SPECIAL PROJECT PROGRESS REPORT

All the following mandatory information needs to be provided. The length should *reflect the complexity and duration* of the project.

Reporting year	2022
Project Title:	AWARE - Assimilating Water vapor during African heavy Rainfall Events
Computer Project Account:	spitmero
Principal Investigator(s):	dr. Agostino N. Meroni
Affiliation:	University of Milano-Bicocca and CIMA Research Foundation
Name of ECMWF scientist(s) collaborating to the project (if applicable)	N/A
Start date of the project:	19th March 2021
Expected end date:	31st December 2022

Computer resources allocated/used for the current year and the previous one
(if applicable)
Please answer for all project resources

		Previous year		Current year	
		Allocated	Used	Allocated	Used
High Performance Computing Facility	(units)	850000	320000	100000	210000
Data storage capacity	(Gbytes)	5000	0	5000	0

Summary of project objectives (10 lines max)

Using the state-of-the-art numerical weather prediction model WRF (Weather Research and Forecasting), at cloud resolving grid spacing, and the 3DVAR code provided in the WRF Data Assimilation tool, a set of simulations is outlined to investigate the effects of changing the spatial and the temporal resolution of the observational data in the assimilation experiments of a heavy rainfall experiment in South Africa.

The numerical setup and the heavy rainfall experiments are described in Meroni et al., *Q. J. R. Meteorol. Soc.* (2021). The observational data are ZTD (Zenith Total Delay) products, that contain information on the columnar water vapour, coming from GNSS (Global Navigation Satellite System) receivers and SAR (Synthetic Aperture Radar) satellite measurements. Examples of such products are described in Lagasio et al., *Remote Sens.* (2019).

Summary of problems encountered (10 lines max)

Some technical issues in the Data Assimilation procedure have emerged during the numerical experiments. In particular, the state-of-the-art numerical setup used to assimilate ZTD observations in other regions of the world did not produce the expected outcomes in South Africa, as described in the ‘Summary of the results’ section.

Summary of plans for the continuation of the project (10 lines max)

As the experiments at different spatio-temporal resolution did not produce the expected improvements of the heavy rainfall forecast, some new experiments where PWV (Precipitable Water Vapor) is assimilated instead of ZTD are foreseen. In fact, as described below, the WRF model treats the assimilation of PWV and ZTD differently.

List of publications/reports from the project with complete references

No publication has been produced so far. A peer-review publication is surely foreseen with the results of the experiments to be performed. The tentative title is: “Water vapour assimilation experiments for heavy rainfall simulations in South Africa: sensitivity to the data spatio-temporal resolution”.

Summary of results

If submitted **during the first project year**, please summarise the results achieved during the period from the project start to June of the current year. A few paragraphs might be sufficient. If submitted **during the second project year**, this summary should be more detailed and cover the period from the project start. The length, at most 8 pages, should reflect the complexity of the project. Alternatively, it could be replaced by a short summary plus an existing scientific report on the project attached to this document. If submitted **during the third project year**, please summarise the results achieved during the period from July of the previous year to June of the current year. A few paragraphs might be sufficient.

The two first assimilation experiments are performed using the background covariance matrix option CV5. In the first one, GNSS ZTD observations are assimilated every 12 hours over the three numerical domains. In the second experiment, SAR ZTD measurements are assimilated at 1700UTC on the 21st of March 2018 at 13.5 km grid spacing, in the innermost domain only. These experiments are named GNSS 12h and InSAR 13.5km CV5, respectively.

The comparison with ground station observations, shown in figure 1 in terms of 2-m temperature and 2-m water vapour mixing ratio biases, indicates that the assimilation procedure is excessively drying and cooling the atmosphere.

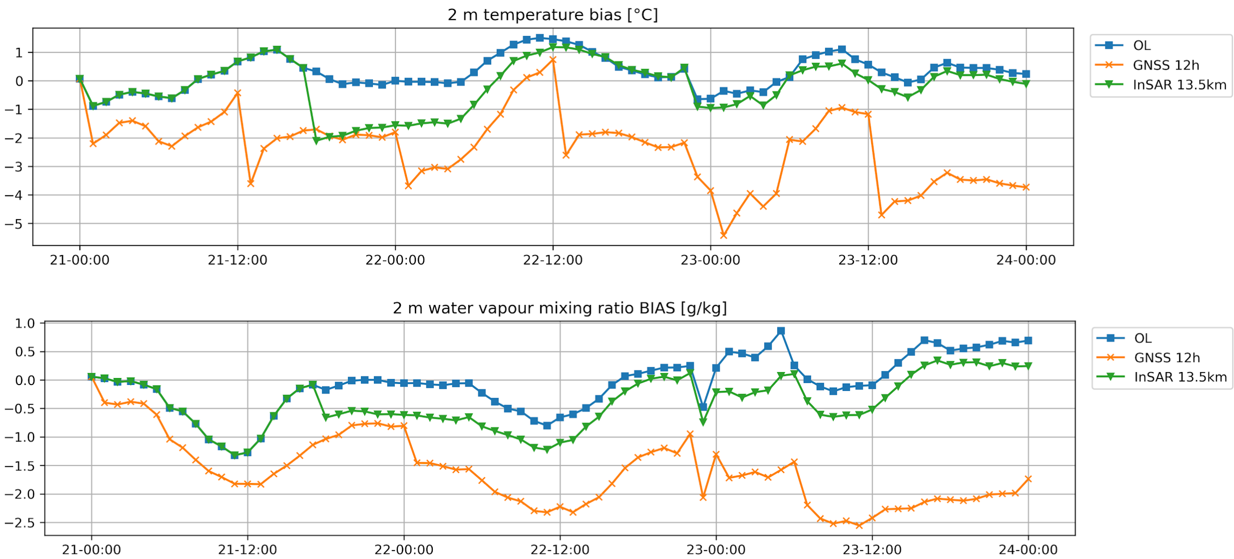

Figure 1: (a) 2 m temperature bias and (b) 2 m water vapour mixing ratio of the OL (Open Loop, no assimilation), GNSS 12 and InSAR 13.5km CV5 experiments. The reference observations are the meteorological ground stations operated by SAWS (South African Weather Service), which is acknowledged for providing the data. There are roughly 200 stations, except for in a few hours around 0000 UTC 23rd March 2018, when there are between 10 to 20 stations available.

The excessive drying and cooling of the atmosphere at the instant of the assimilation is observed to happen over the entire numerical domain, even if the ZTD map is assimilated only over a small fraction of the domain, as in the InSAR 13.5km experiment. Figure 2 shows the instantaneous difference between the modelled and observed 2-m water vapour mixing ratio before the assimilation (panel a) and right after the assimilation (panel b), where a visible overall drying appears. Figure 3 shows the scatterplot of the 2-m temperature (modelled VS observed), with the colours indicating the elevation of the stations, before (panel a) and after (panel b) the assimilation.

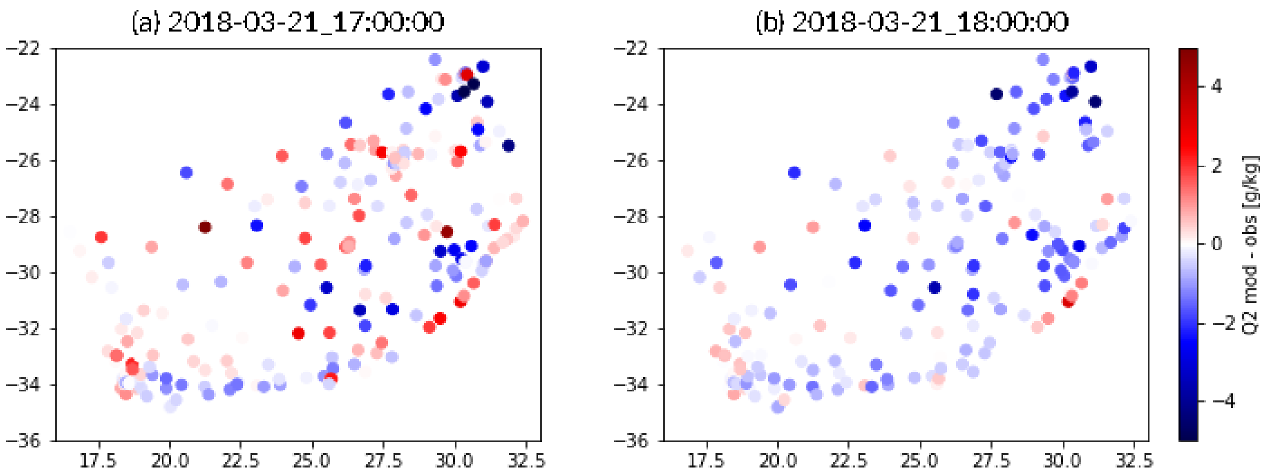

Figure 2: Difference between the modelled and the observed 2-m water vapour mixing ratio before (a) and after (b) the assimilation of the InSAR ZTD map at 13.5 km grid spacing.

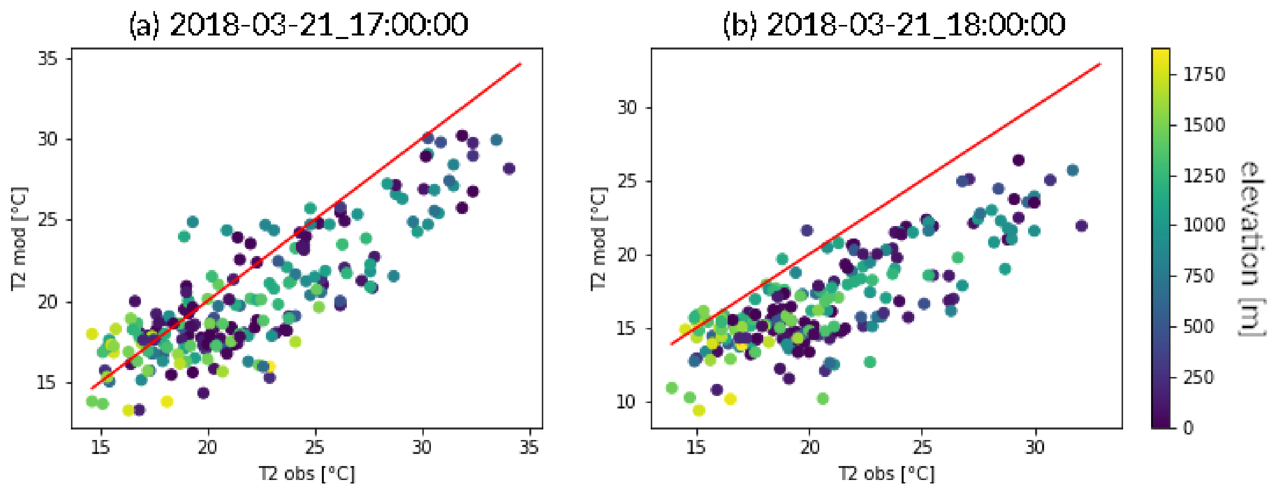

Figure 3: Scatterplot of the modelled and the observed 2-m temperature before (a) and after (b) the assimilation of the InSAR ZTD map at 13.5 km grid spacing. The colours denote the weather station elevation above sea level.

To investigate whether this behaviour persists with other setup of the assimilation procedure of the InSAR data, in addition to the InSAR 13.5 km CV5 experiment, the following simulations have been performed:

- InSAR 4.5 km, CV5
- InSAR 13.5 km, CV7
- InSAR 4.5 km, CV7

It is found that neither the use of a higher resolution ZTD map (at 4.5 km instead of 13.5 km), nor the use of a different choice of the control variables (CV7 instead of CV5) affect the validation: the drying and cooling bias at the instant of assimilation persists (figure 4a). RMSE and correlation coefficient also do not improve (figure 4b-c).

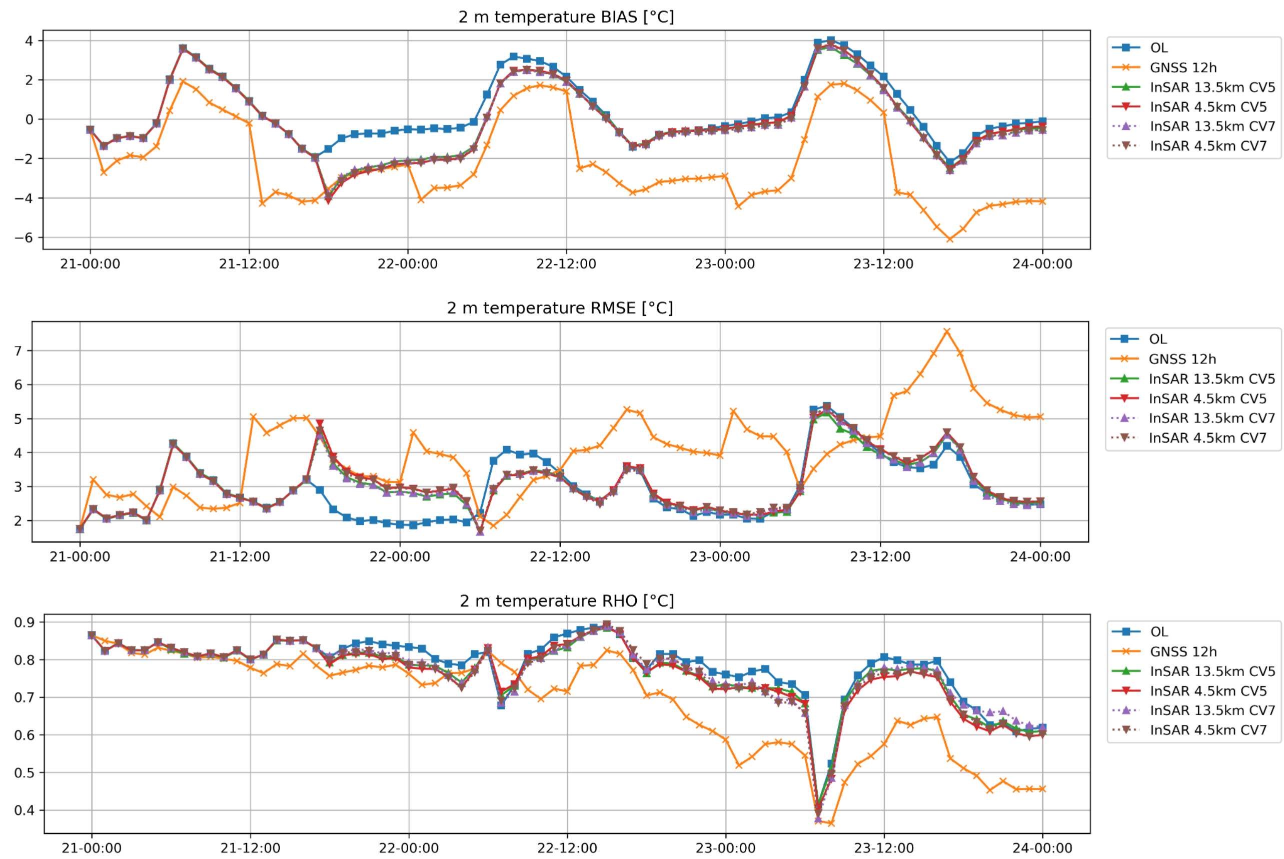

Figure 4: 2-m temperature bias (a), RMSE (b) and correlation coefficient (c) for various InSAR experiments, as introduced in the main text.

In terms of GNSS experiments, instead, both the time frequency of the assimilation (every 6h or every 12 h) and the number of numerical domains in which DA is performed (all three domains or the innermost, only) have been changed. In addition to the GNSS 12h experiment, the following have been run:

- GNSS 12h, d03 only;
- GNSS 6h;
- GNSS 6h, d03 only,

where 'd03 only' indicates that the ZTD observations have been assimilated in the innermost domain only, and not in all three domains. Also in this case, none of the two parameters tested resulted in significant improvements in the forecast (not shown).

These results suggest that it is not the spatio-temporal resolution of the assimilated data that affects the validation of the forecast with respect to the observations, but that there might be something wrong with the kind of observation assimilated. We propose two possible paths to tackle this issue. Figure 5 shows a vertical-meridional section of the instantaneous difference of the potential temperature field at the instant of the assimilation in the InSAR 13.5km, CV5 experiment. The section is taken at 30°E, so that it crosses the area where the InSAR data are assimilated. It appears that a very strong local temperature correction is imposed to the model, which might explain the forecast behaviour and its large observed bias. In fact, typical corrections in the temperature field are fractions of a degree Kelvin. What is found in all the simulations presented in this work is that such strong instantaneous variations of the temperature field bring the dynamics on another trajectory producing significant variations with respect to the observations. One of the options to mitigate this issue is to simultaneously assimilate ZTD and temperature recordings from the weather ground stations, which will be the object of a future set of simulations.

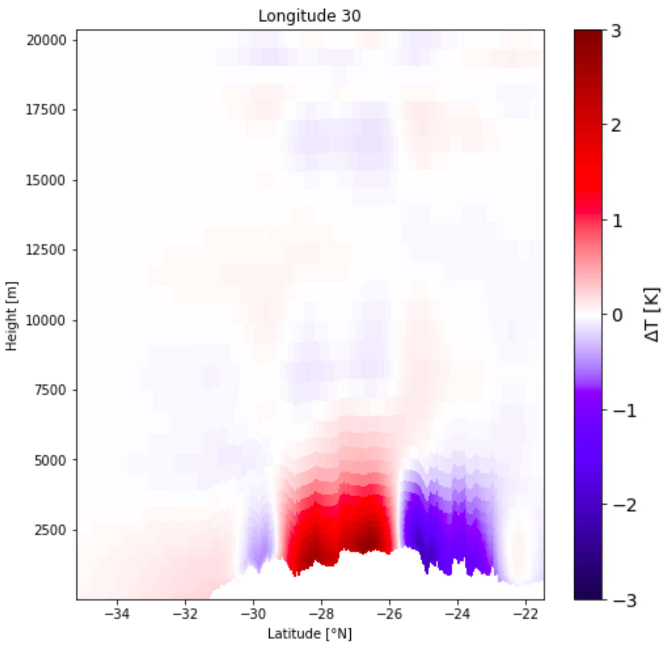

Figure 5: Vertical section of the potential temperature difference at the instant of the assimilation in the InSAR 13.5km CV5 experiment, taken at 30°E.

Another interesting aspect that will be studied with the remaining computational resources concerns the assimilation of the GNSS observations in terms of PWV instead of ZTD. In fact, from GNSS data, by exploiting external information of surface pressure and temperature, time series of PWV can be retrieved. The interesting aspect is that WRF only changes the temperature field when assimilating ZTD (figure 6), whereas it modifies both the temperature and the water vapour mixing ratio when assimilating PWV (M. Lagasio and V. Mazzarella, personal communication). We think that this approach (already well referenced in the literature, as in Mateus et al., *Journal of*

Geophysical Research: Atmospheres, 2018 and in Miranda et al., *Geophysical Research Letters*, 2019) might improve the forecast, as it modifies the atmospheric state in a more thermodynamically consistent way.

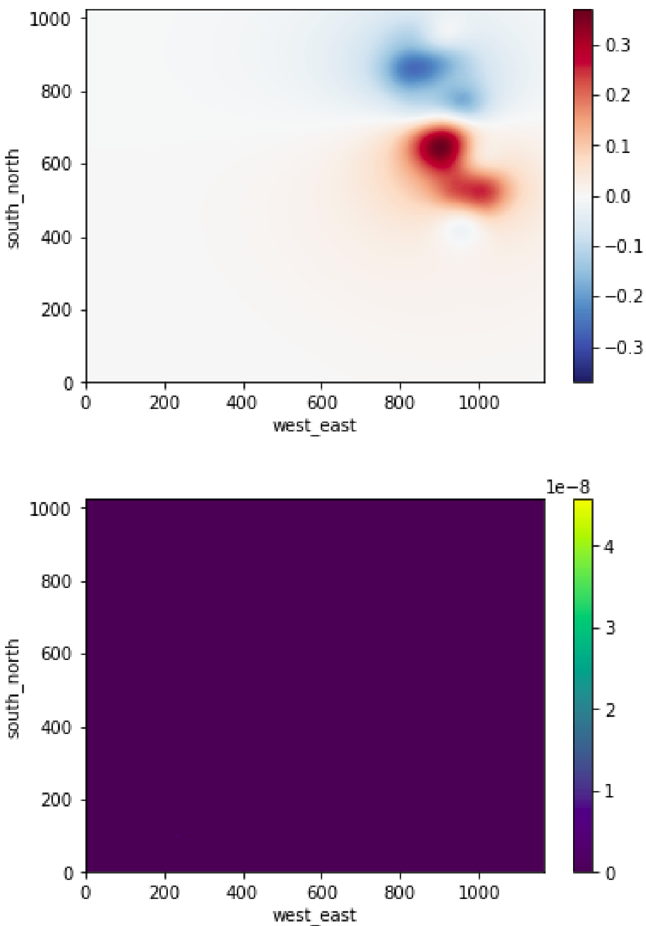

Figure 6: Difference of the vertical integral of the potential temperature (a) and of the water vapour mixing ratio (b) at the instant of the assimilation in the InSAR 13.5km CV5 experiment.