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# Water vapour monitoring over France using the low-cost GNSS collaborative network Centipede

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## Context & Objectives

Founded in 2019, the Centipede network is a collaborative permanent GNSS network that aims to offer free real-time centimeter positioning to any user. The network consists of more than 330 low-cost reference stations mainly located in France and has nearly 500 regular users. Since July 2022, the raw GNSS data acquired by the stations making up this network have been archived by the Réseau National GNSS (RénaG, <https://renag.resif.fr>) scientific network data centre.

The objective of this work is to assess the performance of the low-cost GNSS reference stations in monitoring atmospheric water vapour.

## Dataset, processing & methodology

We consider stations from three reference GNSS networks (RGP, Renag, Orphéon) surrounding Centipede stations with a radius inferior to 20 km and a difference in height inferior to 100 m. GNSS raw data are analysed with GipsyX in PPP-AR mode :

- Only GPS observations are processed, using a 30 h window centred on each day.
- The troposphere is modeled thanks to VMF1 model (a priori and mapping functions); ZTD and horizontal gradients are estimated every 5 min as random walk processes.

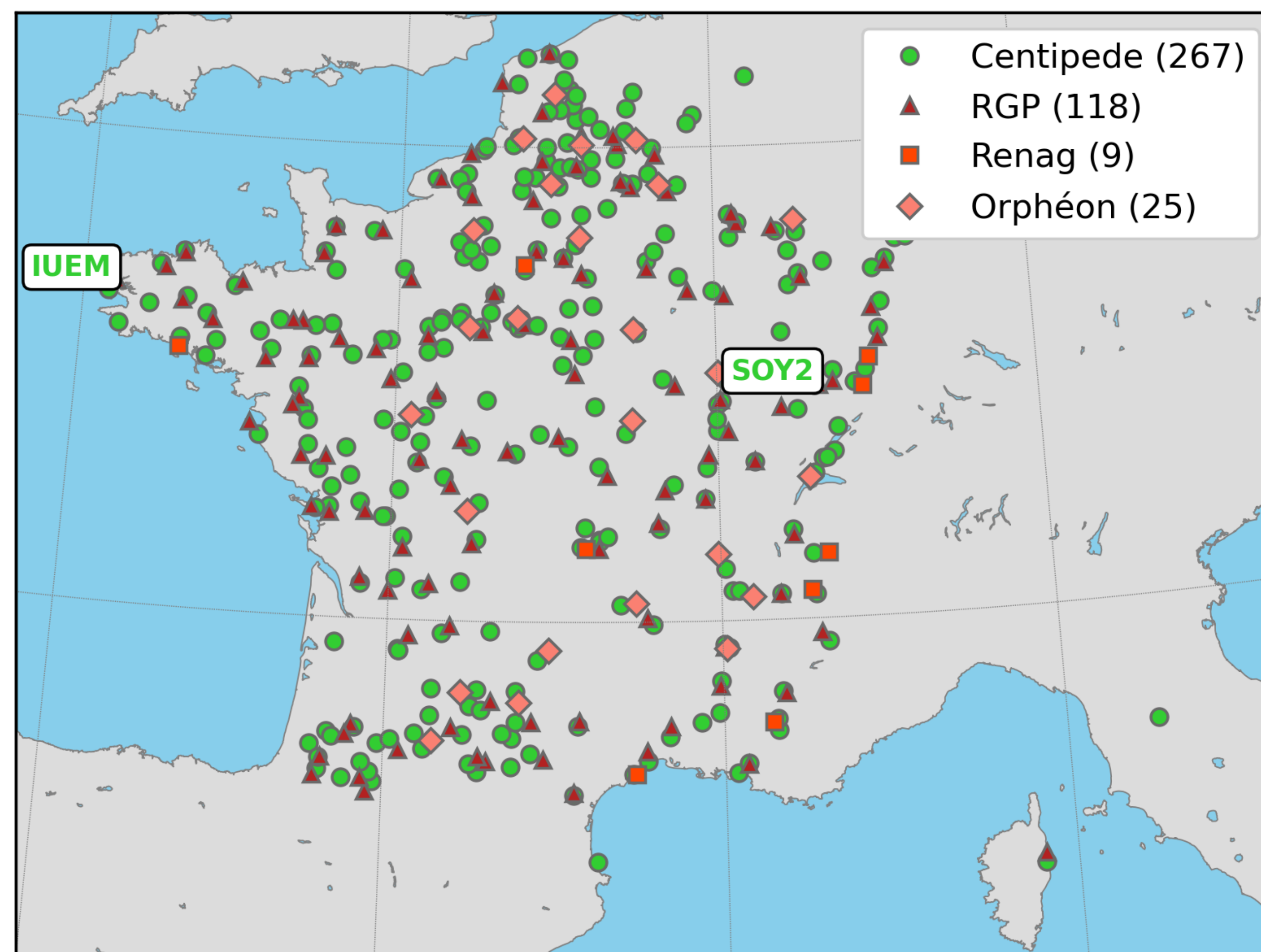


Fig. 1: Map of GNSS stations from the 4 networks and number of stations in consideration.

GNSS troposphere delays are converted into IWV using ERA5 surface pressure fields (0.25 deg×1 h) for ZHD computation. We also used TCWV product from ERA5 to extract IWV at each GNSS location. The methodology is the same as used in [Bos+21].

In the following, IWV from Centipede are compared to ERA5 and reference GNSS IWV:

- By computing bias, standard deviation and correlation coefficient for each Centipede stations (Fig. 3 & 5).
- By computing bias and standard deviation at each epoch for the whole network (Fig. 4 & 6).

## References

- [Bos+21] P. BOSSER et al. "IWV retrieval from ground GNSS receivers during NAWDEX". In : *Advances in Geosciences* 55 (2021), p. 13-22. DOI : 10.5194/adgeo-55-13-2021.
- [Din+23] Junsheng DING et al. "Characteristic differences in tropospheric delay between Nevada Geodetic Laboratory products and NWM ray-tracing". In : *GPS Solutions* 27.1 (Jan. 2023). DOI : 10.1007/s10291-022-01385-2.
- [Ste+22] K. STEPNIAK et al. "On the quality of tropospheric estimates from low-cost GNSS receiver data processing". In : *Measurement* 198 (2022), p. 111350. ISSN : 0263-2241. DOI : <https://doi.org/10.1016/j.measurement.2022.111350>.

## IWV time series

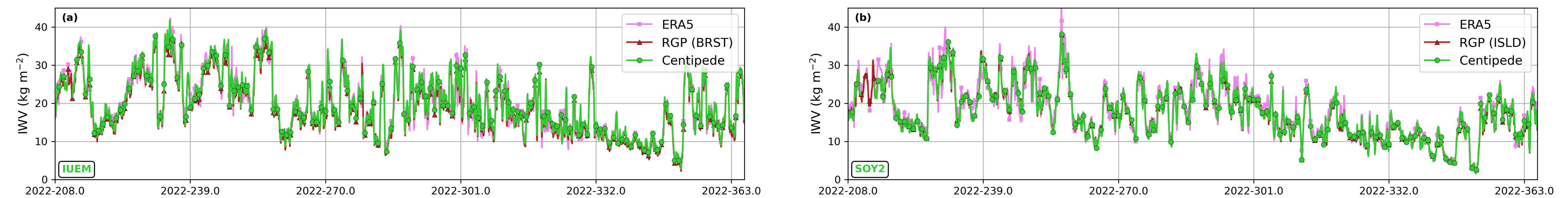


Fig. 2: Time series of IWV derived from ERA5, reference GNSS stations and Centipede station ; (a) IUEM, (b) SOY2 (see Fig. 1 for station locations)

## Comparison to ERA5 reanalysis

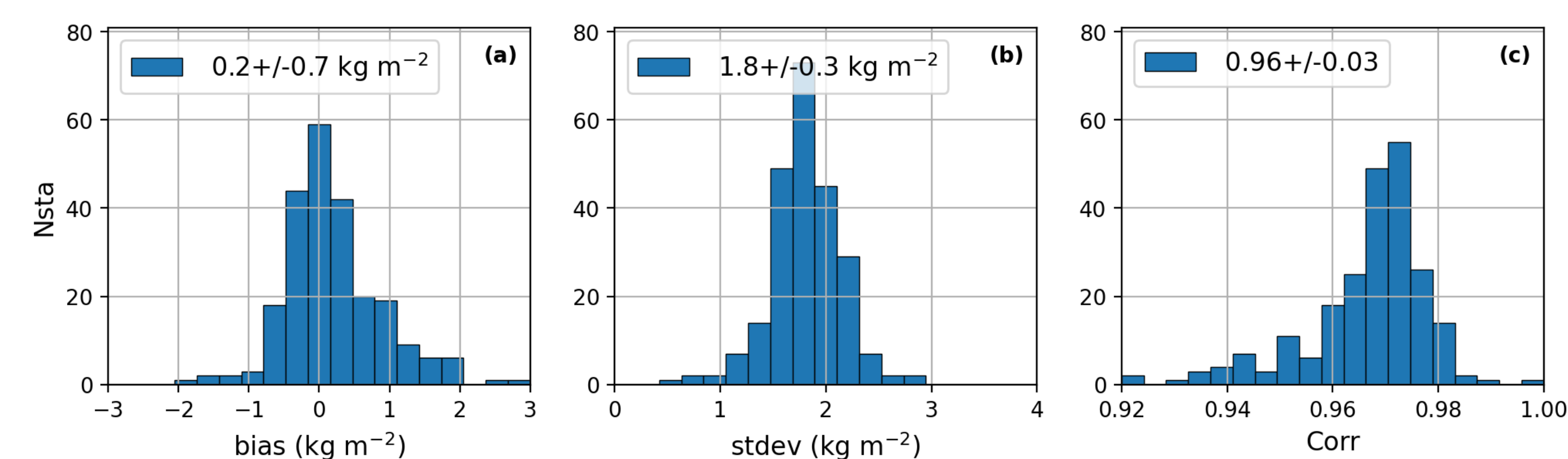


Fig. 3: Bias (a), standard-deviation of difference (b) and correlation coefficient (c)

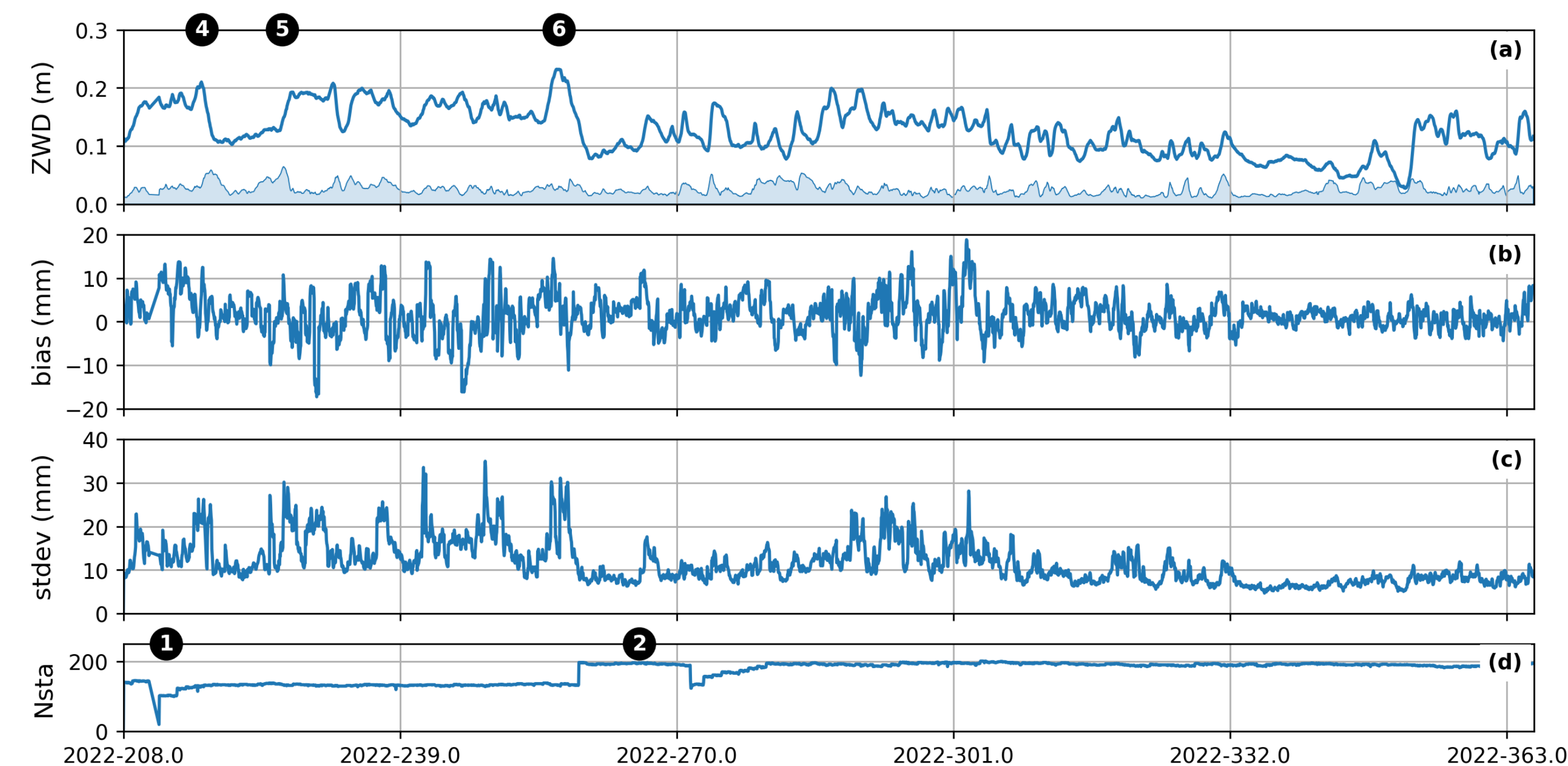


Fig. 4: Time variation of spatial mean IWV and corresponding standard-deviation (a), bias (b), standard-deviation of differences (c) and number of comparison points (d)

## Comparison to reference GNSS stations

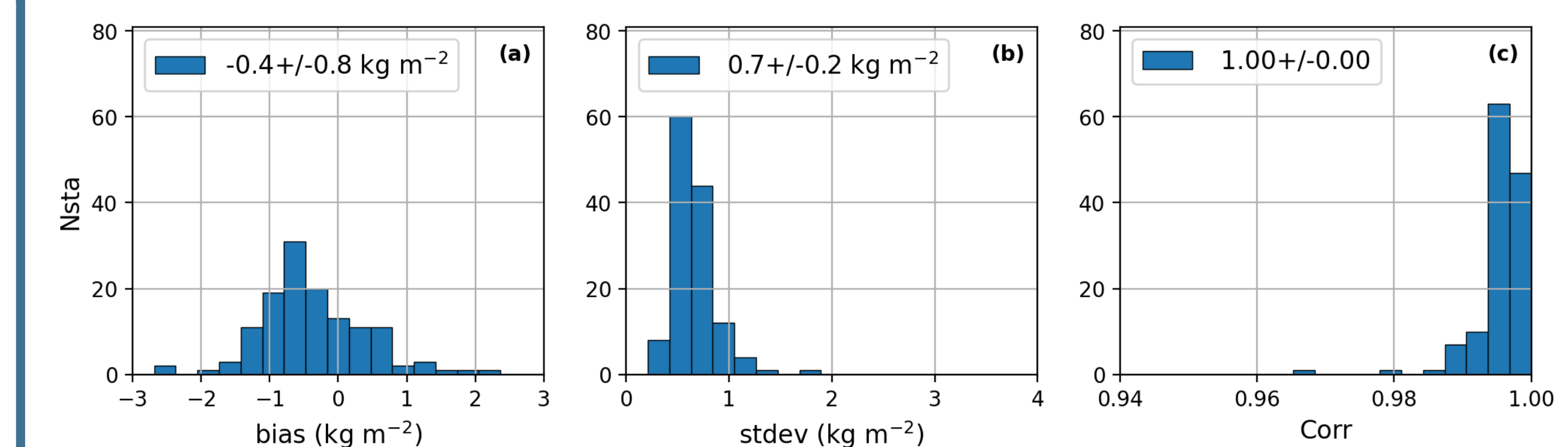


Fig. 5: Bias (a), standard-deviation of difference (b) and correlation coefficient (c)

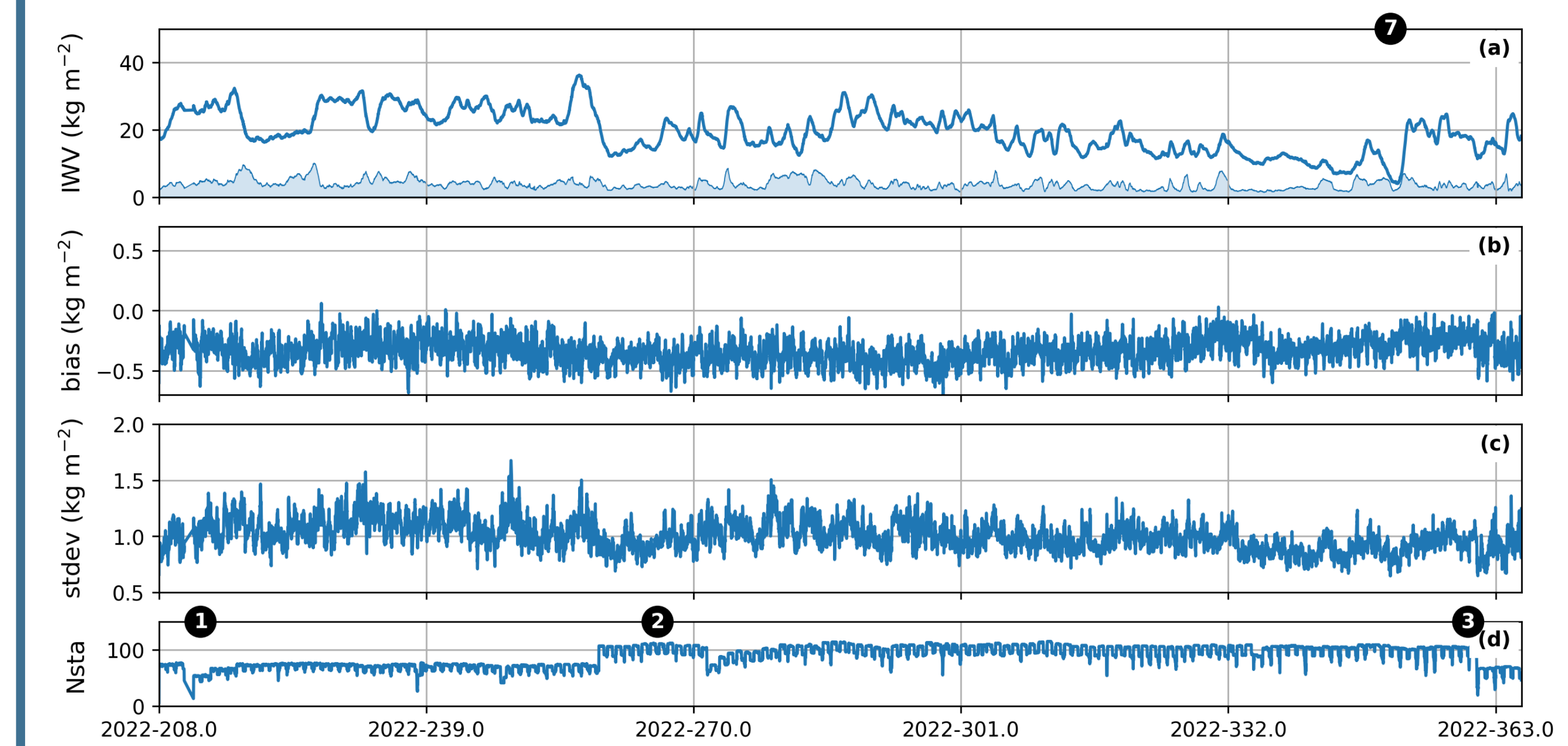


Fig. 6: Time variation of spatial mean IWV and corresponding standard-deviation (a), bias (b), standard-deviation of differences (c) and number of comparison points (d)

## Discussion

- The IWV time series are in very good agreement for a large majority of stations as presented on Fig. 2 for two stations.
- The number of Centipede stations varies over the period, due to a server outage (Fig. 4d & 6d, ①) and a change in the data retrieval mode (Fig. 4d & 6d, ②). The number of reference stations decreased at the end of the year due to a server outage of a sub-network of the RGP (Fig. 6d, ③).
- The bias with ERA5 is small and stable over time (Fig. 3a & 4b). The standard deviation of the difference shows a higher variability over time (Fig. 4c); the highest values seem to correspond to periods of high spatial variability of IWV and/or high IWV values (Fig. 4a, ④, ⑤, ⑥) and to the decreasing number of Centipede stations available. These statistics of the differences with ERA5 are in line with the results obtained in previous studies using geodetic stations [Bos+21; Din+23].
- The histogram of differences (Fig. 5a) calculated by station shows a small but statistically significant bias (Centipede wetter than reference networks). This bias is stable over time (Fig. 6b) and may be linked to a default in the calibration of low-cost antennas as suggested by [Ste+22]; as the IWV decreases, a slight reduction in this bias is observed (Fig. 6a, ⑦). The standard deviation of the differences is small and stable over time (Fig. 5b & 6c); the correlation coefficients are close to 1, with 90% of the stations above 0.99 (Fig. 5c). The largest differences are related to poor configurations of observations of some Centipede stations (not shown here).

**These results confirm the high potential of low-cost GNSS networks.** The development of such network is a real opportunity for geoscience applications, particularly in poorly instrumented areas. In such areas, their contribution could be especially significant for meteorology or climatology for which the monitoring of water vapour by GNSS is widely used.