SPECIAL PROJECT FINAL REPORT

All the following mandatory information needs to be provided.

Project Title:	AWARE - Assimilating Water vapor during African heavy Rainfall Events
Computer Project Account:	spitmero
Start Year - End Year :	2021 - 2022
Principal Investigator(s)	dr. Agostino N. Meroni
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Other Researchers (Name/Affiliation):	Dr. Martina Lagasio (CIMA Research Foundation) Dr. Vincenzo Mazzarella (CIMA Research Foundation) Dr. Massimo Milelli (CIMA Research Foundation) Dr. Antonio Parodi (CIMA Research Foundation)

The following should cover the entire project duration.

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

(If you encountered any problems of a more technical nature, please describe them here.)

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.

Experience with the Special Project framework

(Please let us know about your experience with administrative aspects like the application procedure, progress reporting etc.)

I can say that the experience was very positive. The application procedure was smooth and I find it useful to have the annual progress reporting, as it helps keep the work organised. It was not clear to me that the remaining computing resources allocated for a given could not be available in the next year, but the remote assistance was very clear and timely.

Summary of results

(This section should comprise up to 10 pages, reflecting the complexity and duration of the project, and can be replaced by a short summary plus an existing scientific report on the project.)

Numerical Weather Prediction (NWP) models are a crucial tool to forecast heavy rainfall events. Their successful use at high resolution is known to depend on a correct choice of the numerical parameterizations. This is generally done based on some sensitivity experiments in the region of interest (e.g., Meroni et al., 2021, for heavy precipitation events in the southern Africa region). In the literature, there exist various examples of sensitivity studies for different regions of the world and for different atmospheric phenomena. The Weather Research and Forecasting (WRF) model is a state-of-the-art atmospheric model that has both research and operational applications. Concerning the southern Africa region, Crétat et al. (2012) test the ability of the WRF model in reproducing the South African summer rainfall with different convective, PBL (Planetary Boundary Layer) and microphysical schemes. Somses et al. (2020) study the role of explicit convection on a heavy rainfall event in Namibia.

Data assimilation is a robust technique to improve the realism of NWP simulations by exploiting the information coming from different kinds of observational data. In particular, observational products of the atmospheric water vapour content have been shown to improve the simulation of heavy rainfall events (e.g., Lagasio et al., 2019). Typically, people assimilate ZTD (Zenith Tropospheric Delay) observations coming from GNSS, Global Navigation Satellite System, and SAR, Synthetic Aperture Radar data. These data differ because GNSS observations come with a very high temporal resolution (of the order of a second) from a single station, whereas SAR data come with a very high spatial resolution (of the order of 100 m grid spacing) every few days. Goal of the present project is to evaluate the impact of ZTD on the simulation of a heavy rainfall event in South Africa as a function of different spatio-temporal resolution of the observational data.

A set of different assimilation experiments of the heavy rainfall event that occurred in South Africa in March 2018 (Meroni et al., 2021) is performed, also with different background covariance matrices (that contain information about the spatial and temporal spread of the corrections introduced by the assimilation). 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 indicates that the assimilation procedure is excessively drying and cooling the atmosphere. 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 1 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 2 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.

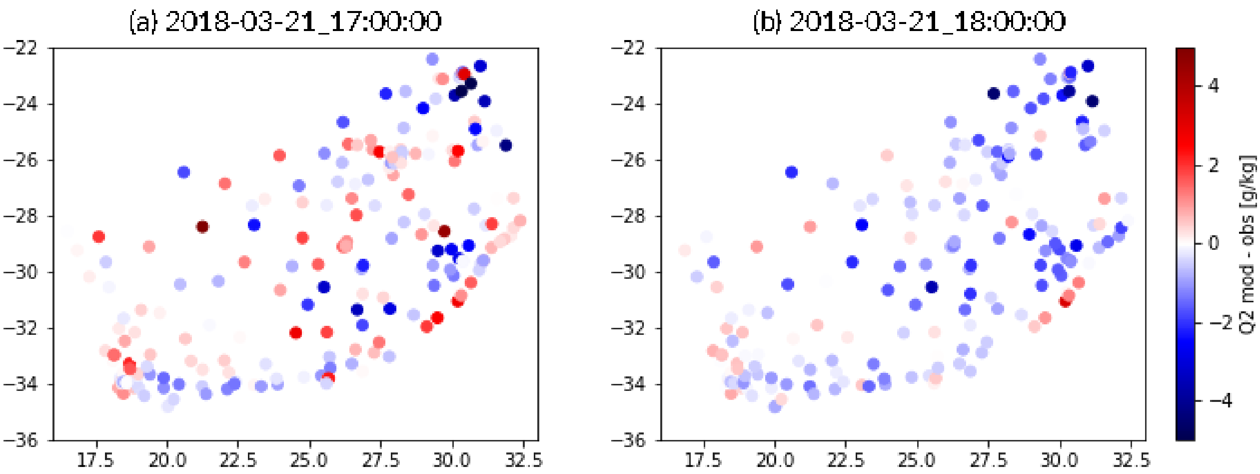

Figure 1: Difference between the modelled and the observed 2-m water vapour mixing ratio before (a) and after (b) the assimilation of the InSAR ZTD map at 13.5 km grid spacing.

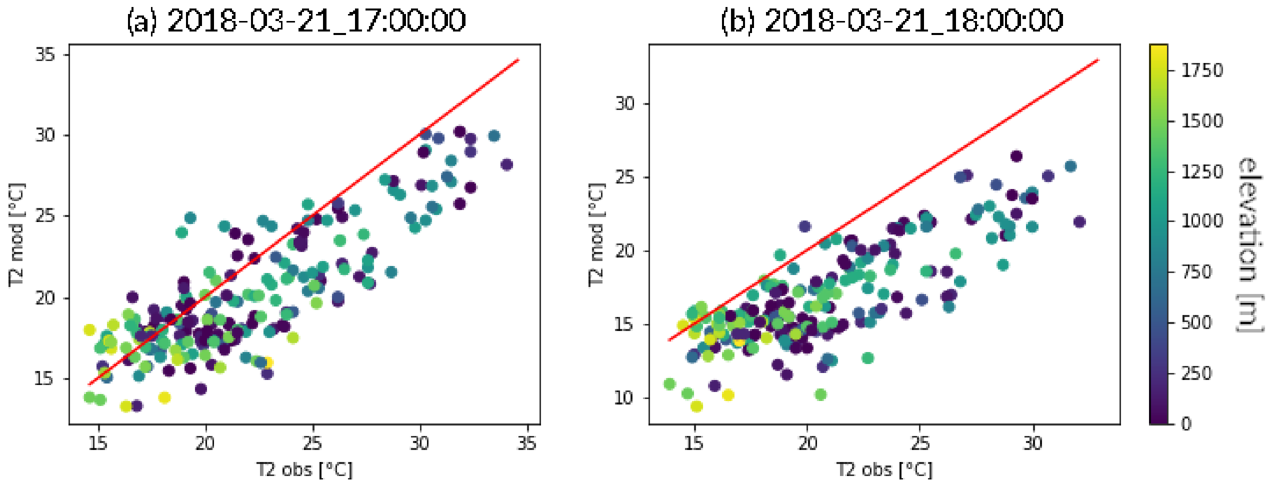

Figure 2: Scatterplot of the modelled and the observed 2-m temperature before (a) and after (b) the assimilation of the InSAR ZTD map at 13.5 km grid spacing. The colours denote the weather station elevation above sea level.

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.

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.

These results suggest that it is not the spatio-temporal resolution of the assimilated data that modifies the quality of the forecast (which, in any case, is already very high in the Open Loop - OL - simulation, where no data is assimilated), but that there might be something wrong with the kind of observation assimilated. We tested, thus, a different setup where the assimilation of the GNSS observations is done in terms of PWV (Precipitable Water Vapour) 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 the WRF model only changes the temperature field when assimilating ZTD (figure 3), whereas it modifies both the temperature and the water vapour mixing ratio when assimilating PWV (not shown). We think that this approach (already well referenced in the literature, as in Mateus et al., 2018 and in Miranda et al., 2019) might improve the forecast, as it modifies the atmospheric state in a more thermodynamically consistent way.

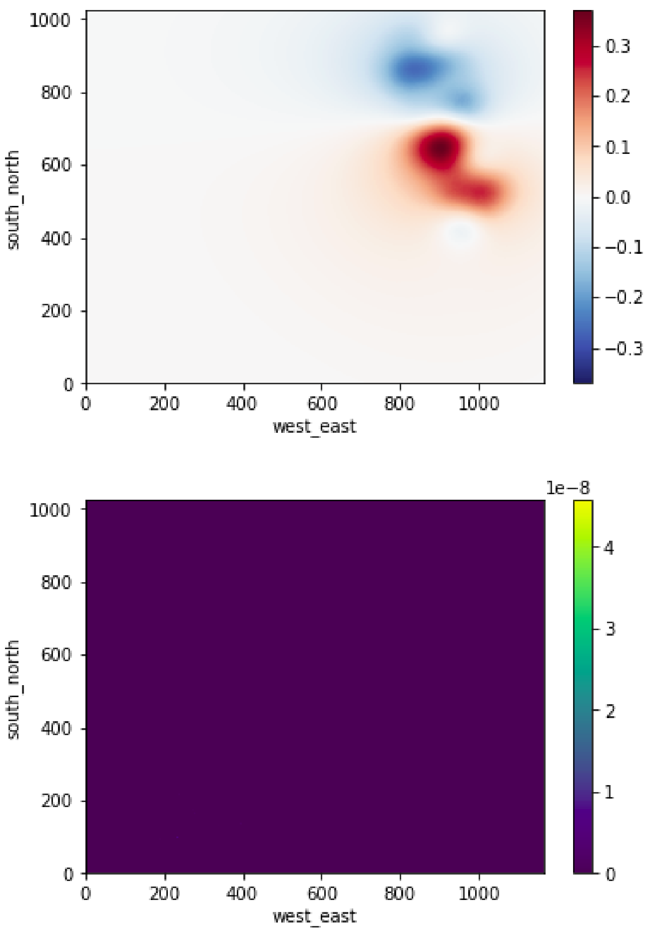

Figure 3: Difference of the vertical integral of the potential temperature (a) and of the water vapour mixing ratio (b) at the instant of the assimilation in the InSAR 13.5km CV5 experiment.

Differently from what we expected, also in the case of assimilation of PWV data, no improvement with respect to the OL simulation is found, as shown from the 2-m temperature and 2-m water vapour mixing ratio bias in figure 4.

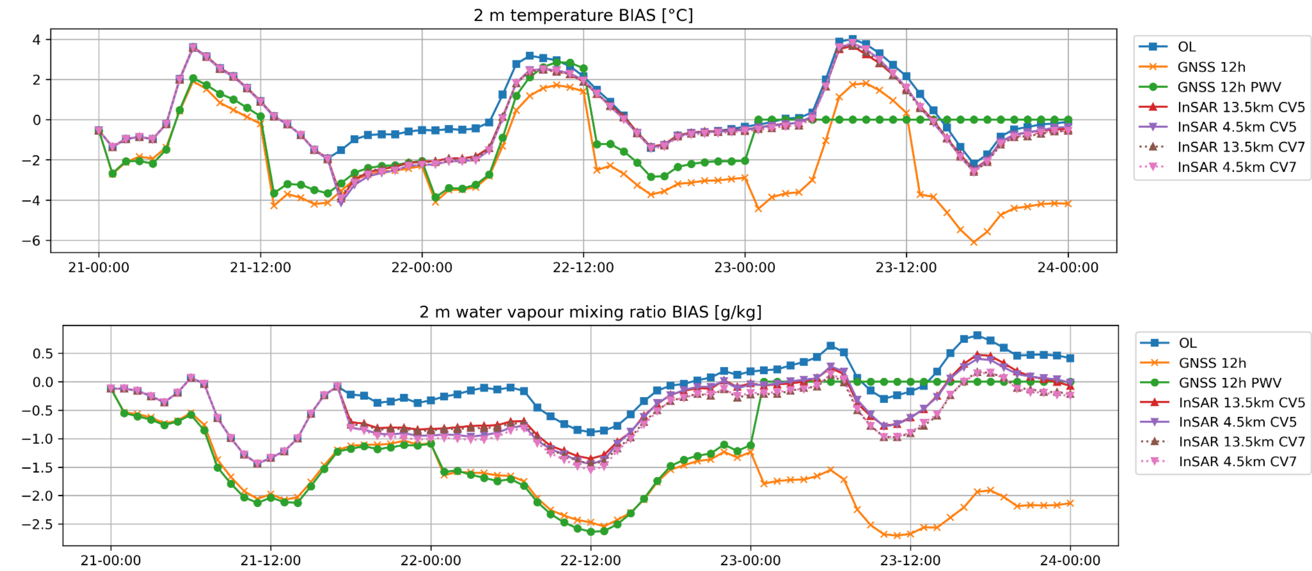

Figure 4: (a) 2-m temperature and (b) 2-m water vapour mixing ratio bias for various InSAR and GNSS experiments, as introduced in the main text (note that the GNSS 12h PWV simulation is stopped at midnight of the 23rd March).

Possible explanations of this unexpected behaviour can be (1) that the background covariance matrices are flawed or (2) that the corrections introduced by the assimilation are too strong and bring the atmospheric dynamics on a different trajectory. To properly address this issue, new long-term simulations should be run in order to estimate the background covariance matrices again. This is beyond the reach of the present project and new resources (both human and computational) will be secured in another project in order to clarify the issues emerged in the present one.

List of publications/reports from the project with complete references

Because of the remaining open issues that emerged during the numerical simulations, no publication has been produced so far. A peer-review publication is foreseen with the results of the experiments, once these open issues have been understood and clarified. The tentative title is: “Water vapour assimilation experiments for heavy rainfall simulations in South Africa: sensitivity to the data spatio-temporal resolution”.

Future plans

(Please let us know of any imminent plans regarding a continuation of this research activity, in particular if they are linked to another/new Special Project.)

Personally, I will be mostly focusing on large scale atmospheric dynamics in my future research. The group in CIMA Research Foundation is still involved in Data Assimilation activity and, possibly, will be able to address some of the open issues that emerged in this work. Possible future coordinated activities with the group in Politecnico of Milan, where ZTD data are produced, are also envisaged, to fully understand and clarify the issues emerged in this project.