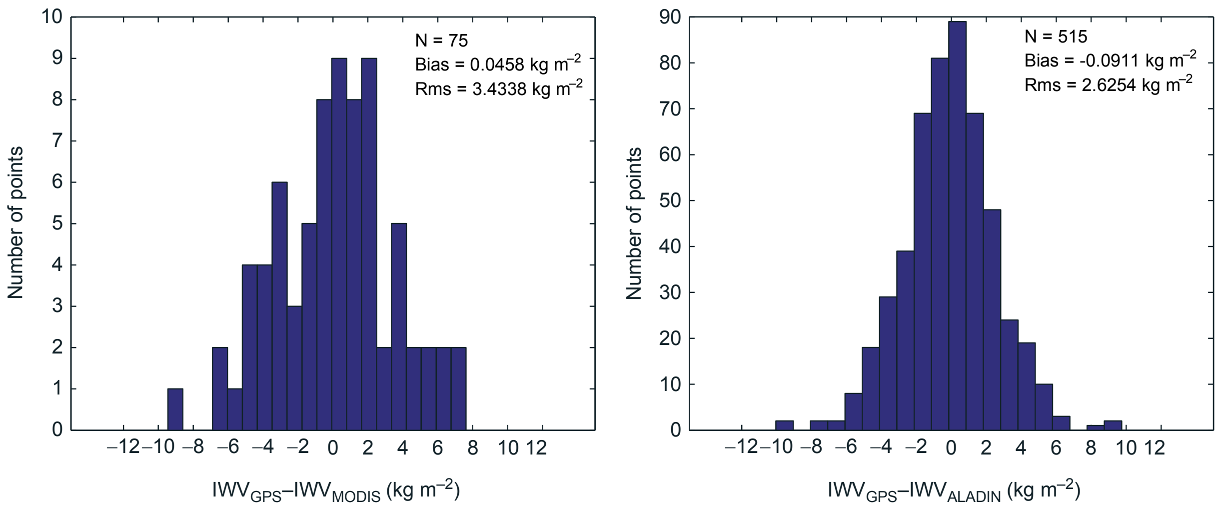

Figure 4. Histogram of the residual distributions of IWV$_{GPS}$–IWV$_{MODIS}$ (left) and IWV$_{GPS}$–IWV$_{ALADIN}$ (right) for available coincidence data of MODIS and ALADIN. Statistics are computed over the entire VAPIMED campaign.

The technique used for retrieving MODIS IWV consists in using ratios of radiance from water vapor absorbing channels centered near 0.905, 0.936 and 0.94 μm with atmospheric window channels at 0.865 and 1 .24 μm. From the MODIS sensors (TERRA and AQUA satellites), we get directly an IWV quantity during clear sky meteorological conditions. These satellites provide a complete view of the earth each 1 – 2 days with a resolution of 1 km during daytime and 5 km during nighttime. We use MODIS IWV retrievals from the near-infrared and infrared channels (King *et al*., 2003). MODIS IWV appeared to overestimate IWV against GPS, with scale factors from 1.07 to 1.14 and standard deviations varying from 0.8 to 1.4 kg m^{-2} over continental areas (Li *et al*., 2003).

Because the accuracy of PPP processing is well established we do not attempt to validate again the GPS data processing for GNSS applications in the ocean. Rather, we draw attention on the possible discrepancy between GPS retrievals and NWP quantification of IWV. The novel aspect of this study is the use of continuous NWP models and satellite products in comparison with IWV-GPS retrievals for marine conditions.

3. Results

We first describe IWV comparisons and residual analysis that have been conducted for ALADIN NWP outputs, MODIS data and GPS-IWV retrievals. Overall GPS, ALADIN and MODIS time series of IWV are shown in Figure 3. In comparison with Li *et al*., (2003), there is no significant IWV bias (less than 0.1 kg m^{-2}) between GPS and MODIS; however, RMS difference is larger (3.5 kg m^{-2} instead of 1.4 kg m^{-2}). The larger RMS of the MODIS-GPS comparison with respect to ALADIN-GPS could be explained by the resolution of the MODIS images, the sampling times differences or a partially cloudy sky (only explaining an underestimation of the MODIS IWV). The IWV differences between ALADIN and GPS are in average equal to 2.6 kg m^{-2}. The IWV RMS differences are linked to the forecasts quality or the initial conditions errors of the model.

A fairly good agreement is observed between the three IWV time series except for some particular events. For example, IWV differences are greater than 5 to up to 10 kg m^{-2} between GPS/ALADIN for GPS days 277.75, 288, 304 and 309. For some case studies a better agreement is found between MODIS and GPS data than ALADIN/GPS data (GPS days 283.5, 288.5, 295.5 and 307.5). However, we have to be cautious with the reliability of the MODIS data especially when sky conditions are not completely clear (Gao and Kaufman, 2003). Precipitable water products from MODIS collection 005 under clear sky conditions have been used. Additional quality control has been performed to remove a particular case that contains very bright clouds.

The histograms of the residual distributions of IWV$_{GPS}$–IWV$_{MODIS}$ and IWV$_{GPS}$–IWV$_{ALADIN}$ along the entire campaign are represented in Figure 4. More than 20% of data reveal significant differences of order of magnitude of ± 4 kg m^{-2}. RMS around 3 kg m^{-2} is consistent with previous comparisons (Li *et al*., 2003; Yan *et al*., 2009) between MODIS, GPS and ALADIN confirming the quality of GPS shipborne IWV estimates.

4. Discussion

The results of the campaign have been depicted so far using a statistical and quantitative approach. Two particular events that draw our attention because of the high differences between model and GPS found in Figure 3 are discussed. Figure 5 presents close-ups of the IWV time series during the two events. Figure 6 gives an overview of the general ALADIN

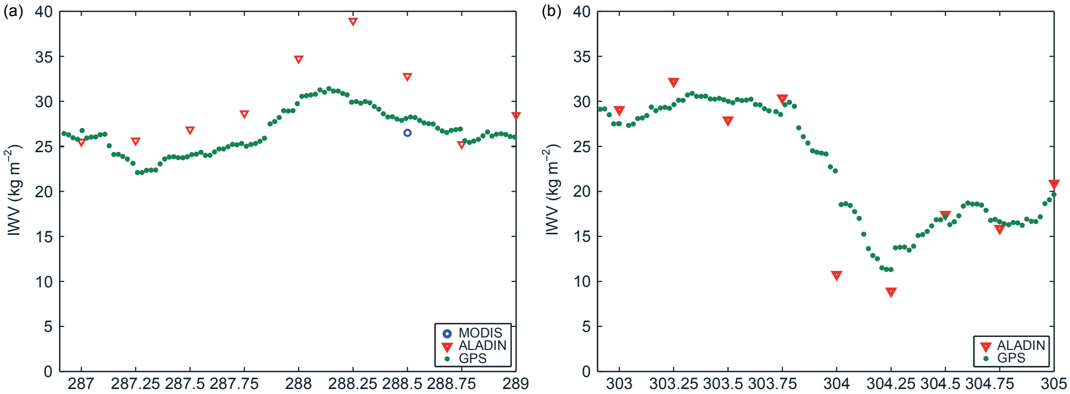

Figure 5. IWV retrieved with the ALADIN model and the GPS data for two particular study cases around GPS day 288 (14 October 2008, left side) and GPS day 304 (30 October 2008, right side).

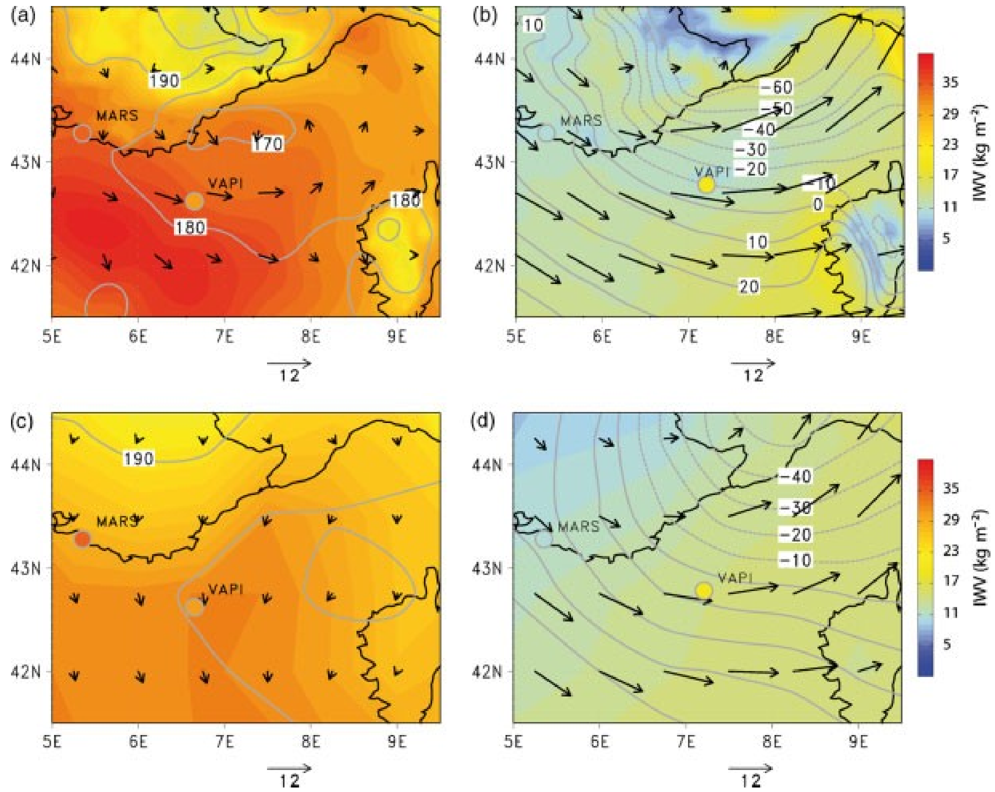

Figure 6. Integrated water vapor (IWV) (kg m^{-2}) field retrieved by GPS on sea (VAPI) and at Marseille (MARS). IWV field (colored), 1000-hPa geopotential heights (contour lines) and 10 m wind speed vectors from the 12 h ALADIN forecasts are depicted for (a) 14 October 2008 at 00 UTC (Julian day 288), (b) 30 October 2008 at 00 UTC (Julian day 304); (c) and (d) same as (a) and (b) but using the ERA-interim reanalysis from ECMWF.

IWV field over the Mediterranean area with the corresponding GPS value on sea and at Marseille. The ERA-interim reanalysis (Berrisford *et al*., 2009) produced by the European Centre for Medium Range Weather Forecasts (ECMWF) is depicted to show the corresponding 10 m surface wind fields and the 1000 hPa geopotential heights for these two events.

A first case of interest occurs on days 287–289. A small overestimation by the ALADIN NWP of the IWV in comparison with the GPS is seen between days 287 and 288 (about 3 kg m^{-2}). Then ALADIN exhibits a maximum of IWV around 40 kg m^{-2} equivalent to an overestimation of 10 kg m^{-2} compared with GPS and MODIS IWV. The synoptic meteorological situation shows a high pressure situation over continental France and a small low pressure near the southeast coast of France during the day 288 (Figure 6(a)). The wind is weak and oriented mainly west and northwest but changing during the days. The ALADIN does not seem to locate adequately the low pressure center and does not simulate correctly the advection of water vapor due to the west/northwest wind in such a changing local situation in comparison with the ERA-interim (Figure 6(c)). While GPS-IWV values are in accordance with the ALADIN forecasts at Marseille, difference of 5 kg m^{-2} arises on sea.

The ERA-interim shows a better agreement with the observations on sea but a largest discrepancy at Marseille (higher than 5 kg m $^{-2}$, Figure 6(c)).

Around day 304, GPS and ALADIN IWV trends are markedly different during a strong and rapid decrease of 20 kg m^{-2}. The model is unbiased during days 303 and 305 but exhibits a severe IWV underestimation (∼10 kg m^{-2}) compared with GPS data on day 304. The meteorological situation is of a particular interest as a HPE in the South of France occurs before and after the day 304 with severe floods. The day 304 is a transition between those two HPE with moderate to strong wind. ALADIN forecasts reveal shallow depression around 44 °N associated with strong 10 m wind speed over the Mediterranean area. This northwest mistral continental wind brings cold and dry air masses over the Mediterranean Sea (Figure 6(b)). IWV-GPS on sea shows large discrepancies (greater than 10 kg m $^{-2}$) compared with the ALADIN forecasts IWV fields. Regarding the ERA-Interim reanalysis the trough location is similar but less intense. The 10 m wind speed is weaker that tends to reduce the advection of dry air from the continent. This could explain the better agreement of the GPS observation with ERA-interim (Figure 6(d)). In this case, simulation errors from ALADIN forecast act to increase the difference. Nevertheless, discrepancies are still observed over the Mediterranean Sea also with the ERA-interim reanalysis. This has been verified against wind observations at Marseille which report a mistral situation overnight between days 304 and 305.

The GPS receiver on board the ferry is thus able to provide significant new information on spatial and temporal humidity gradients related to the intense Mediterranean events, and that in the marine domain which is almost void of *in situ* observations of humidity. GPS measurements are not influenced by the surrounding marine conditions contrary to *in situ* humidity measurement recorded on buoys. Currently there are only two buoys deployed in the Northwestern Mediterranean Sea and measuring near-surface humidity among others quantities and very few instrumented commercial ships.

5. Conclusions and perspectives

In this foremost exploratory experiment of the HyMeX project, we evaluate for the first time the performance of NWPs of IWV in the North Mediterranean Sea. Like in previous comparisons in continental areas, our shipborne GPS data show that IWV model prediction is unbiased in average, over sea. However, our analysis points out large model excursions during transition between local Mediterranean weather conditions such as mistral winds or HPEs. This suggests that continuous and accurate observations of water vapor recorded by shipborne GPS are useful. In the future, GPS-IWV measured on board of ships for DA applications should bring constraints in NWP analyses, especially in the Mediterranean area where the transport of marine air masses toward the coasts is crucial for accurate precipitation forecasts.

However, the potential impact of GPS measurements is closely linked to the quality of the forecasts. Although IWV-GPS data seem valuable during precipitation events, their assimilation could offer a limited potential of improvement of the prediction when advection is not well described by NWP models. Increasing the number of these measurements should enhance efficiency of the initial conditions and help compensating advection errors.

Acknowledgements

The authors wish to thank the CNRS/INSU/LEFE Program (VAPIMED project) and the SNCM. K. B. is grateful to NSERC for post-doctoral fellowship. Thanks go also to the three reviewers who helped to improve the manuscript.

References

Berrisford P, Dee D, Fielding K, Fuentes M, Kållberg PW, Kobayashi S, Uppala SM. 2009. The ERA-Interim archive ERA Report Series, No. 1. ECMWF: Reading, UK.

Bevis M, Businger S, Herring T, Rocken C, Anthes R, Ware R. 1992. GPS meteorology, remote sensing of atmospheric water vapor using the global positioning system. *Journal of Geophysical Research* **97**(D14): 15787–15801.

Boehm J, Niell A, Tregoning P, Schuh H. 2006. Global mapping function (GMF): a new empirical mapping function based on numerical weather model data. *Geophysical Research Letters* **33**: L07304.

Boniface K, Ducrocq V, Jaubert G, Yan X, Brousseau P, Masson F, Champollion C, Chéry J, Doerflinger E. 2009. Impact of high-resolution data assimilation of GPS zenith delay on Mediterranean heavy rainfall forecasting. *Annales Geophysicae* **27**: 2739–2753.

Brenot H, Ducrocq V, Walpersdorf A, Champollion C, Caumont O. 2006. GPS zenith delay sensitivity evaluated from high-resolution numerical weather prediction simulations of the 8–9 September 2002 flash flood over southeastern France. *Journal of Geophysical Research* **111**: D15105.

Bubnova R, Hello G, Bénard P, Geleyn J-F. 1995. Integration of the fully elastic equations cast in the hydrostatic pressure terrain-following coordinate in the framework of the ARPEGE/Aladin NWP system. *Monthly Weather Review* **123**: 515–535.

Cucurull L, Vandenberghe F, Barker D, Vilaclara E, Rius A. 2004. Three-dimensional variational data assimilation of ground-based GPS ZTD and meteorological observations during the 14 December 2001 storm event over the Western Mediterranean Sea. *Monthly Weather Review* **132**(3): 749–763.

Ducrocq V, Ricard D, Lafore JP, Orain F. 2002. Storm-scale numerical rainfall prediction for five precipitating events over France: on the importance of the initial humidity field. *Weather and Forecasting* **17**: 1236–1256.

Emardson TR, Derks HJP. 1999. On the relation between the wet delay and the integrated precipitable water vapour in the European atmosphere. *Meteorological Applications* **7**: 61 – 68.

Fujita M, Kimura F, Yoneyama K, Yoshizaki M. 2008. Verification of precipitable water vapor estimated from shipborne GPS measurements. *Geophysical Research Letters* **35**: L13803.

Gao B-C, Kaufman YJ. 2003. Water vapor retrievals using moderate resolution imaging spectroradiometer (MODIS) near-infrared channels. *Journal of Geophysical Research* **108**: 4389.

King MD, Menzel P, Kaufman YJ, Tanr D, Gao B-G, Platnick S, Ackerman SA, Remer LA, Pincus R, Hubanks PA. 2003. Cloud and aerosol properties, precipitable water, and profiles of temperature and water vapor from MODIS. *IEEE Transactions on Geoscience and Remote Sensing* **41**: 442–458.

Li Z, Muller J, Cross P. 2003. Comparison of precipitable water vapor derived from radiosonde, GPS, and moderate-resolution imaging spectroradiometer measurements. *Journal of Geophysical Research* **108**: 4651.

Mervart L, Lukes Z, Rocken C, Iwabuchi T. 2008. Precise point positioning with ambiguity resolution in real-time, paper presented at *ION GNSS*, Savannah, Georgia, USA.

Rocken C, Iwabuchi T, Lukes Z, Mervart L, Fujita M, Kanzaki M. 2008. Precise positioning of ships and buoys in the open ocean. Results from a 3-month Indian ocean cruise and a tsunami buoy off Japan's coast, paper presented at *ION GNSS*, Savannah, Georgia, USA.

Yan X, Ducrocq V, Poli P, Jaubert G, Walpersdorf A. 2008. Mesoscale GPS Zenith Delay assimilation during a Mediterranean heavy precipitation event. *Advanced Geosciences* **17**: 71–77.

Yan X, Ducrocq V, Jaubert G, Brousseau P, Poli P, Champollion C, Boniface K. 2009. Benefit of GPS Zenith Delay assimilation on high-resolution quantitative precipitation forecast of the COPS cases IOP9. *Quarterly Journal of the Royal Meteorological Society* **135**: 1788–1800.

Vedel H, Huang X-Y. 2004. Impact of Ground Based GPS Data on Numerical Weather Prediction. *Journal of Meteorological Society Japan* **82**: 459–472.

Zumberge JF, Heflin MB, Jefferson DC, Watkins MM, Webb FH. 1997. Precise point positioning for the efficient and robust analysis of GPS data from large networks. *Journal of Geophysical Research* **102**(B3): 5005–5017.