GPS tomographic experiment on water vapour dynamics in the troposphere over Lisbon

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1. Introduction

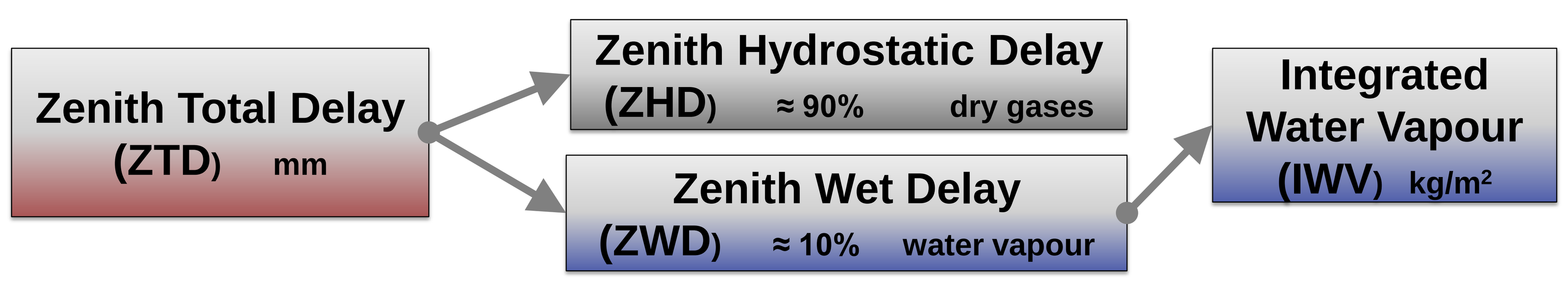
•The aim of this study is to characterize the 3D water vapour field on the troposphere in time by GNSS tomography techniques.

•A tomographic experiment was developed over an area of 60x60 km² (Lisbon, Portugal) using GPS data from a GNSS network of 17 stations: 9 permanent receivers and 8 temporarily installed in a field campaign (July, 2013) for the densification of the GNSS network.

•Preliminary results are shown: water vapour tomography cross-section profiles, 2D IWV maps from GPS atmospheric processing and radiosonde vertical profile comparison for tomography solution validation.

2. GPS atmospheric processing

The GPS signal transmission is affected by atmospheric effects causing delay, that can be minimized at the ionosphere and measured in the troposphere. The delay occurred in the troposphere is caused mainly by its water vapour content. In the GPS processing, in order to improve the GPS positioning one needs to estimate the tropospheric delay with precision and separate it from other perturbation sources. These quantities are calculated integrally, in mm, at the vertical profile position of each GNSS station, namely:



ZTD is determined from the sum of the two components, ZHD and ZWD. Usually ZHD varies very slowly in time and can be very accurately estimated using surface pressure measurements at the GPS station. ZWD is highly variable given the variability of the water vapour and the deficiencies in its observations. For this work we use the GAMIT\GLOBK software (v10.5) to process the GPS data in daily solutions.

The obtained ZWD can be related with the IWV, throughout an empirical relation considering water vapour constants and a mean temperature of the tropospheric column (Tm), often calculated from the surface temperature. Tm was constrained for this study with a yearly set of radiosondes over the Lisbon region.

Integrated water vapour estimates using GNSS atmospheric processing provide measurements with 1 to 2 kg/m² bias comparing with other meteorological sensors, but lack vertical discretization.

3. GPS tomography setup and processing

IWV determination by means of GNSS meteorology techniques combined with the reconstruction of the original slant path delay rays in the satellite line of view, provides an opportunity to sense the troposphere in 3 dimensions plus time. The tomography principle is based on the examination of an area using ray tracing observations throughout some parts of its domain that are parametrized in a system of equations that is resolved applying the inverse theory. Hence discretization of the domain, in this case the troposphere, is needed (Fig.1). The ray tracing observations in the GPS tomography are the slant wet delay (SWD), which are obtained simply projecting the ZWD from each station into the direction of each observed satellite in the horizon, using the wet mapping functions (mf_w) only depending on the elevation angle ε (eq.1). In this work we use the Vienna mapping function 1 (VMF1).

A 3D grid composed by volumetric cells was setup for the study area (Fig.2) being composed by 5x6x18 in the longitudinal, latitudinal and height directions. Densification of the available GNSS permanent network over a 60x60 km² area in Lisbon was performed increasing the number of stations from 9 to 17, with 8 temporarily installed stations in a field campaign during July 2013. Locations were chosen to minimize empty columns of cells. Horizontal size of the cells is about 11x11 km, while the vertical spacing is thinner with the first layer set at 0.5 km and the top limit at 10 km (near tropopause). Vertical spacing is variable being tighter at the low troposphere, increasing spacing with altitude, following the expected water vapour vertical distribution.

$$SWD = ZWD . mf_w(\varepsilon) \quad (1)$$

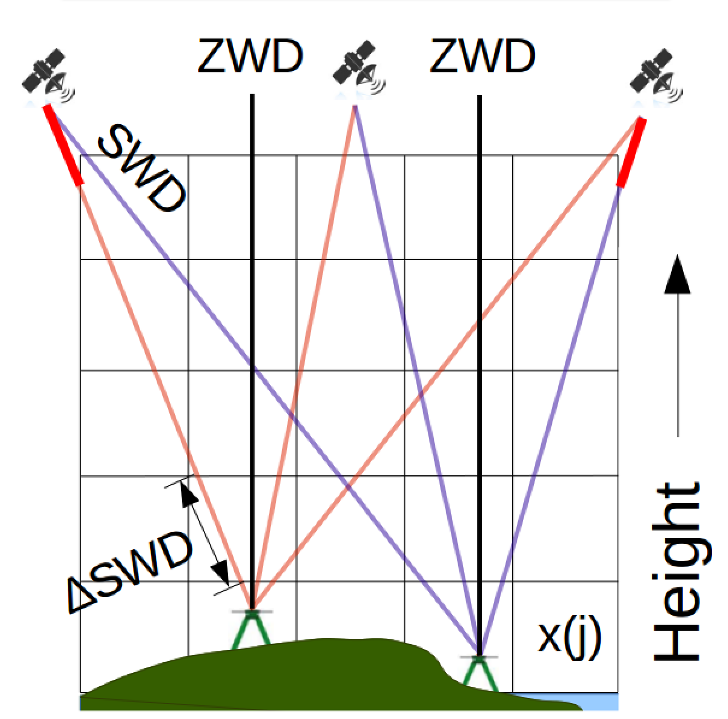


Figure 1 – GPS Tomography vertical cross section scheme.

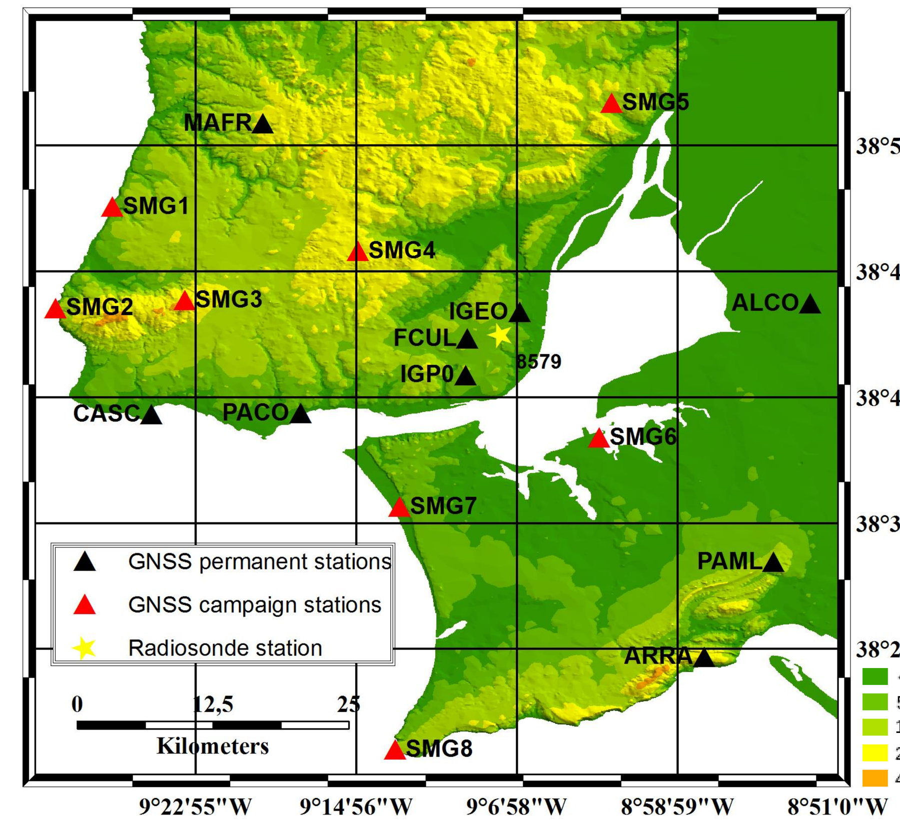


Figure 2 – Tomographic grid over study area.

The water vapour density solution is obtained in each grid cell relating the SWD observations and the 3D grid setup during a short time interval, assuming a constant density. Thus the tomography can be represented by a system of equations based on a simple inverse problem (Y=AX), where A is the matrix relating the ΔSWD sub-path distance (d_{nm}) crossing the cells from the total SWD traveling along the model:

$$SWD = A.X \Leftrightarrow \begin{bmatrix} SWD_1 \\ \vdots \\ SWD_n \end{bmatrix} = \begin{bmatrix} d_{11} & \cdots & d_{1m} \\ \vdots & \ddots & \vdots \\ d_{n1} & \cdots & d_{nm} \end{bmatrix} \cdot \begin{bmatrix} X_1 \\ \vdots \\ X_m \end{bmatrix} \quad \begin{matrix} n-observations \\ m-grid\ cells \end{matrix}$$

Assuming the slant path bending negligible the problem becomes linear enabling the application of the damped least square method to solve X:

$$X = X_0 + (A^T.P.A + P_0)^{-1}(A^T.P)(SWD - A.X_0)$$

P are the weights given to SWD, X_0 is a prior solution of the water vapour state and P_0 is the respective covariance matrix. Weights assigned in P result from the ZWD precision obtained in GAMIT combined with an elevation angle error model (following eq.1).

However the GPS Tomography has some drawbacks:

1) requirement for a dense station network sparsely distributed on the area.
2) ill-posed problem due the sub optimal coverage of the grid caused by the slant path GPS geometry limitation.

Despite the fact that 1) is minimized by the GNSS field campaign, there is still need to overcome 2) since the A matrix will be composed by a large amount of zero values mainly in the lower grid cells. Therefore a set of constraints or additional information concerning the grid model are introduced in the tomography system of equations: horizontal layer weighting based on the inverse distance (horizontal smoothing), top boundary layer equalling zero wet density, side face boundary exiting SWD observations re-estimation (Fig.1 red trace) based on an exponential law following the water vapour vertical behaviour.

5. Conclusions

- Preliminary results show good agreement between radiosonde profiles of water vapour and the correspondent columnar profile of the tomographic solution.
- The 3D water vapour tomography results reveal the local dynamic vertical variation in the Lisbon area, demonstrating the technique potential for monitor small scale air circulation on coastal areas like sea breeze.
- The GPS Tomography is one of the most promising techniques for sensing the 3D tropospheric water vapour state, with potential to analyse large convective precipitation and other severe weather phenomena. Therefore, numerical weather prediction models can benefit if a near-real-time processing chain is assembled.

Acknowledgements

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4. Results

Day 18 July 2013 was chosen to evaluate the preliminary GPS tomography solutions. Radiosonde at 0h was defined as initial X_0 and solutions with a 2h interval were calculated. Values are in kg.m^{-3}. Origin *x,y* of the 3D grid (Fig.1) is top left. A radiosonde campaign was also held in order to validate the results.

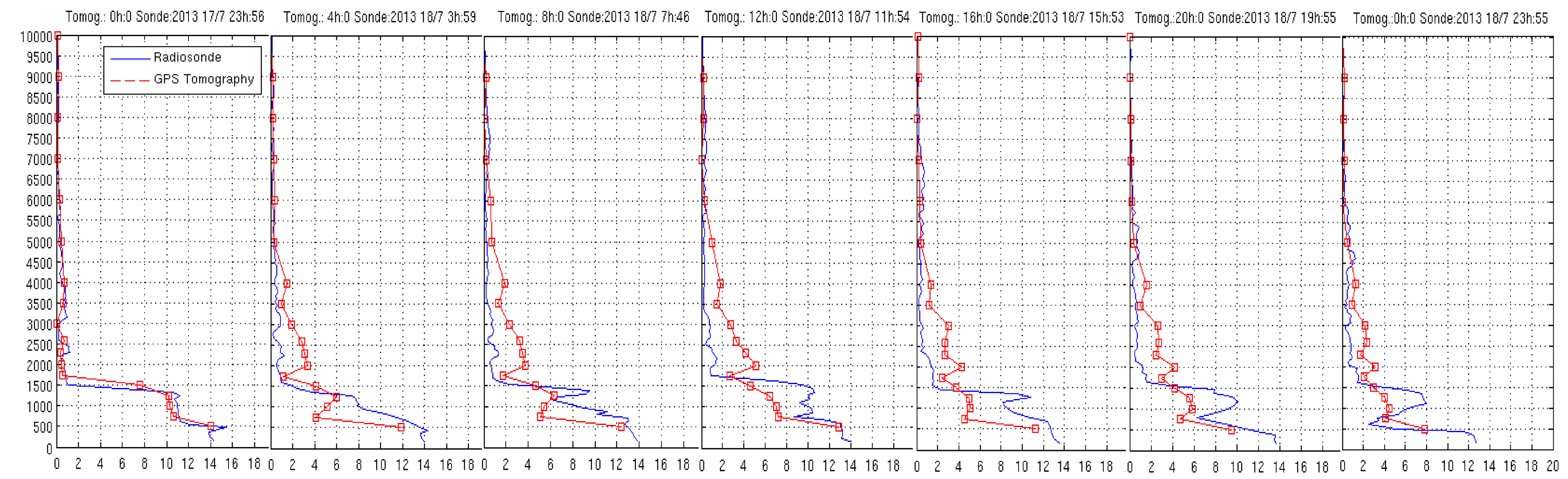

Figure 3 – Comparison between GPS tomography (x=3,y=3 column) (red), and radiosonde water vapour density (blue); 4h interval.

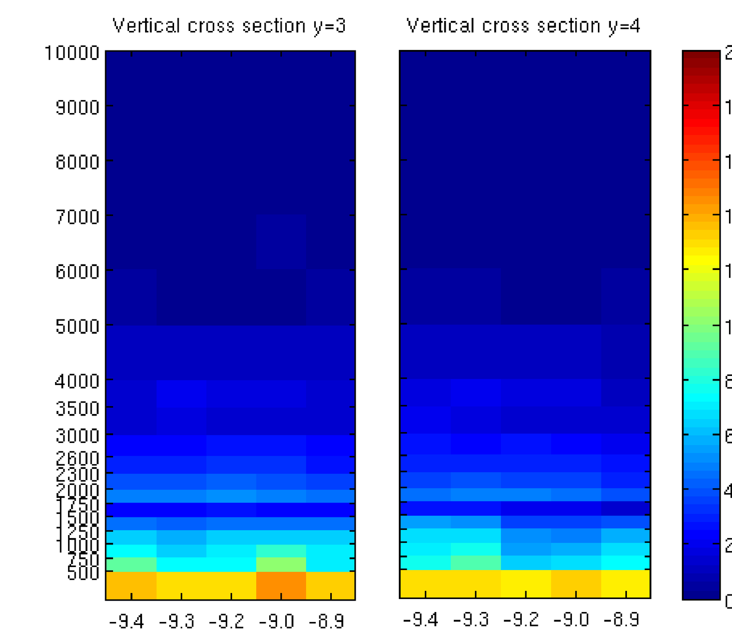

Figure 4 – West-East profiles at 12h 18/07/13.

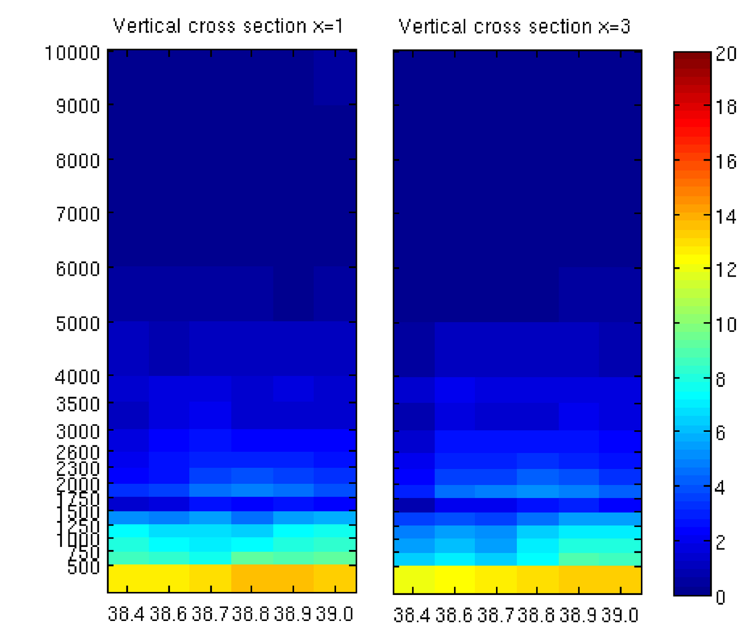

Figure 5 – South-North profiles at 12h 18/07/13.

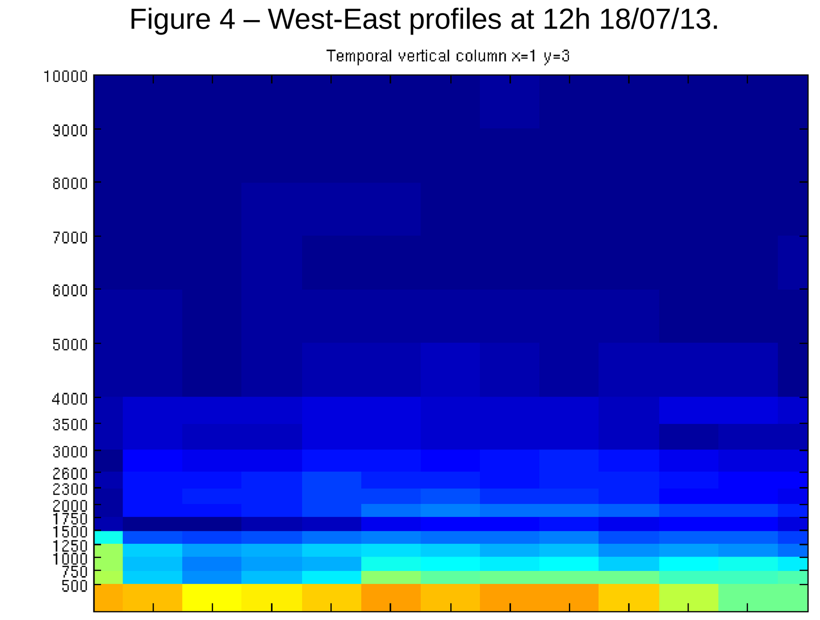

Figure 6 – Temporal solution (2h interval) (x=1,y=3 column), coast.

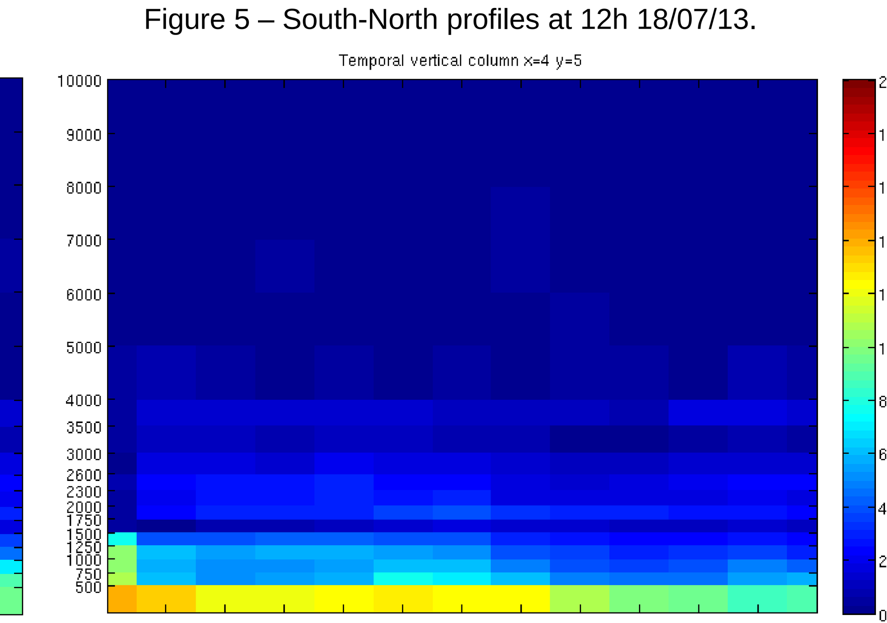

Figure 7 – Temporal solution (2h interval) (x=4,y=5 column), interior.

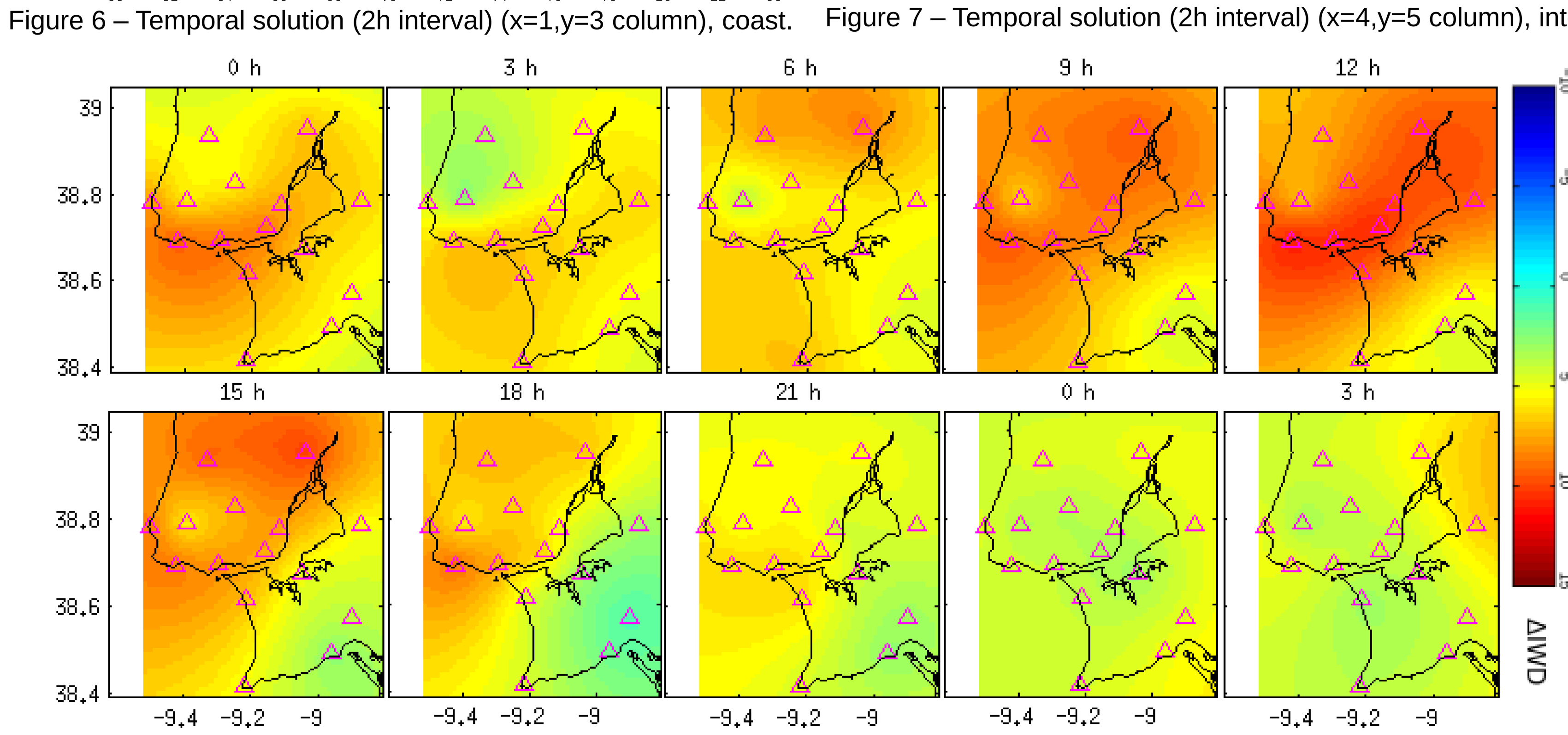

Figure 8 – 2D ΔIWV maps from 0h July 18 to 3h July 18. Reference IWV is 0h July 17 with IWV min. to max. of 8 to 11 kg/m²

2D IWV maps are calculated differentially, but obtained interpolating directly the IWV GPS results. ΔIWV maps (Fig.8) show a possible sea breeze circulation front heading eastward penetrating the estuary until noon and then receding afterwards into the ocean, likewise the tomography results in Fig.6.