



From InSAR derived relative tropospheric Slant Total Delay maps to absolute Zenith Total Delay maps: comparisons between tropospheric delay products to define a strategy for meteorological applications

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RESEARCH QUESTION

InSAR Atmospheric Phase Screen (**APS**) are observations of the **difference of the tropospheric delay** induced by the presence of **water vapor** between two epochs: the **slave** and the **master** (i.e. the reference date) [Hanssen et al, 1999].

Goal of the work is to **compare various methods** to make the InSAR measurements **absolute**, so that high resolution maps of **integrated water vapor content** can be retrieved.

In particular, we seek to find the most suitable method for **meteorological applications**, such as:

- studies of the small scale features and **water vapor inhomogeneities** in relationship with convective activity [Shoji, 2013], and
- **data assimilation experiments** in Numerical Weather Prediction (NWP) models to improve the forecast skills [Pichelli et al, 2015; Mateus et al, 2018; Lagasio et al, 2019].

This work has been submitted to *Frontiers in Earth Science* for publication as A. N. Meroni, M. Montrasio, G. Venuti, S. Barindelli, A. Mascitelli, M. Manzoni, A. Monti Guarnieri, A. Gatti, M. Lagasio, A. Parodi, E. Realini and G. Tagliaferro (2020), On the definition of the strategy to obtain absolute InSAR Zenith Total Delay maps for meteorological applications

INTRODUCTION

To observe the tropospheric **Zenith Total Delay (ZTD)**, which is the result of the reduced propagation speed of some electromagnetic waves due to the atmosphere and, in particular, to the water vapor [Bevis et al, 1992], nowadays we use:

1. Global Navigation Satellite System (**GNSS**) data, characterized by a **very high temporal resolution** (30 s) but a **relatively low spatial one** (inter-distance of roughly 30-40 km);
2. **InSAR APS** with **high spatial resolution** (order 100 m) and a **low temporal one** (the revisiting time of Sentinel 1 at midlatitudes is roughly 3-6 days)

InSAR APS can be calibrated and converted along the zenithal direction to obtain the difference of ZTD between two epochs, namely

$$\begin{aligned}\Delta ZTD(P, t, t_M) &= [L(P, t) - L(P, t_M)] \cos(\theta) + \nu_{\Delta}(P, t, t_M) \\ &= ZTD(P, t) - ZTD(P, t_M) + \nu_{\Delta}(P, t, t_M)\end{aligned}$$

where ν_{Δ} is the model error, due to the observational uncertainties and the approximations introduced by the algorithm. In this way, once the ZTD map at the master epoch is known, it is enough to sum it to the differential ZTD measured by the InSAR to get the instantaneous ZTD map at high spatial resolution.

INTRODUCTION

In the literature, various methods have been used to get absolute ZTD maps from InSAR data:

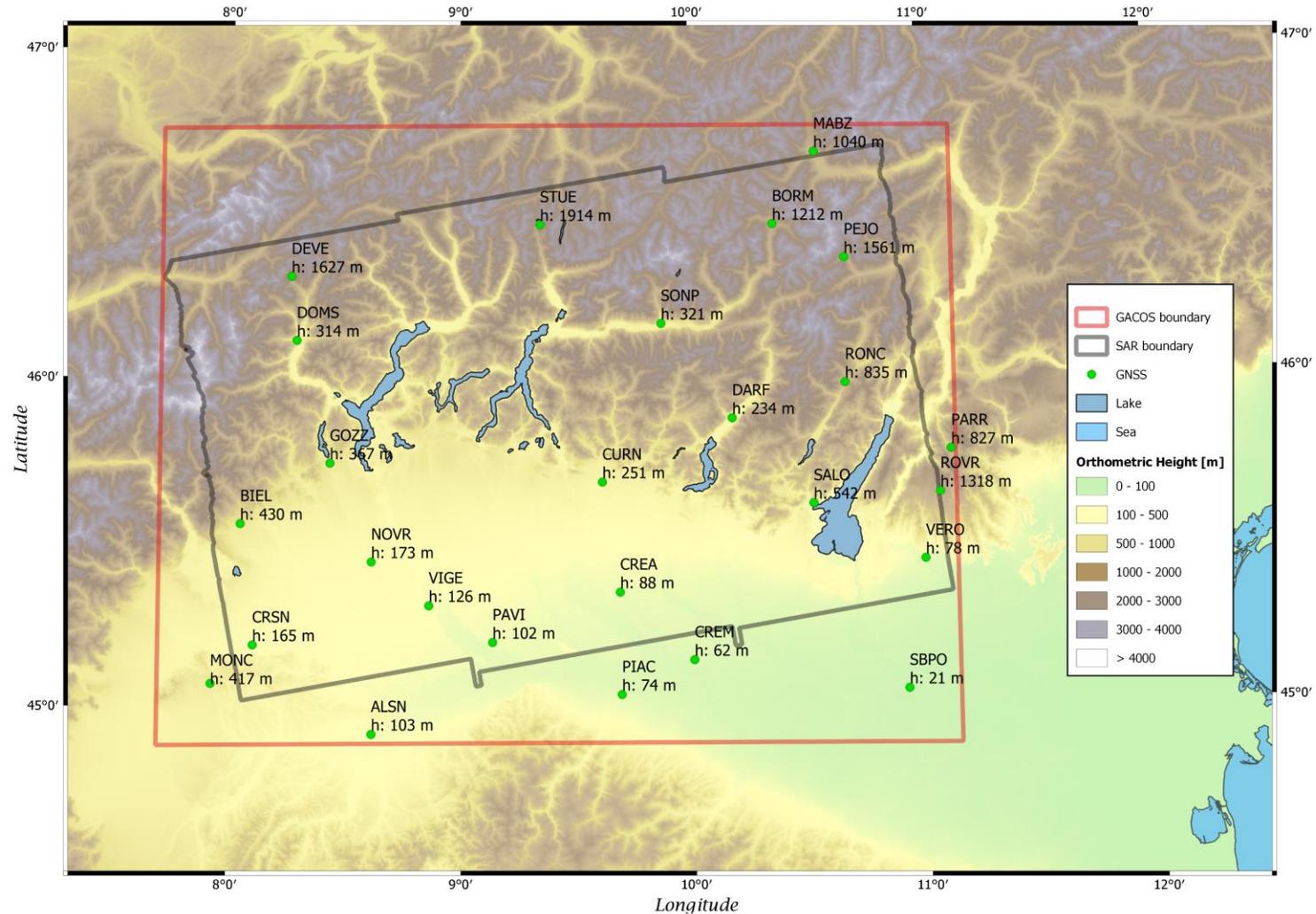
- Pichelli et al (2015) used water vapor maps obtained from the **MEdium Resolution Imaging Spectrometer (MERIS) mission**. This approach requires the simultaneous acquisition of the external data and of the SAR data, which is not always feasible;
- Mateus et al (2016) suggested the use of a **reanalysis product**, opportunely oversampled over a NWP model grid, to reach a finer spatial resolution;
- Mateus et al (2018), instead, tried to obtain a relatively fine resolution master map with a **NWP model run**;
- Lagasio et al (2019) proposed the use of ZTD maps produced by the Generic Atmospheric Correction Online Service (**GACOS**) product [Yu et al, 2018a,b]. GACOS maps are generated from the outputs of a global weather numerical model by applying an iterative method to estimate both the height-dependent hydrostatic component of the delay and the turbulent one;
- Pierdicca et al (2020) proposed to use the outputs of a **3DVAR** assimilation package, that is a way to combine the physically consistent ZTD field produced by a NWP model with the ZTD values observed by a GNSS network.

A validation with respect to InSAR and GNSS observations and a systematic comparison of the previous methods are performed. Most of the analysis focus on GACOS and 3DVAR.

DATA and METHODS

The following data sets throughout the year 2017 have been used:

1. GNSS time series obtained with the goGPS software [Realini and Reguzzoni, 2013; Herrera et al, 2016];
2. InSAR APS maps retrieved from Sentinel-1 data with SqueeSAR algorithm [Ferretti et al, 2011] at $\Delta x \approx 100$ m;
3. GACOS ZTD maps [Yu et al, 2018a, b] downloaded at $\Delta x \approx 100$ m from their website at <http://ceg-research.ncl.ac.uk/v2/gacos/>;
4. 3DVAR ZTD maps obtained with WRFDA [Barker et al, 2012], the data assimilation package of the WRF model [Skamarock et al, 2008], blending the NWP outputs at 1.5 km grid spacing with GNSS ZTD observations.



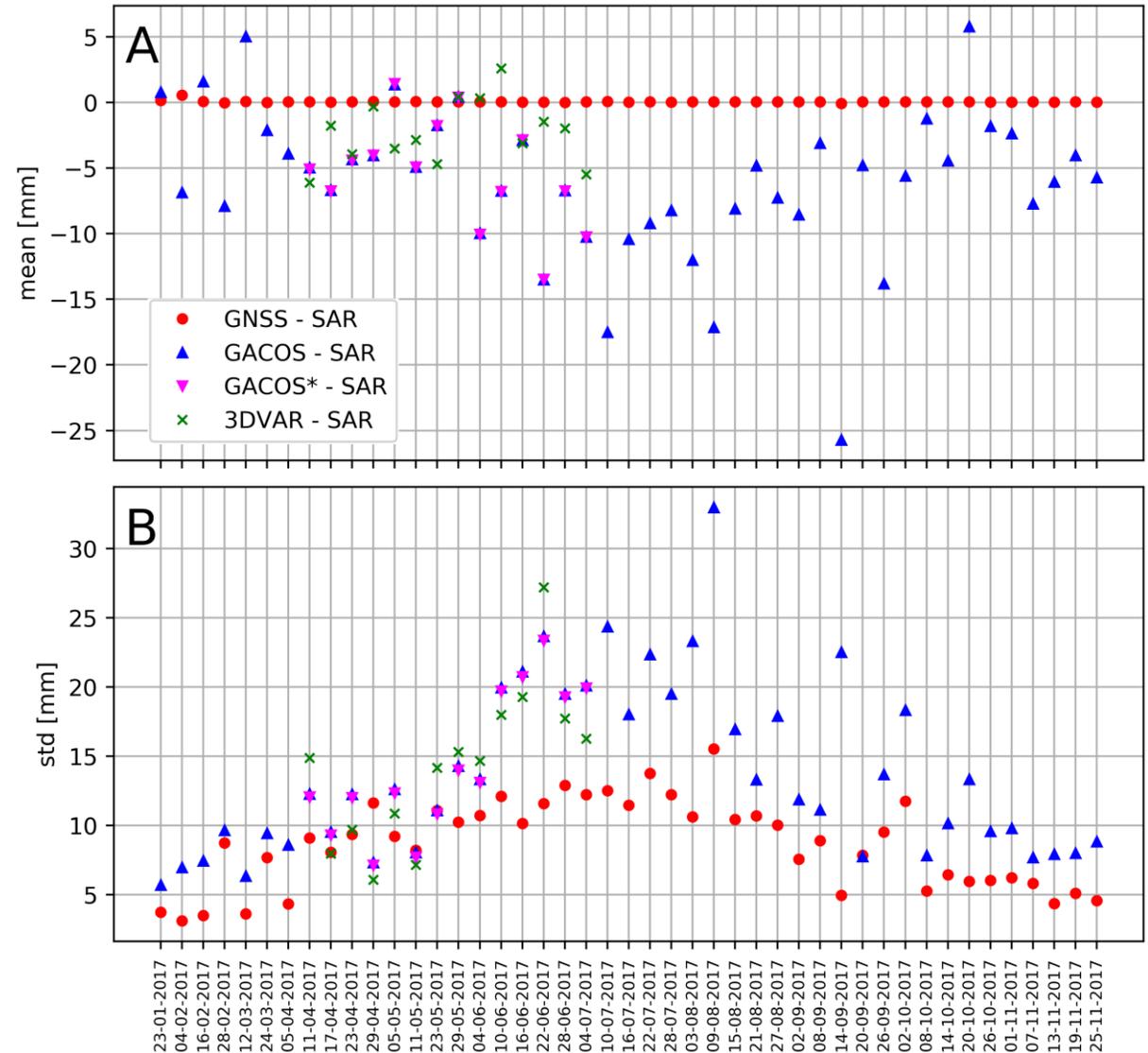
VALIDATION WITH SAR OBSERVATIONS

Spatial statistics of the difference between the differential ZTD from GNSS, GACOS and 3DVAR and the differential ZTD from InSAR are shown: mean in panel A and standard deviation in panel B.

GACOS* is obtained by undersampling GACOS maps on the 3DVAR grid to allow for a direct comparison.

GNSS and SAR have a null bias because the GNSS are used to calibrate the SAR data.

GACOS reproduces the InSAR measurements within the observational uncertainty from Oct to May and it has lower skills in summer, when there is more water vapor. 3DVAR behaves similarly.

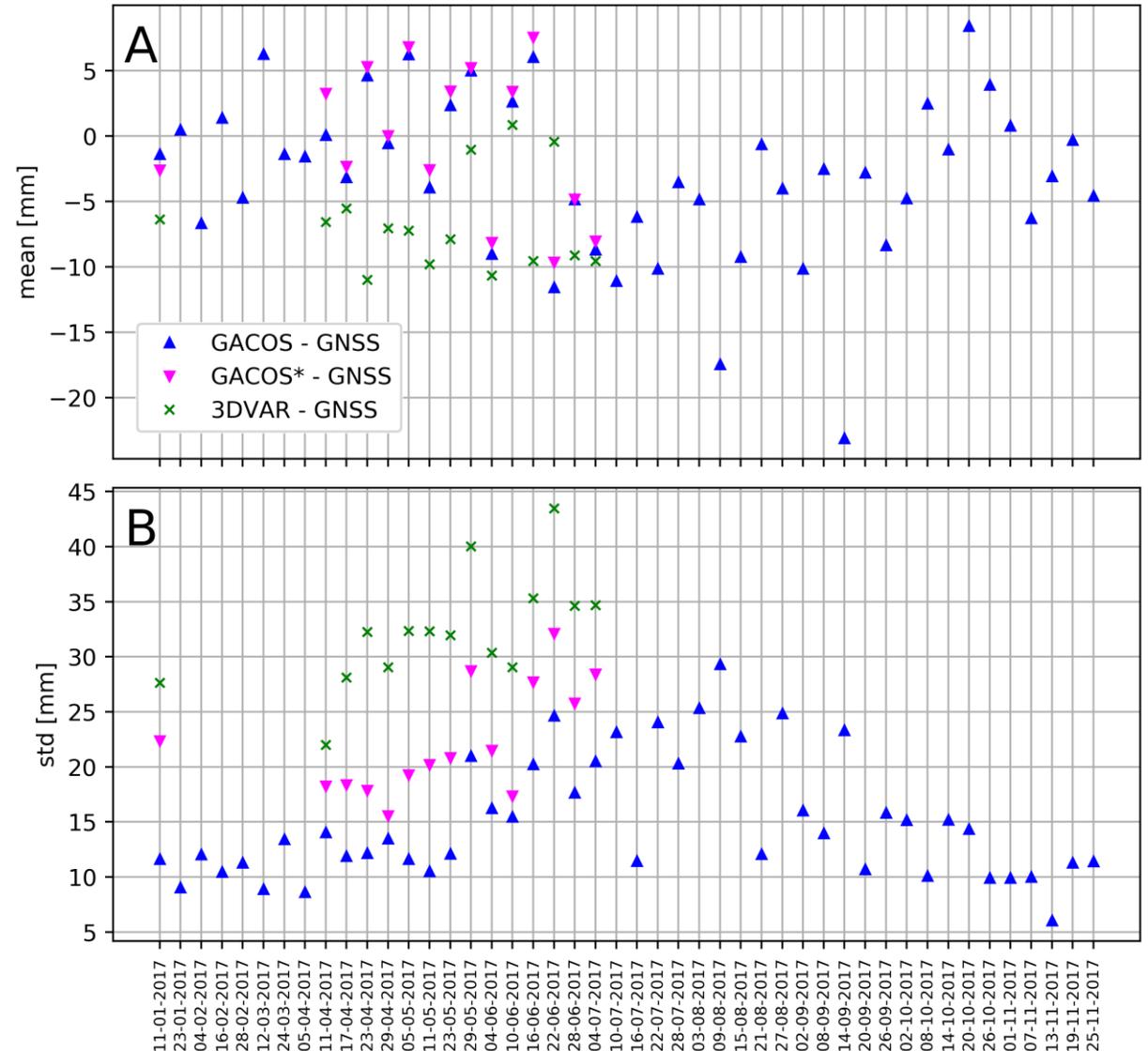
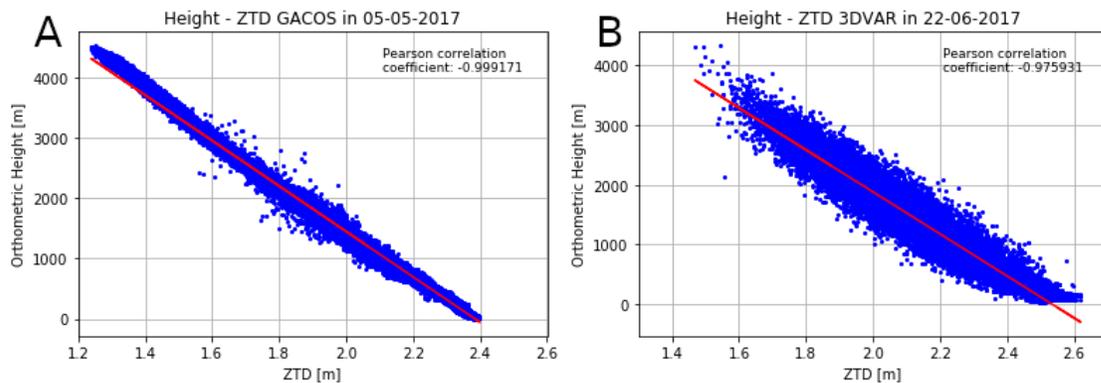


VALIDATION WITH GNSS ZTD OBSERVATIONS

Spatial statistics of the difference between the ZTD of the models (GACOS and 3DVAR) and the ZTD derived from GNSS are shown: mean in panel A and standard deviation in panel B.

Once again the statistics indicate that the models struggle to reproduce the water vapor spatial distribution in summer.

3DVAR has larger spatial variability than GACOS, which results in larger uncertainties with respect to the observations.



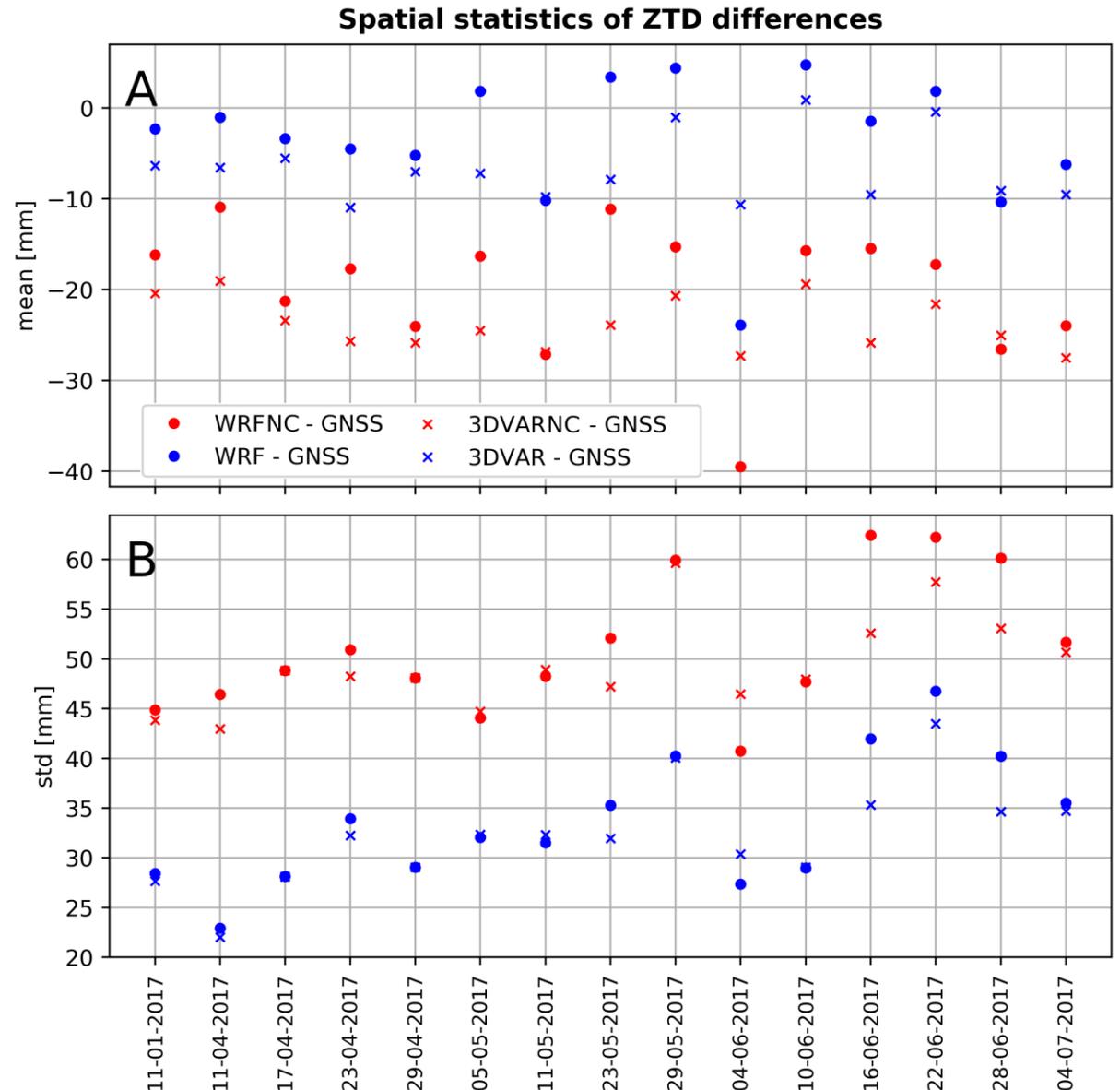
IMPORTANCE OF THE ZTD HEIGHT DEPENDENCE

The 3DVAR data set is obtained from the WRF outputs with two steps:

1. the **assimilation of GNSS observations**;
2. the **correction** of the ZTD due to the **height discrepancy** between the orography used by WRF (which is smooth) and the fine-scale Digital Elevation Model associated with the InSAR measurements.

To assess the importance of these two steps, the same spatial statistics with respect to the GNSS ZTD are also calculated for:

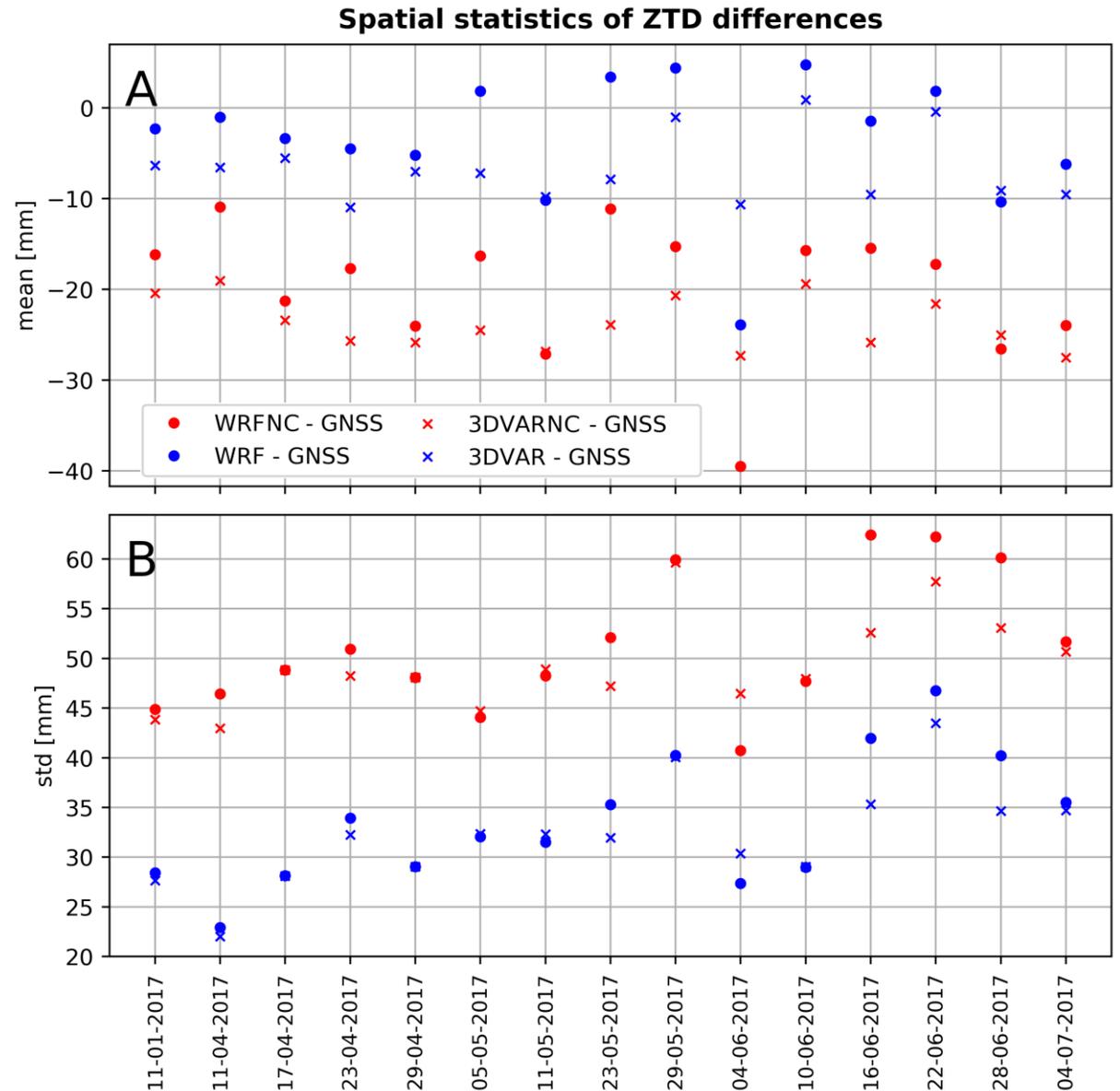
- the outputs of the WRF model before performing the GNSS assimilation and with no height correction: **'WRFNC'**;
- the WRF outputs with no data assimilation but with the height difference correction: **'WRF'**;
- the WRFDA outputs with no height correction, named **'3DVARNC'**.



IMPORTANCE OF THE ZTD HEIGHT DEPENDENCE

It is found that the height correction leads to a larger improvement than the 3DVAR.

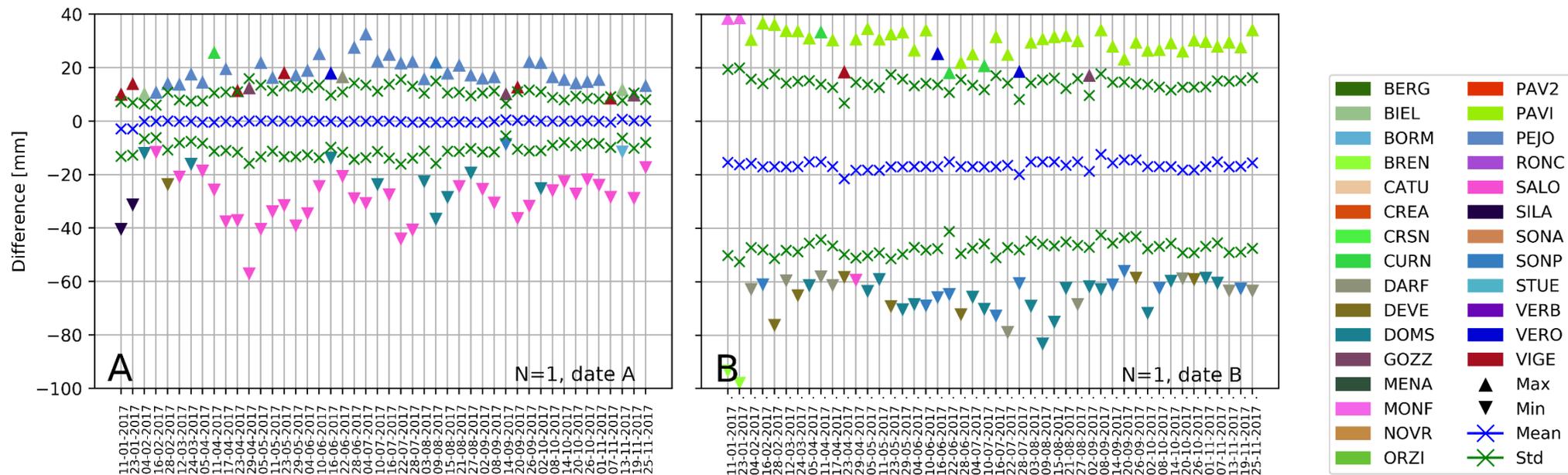
This is interpreted with the fact that the water vapor is a highly turbulent field, which is hard to describe pointwise by a NWP model. But since the ZTD has a strong dependence on the terrain elevation, the discrepancy is mainly due to the errors in the height, whose correction impacts more than the assimilation of the GNSS ZTDs.



ABSOLUTE ZTD INSAR MAPS WITH AN INSTANTANEOUS MASTER

Two dates were considered as master epochs to find the absolute ZTD InSAR maps for the entire year under study: the 5 May (date A) and the 22 June 2017 (date B). They were chosen because they differ in the amount of water vapor, with the spring date being drier than the summer one.

The spatial statistics of the difference of the absolute InSAR ZTD maps calculated using these two dates as master epochs with respect to the GNSS data show that if the master has a large discrepancy with respect to the observations, as in date B (panel B) this discrepancy propagates to all the instants. In the figure GACOS data are used.

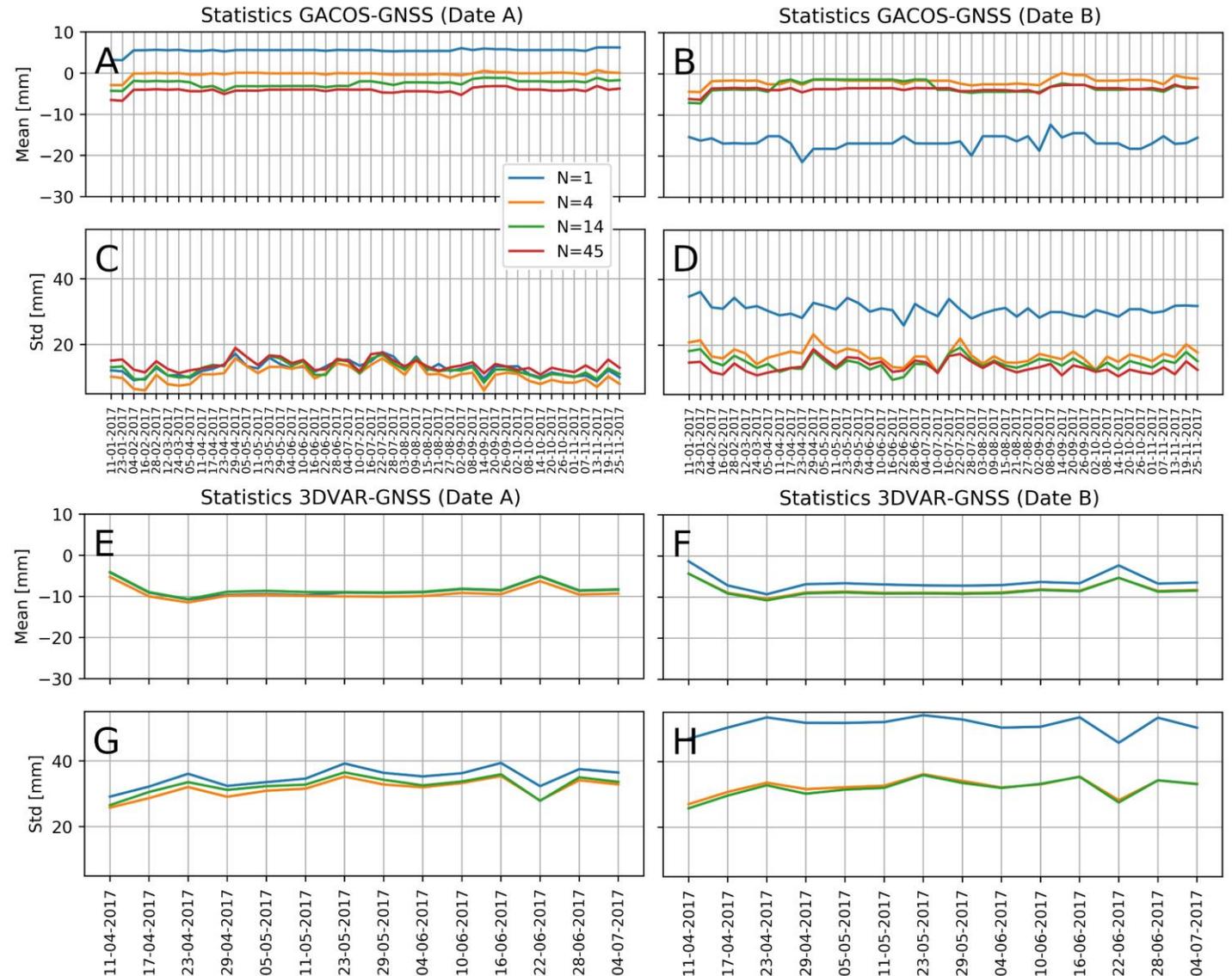


ABSOLUTE ZTD INSAR MAPS WITH TIME AVERAGED MASTER

Pichelli et al (2015) suggested that taking a time average of the external product (GACOS or 3DVAR) ZTD maps, denoted with ZTD^x , and the corresponding InSAR differential ZTDs to estimate the master map could reduce the variance of the model error, leading to a more accurate estimate. In particular they suggest to calculate the master as

$$\overline{ZTD}(P, t_M) = \frac{1}{N} \sum_{i=1}^N ZTD^x(P, t_i) - \frac{1}{N} \sum_{i=1}^N \Delta ZTD(P, t_i, t_M)$$

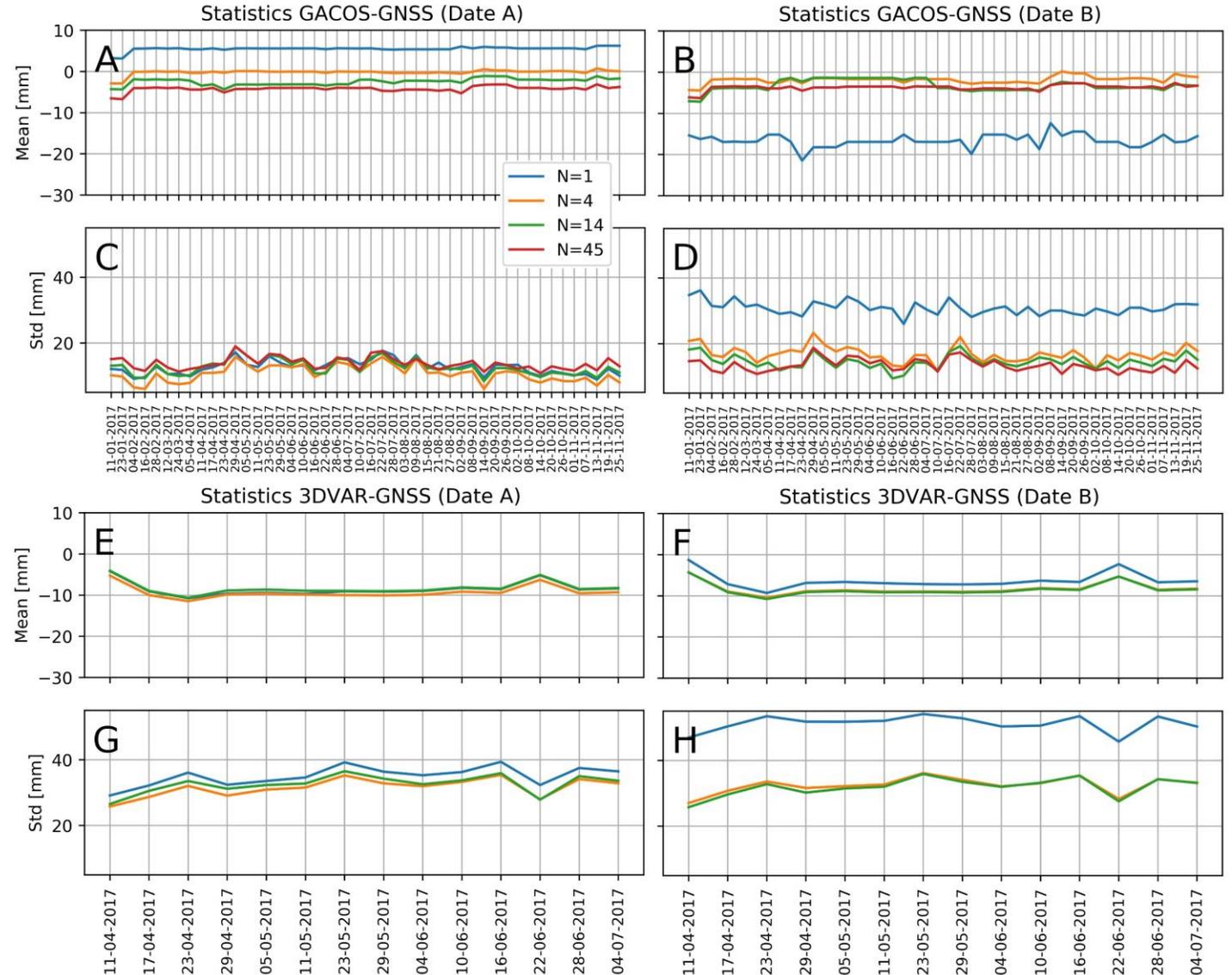
The spatial statistics of the difference with respect to the GNSS are shown for the two reference dates and for the two models as a function of N.



ABSOLUTE ZTD INSAR MAPS WITH TIME AVERAGED MASTER

It is found that if ZTD maps with a large spatial bias are included in the master estimate, the master can get worse with respect to the GNSS ZTDs. In general, it seems that time averaging over few images reduces the bias with respect to the GNSS observations.

Concerning the standard deviation by comparing the two products, GACOS and 3DVAR, it appears that GACOS performs better than 3DVAR.



CONCLUSIONS

- In terms of the NWP products, the assimilation of ZTD GNSS observations introduces a smaller variation with respect to the **correction due to the height difference** between the numerical model orography and the fine-scale InSAR DEM;
- The fine-scale spatial features of the water vapor field cannot be captured by the NWP models to a degree of accuracy higher than a **simpler iterative method**, such as the one implemented in GACOS, where the **ZTD dependence on the height** is stronger. Thus, it is not worth implementing the 3DVAR approach to derive the master map because it is more numerically demanding;
- The analysis on two different reference dates, characterized by significantly different amount of water vapor in the atmosphere, then, suggest that it is crucial to **choose a reliable master map**, meaning that it compares well with GNSS because if the master significantly differ from the observations, all the absolute ZTD maps will do so;
- **Time averaging** external ZTD maps and the corresponding APSs does not guarantee that the master is better, because if the instants included in the estimate have a large bias, the resulting master map will also be significantly different from the observations;
- Care must be taken in **summer**, where the models have more difficulty in reproducing the water vapor spatial distribution.

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