SPECIAL PROJECT FINAL REPORT

All the following mandatory information needs to be provided.

Project Title:	Study of different configurations of the RAMS model for precipitation and lightning forecast over Italy at high horizontal resolution
Computer Project Account:	SPITFEDE
Start Year - End Year :	2018 (1 January) – 2020 (31 December)
Principal Investigator(s)	Stefano Federico
Affiliation/Address:	National Research Council of Italy – Institute of Atmospheric Sciences and Climate
Other Researchers (Name/Affiliation):	Name: Claudio Transerici (user cmn) Affiliation: National Research Council of Italy – Institute of Atmospheric Sciences and Climate

The following should cover the entire project duration.

Summary of project objectives

(10 lines max)

The aim of this project is to test several configurations of the RAMS@ISAC model for one-day precipitation forecast and for the lightning forecast. During the project the objectives were mainly focused (and somewhat changed compared to the original plan) on the impact of lightning data assimilation (LDA) on the Very Short-Range precipitation forecast (VSF), especially at 3h. The impact of lightning data assimilation was discussed for some specific case studies and was compared also with radar reflectivity data assimilation. Also, the assimilation of GPS-ZTD (total delay at the zenith) and of Integrated Water Vapour were considered, even if with minor emphasis.
Case studies are useful to understand the impact of lightning data assimilation for challenging forecasts. During the project, it was necessary to test lightning data assimilation for a whole year to quantify the impact of lightning data assimilation in different seasons. This experiment was performed in the second semester of 2019, and results will be summarized in a chapter of a book, which is in review at the moment of writing.

Summary of problems encountered

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

During the second year of the project an annoying problem occurred when connecting from my tablet to cca. At the end we solved it with the help of Dominique Lucas. No problems were encountered in other years.

Experience with the Special Project framework

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

The experience with administrative aspects is positive. The submission of both the project and reports is easy to manage and understandable.
………

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.)

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Five papers have been published within this project. A summary of their results is the best way to address the summary of the results of this project. The main focus of the project was the improvement of the precipitation forecast at the short-range (0-3h) by lightning data assimilation. The region considered was Italy and the Mediterranean. During the project, however, other types of data where considered for assimilation: radar reflectivity and GPS-ZTD (Global Positioning System – Zenit Total Delay). The list of the publications is shown in the next section and comments are reported in the same order as the list of the next section.

The paper **Marra et al. (2019)** examined the Medicane Numa occurred over the Ionian Sea on 15-19 November 2017 using data from the NASA/JAXA GPM-CO (Global Precipitation Mission Core Observatory) and model simulations from RAMS@ISAC model.
Model simulations were used to characterize the storm during its transition from a Mediterranean cyclone to a Medicane phase with a warm convective core.
The simulation of RAMS@ISAC initialized at 12 UTC on 17 November was able to simulate the cyclone track and the rainfall over Apulia, as shown by the comparison with raingauges observations.
The 3D-Var data assimilation system of RAMS@ISAC was adapted to assimilate the reflectivity observed by the DPR radar onboard GPM satellites. The impact of DPR data assimilation on RAMS@ISAC simulation was marginal because only a passage was assimilated, nevertheless the paper shows the feasibility of the method and some positive impact on the rain rate simulation of RAMS@ISAC (see Figure 18 of Marra et al., 2019).

The paper **Federico et al. (2019)** studies the improvement of the precipitation forecast for an intense precipitation case occurred in central Italy, with dramatic effect in the Livorno city where nine people died for causes related to the severe weather. The method to assimilate lightning is that of Fierro et al., (2012), while the method to assimilate radar reflectivity is that of Caumont et al., (2010). The detailed implementation of the lightning and radar reflectivity data assimilation into the RAMS@ISAC model are detailed in this same paper. It is important to note that while lightning can only increase the water vapour of the model, radar data assimilation can both increase and decrease the model humidity.
Figure 1 shows the rainfall forecast for the most intense phase of the Livorno case for different settings of RAMS@ISAC. It is important to note that control forecast, which does not assimilate lightning nor radar reflectivity underestimates the precipitation over Livorno (label A of Figure 2).
The improvement given by lightning and radar reflectivity data assimilation is notable both in intensity and location of the precipitation swath position, which is very close to the observations.
The simulation assimilating both lightning and radar reflectivity factor overestimates the precipitation. This is the major drawback with both lightning and radar reflectivity data assimilation. These results are confirmed by the the performance diagram shown in Figure 2. The reader is referred to Federico et. al. (2019) for a detailed analysis of the performance diagram.
Another intense phase of this same storm occurred between 06 and 09 UTC on 10 September 2017, when more than 100 mm fell in more than 30 raingauges around Rome. The precipitation was forecasted by the control simulation at the border between Rome and Tuscany, about 50 km north of the real occurrence. For this specific time-interval the radar reflectivity data assimilation was vey important for improving the rainfall prediction around the Rome area (see Figure 17 of Federico et al, (2019)).
Another interesting result of this study was the complementary action of radar and lightning data assimilation, even though both observations assimilated water vapour. In particular, lightning is observed for deep convection, while radar data are available for both convective and stratiform rain; in addition, lightning are available over the sea, in areas not covered by radar, and in complex terrain, where ground clutter and beam blocking are important issues for radar observations.

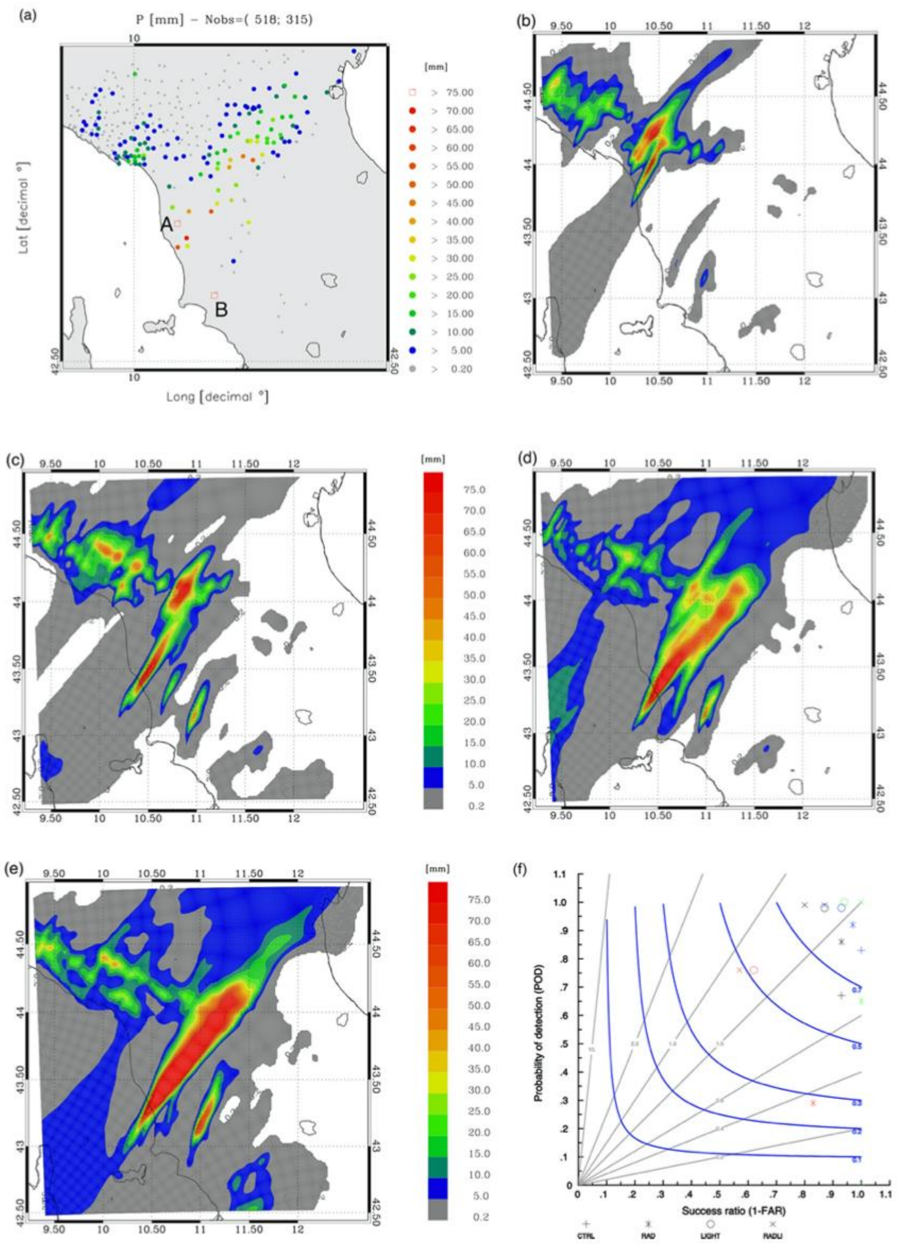

Figure 1: Rainfall between 00 and 03 UTC on 10 September 2017 by: a) raingauges; b) control forecast; c) forecast with radar reflectivity data assimilation; d) forecast with lightning data assimilation; e) forecast with radar and lightning data assimilation; d) performance diagram for the period 00-03 UTC. Reproduced from Federico et al., (2019).

Despite the tendency to overestimate the precipitation for the simulation assimilating both lightning and radar reflectivity, the results of the paper of Federico et al. (2019), clearly shows the positive impact of data assimilation at the local scale for the prediction of intense precipitation events over Italy for short temporal ranges (3h).

The paper **Mascitelli et al. (2019)** considers the impact of GPS-ZTD data assimilation on the rainfall forecast of RAMS@ISAC over Italy. It is the first time that GPS-ZTD is assimilated in RAMS@ISAC by 3D-Var. A total of 29 geodetic receivers available over Lazio, in Central Italy, are assimilated, and the paper gives the detailed methodology and the forward observation operator formulation. The period considered is July-September 2017.
The paper considers the impact of GPS-ZTD data assimilation on the short-term precipitation forecast (3h) using the following scheme: for each day of the period a 9 h forecast is done starting at 06 UTC on each day. A 6 h forecast follows, then an analysis is performed and followed by an additional 3h forecast. The rainfall forecast of the last 3h is compared between the control forecast,

without GPS-ZTD data assimilation, and the forecast assimilating GPS-ZTD. The horizontal resolution of RAMS@ISAC is 4km. The vertical domain covers the whole troposphere with 42 vertical levels.
Results shows a minor, but positive, impact of the assimilation of GPS-ZTD on the precipitation forecast over central Italy. The improvement is mainly determined by the decrease of false alarms.
As an aside result of this paper it is shown that the assimilation of low-cost receiver, whose second frequency is reconstructed from data of nearby geodetic receivers, can give an added value to the forecast of water vapor and precipitation by the refinement of the resolution of the observations.

The paper of **Torcasio et al. (2020)** is focused on the forecast of a heavy precipitation event occurred in Sardinia on 10 October 2018. In this day, two precipitation maxima were detected by rain gauges: one with a rainfall amount of 360.4 mm/24h on eastern Sardinia and one with a recorded precipitation of 452.4 mm/24h in south-central Sardinia. Two intense precipitation phases can be identified for this event. The first phase covers the beginning of the day, i.e. between 03 and 06 UTC, while the second phase spans the last part of the day, between 18 and 24 UTC. In Figure 2, the observed precipitation (OBS) is shown for the phase 03-06 UTC, with two maxima of 142mm/3h and 67mm/3h, respectively, for eastern and south-central Sardinia locations mentioned above.
This event was difficult to forecast because of the heavy and localized rainfall. The paper aimed to show the impact of lightning data assimilation for this challenging case. The forecast is provided in this study by the RAMS@ISAC model with a horizontal spatial resolution of 3km. The control forecast (CTRL), without lightning data assimilation, gave a good prediction only for the last part of the day (21 UTC on 10 October–00 UTC on 11 October), while observed precipitation revealed intense rainfall for most of the day. Lightning data assimilation had a considerable impact on the precipitation forecast. This impact was confirmed also by a comparison between the reflectivity simulated by the model and that observed by the national radar network, showing an important improvement in simulations assimilating lightning compared to control simulations.
The precipitation forecast of this study is implemented using a Very Short-term Forecast (VSF) configuration. This forecast (VSF_3h) consists of a lightning data assimilation period for the first six hours of the run, followed by a forecast period, without lightning data assimilation, for the following three hours. The VSF_3h run simulated deep convection and rainfall for eastern and south-central Sardinia for the whole day. However, the VSF_3h configuration is not fully satisfying since some precipitation spells are missed by this run.
For a further improvement of the precipitation forecast, a sensitivity to a more frequent assimilation cycle is tested. In this case the forecast period lasts 1h instead of 3h from the end of the assimilation phase. For this new run (VSF_1h) three different simulations are needed to cover a 3h forecast period. The VSF_1h run gave an additional refinement to precipitation forecast, with a good forecast of the precipitation field in eastern and south-central Sardinia. While VSF_3h simulation produced a sudden decay of convection for some phases of the storm, VSF_1h restored convection through a more frequent lightning data assimilation, giving an improvement to the precipitation forecast.
The weak point of the VSF_1h is the increase in false alarms. For the second part of the event, between 21 UTC on 10 October and 00 UTC on 11 October, when the CTRL run correctly simulates convection, the VSF_1h overestimates rainfall amount. For this reason, another simulation was conducted. Since the event is characterized by a heavy and localized precipitation, the model horizontal spatial resolution is an important parameter to be considered. The impact of the spatial horizontal resolution on the precipitation forecast was therefore studied, performing simulation with a 2km resolution (VSF_2km). The enhancement of the horizontal resolution from 3km to 2km reduces false alarms and improves model performances. For the VSF_2km run, a VFS configuration like that described above for the VSF_1h is used. At the end of the assimilation phase, the VSF_2km run gives a lower water vapor amount than VSF_1h. This causes the forecast of a lower precipitation amount and the reduction of false alarms for the VSF_2km run compared to VSF_1h, resulting in a better forecast for the VSF_2km configuration.

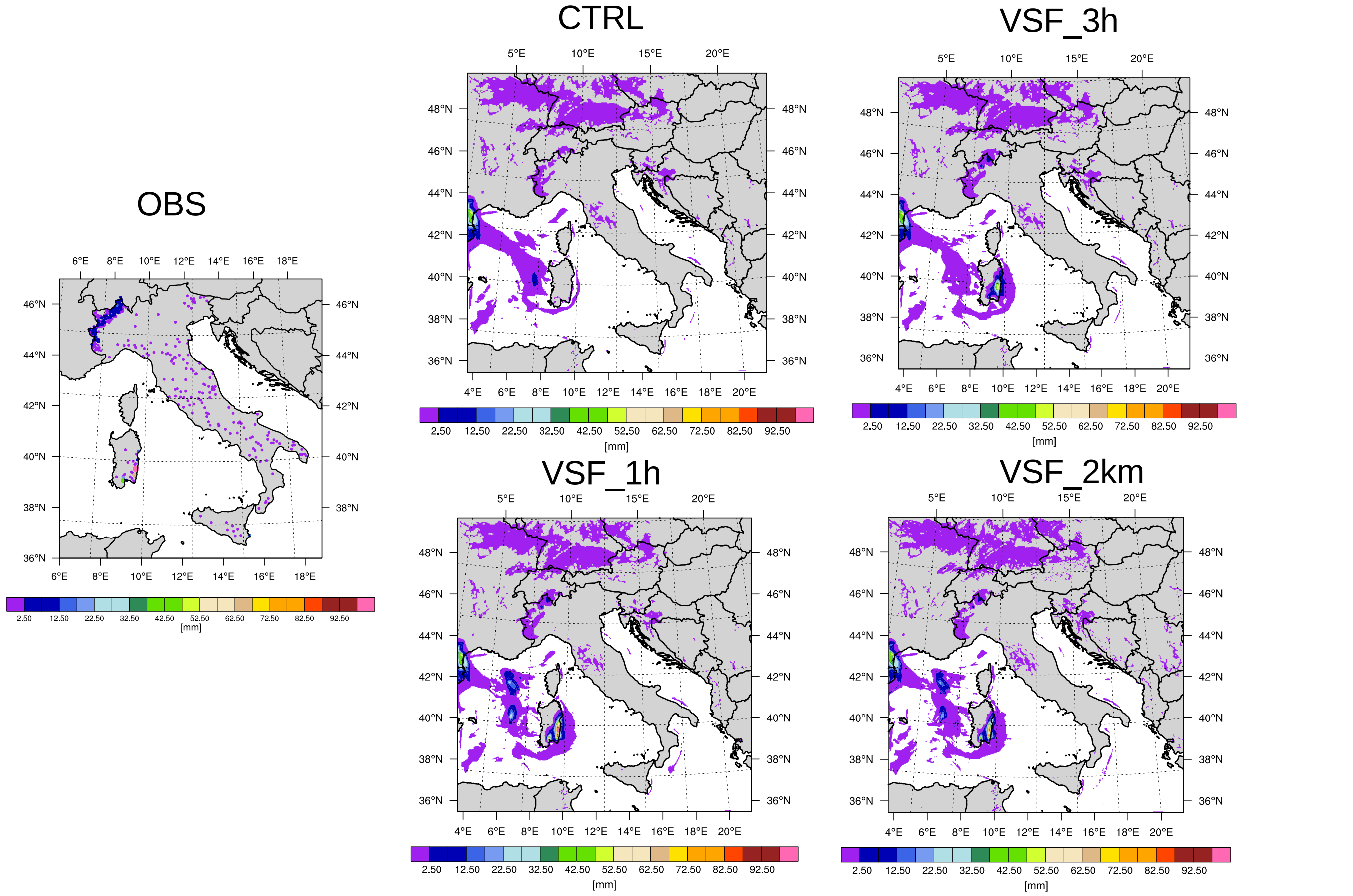

Figure 2: Precipitation observed (OBS) and modelled by the different configuration described above (CTRL, VSF_3h, VSF_1h and VSF_2km) for the 03-06 UTC period of the Sardinia event (Figure from Torcasio et al., 2020).

The paper **Mascitelli et al. (2020)** shows the impact of GPS-ZTD on the simulation of the water vapour field and of the rainfall over central Italy. In particular, a network of about 50 geodetic receiver is available in the Lazio and Abruzzo regions, in central Italy. The integrated water vapour content is computed from GPS-ZTD and assimilated in RAMS@ISAC model by nudging. This method is different from that proposed in Mascitelli et al. (2019), where the ZTD is assimilated by 3D-Var.

The idea behind this approach, compared to that of Mascitelli et al. (2019), is that assimilation can be done much more frequently using nudging compared to 3D-Var. For example, in Mascitelli et al. (2019) a 3D-Var cycle was performed every hour, while in Mascitelli et al. (2020) the data to be assimilated by nudging are updated every 5 minutes, and nudging is applied for the following 5 minutes. With this method a much larger number of data can be assimilated in RAMS@ISAC but nudging is used in place of 3D-Var.

Two important results are obtained in the paper: a) the integrated water vapour forecast is improved by the method; b) the impact on the precipitation is small but positive. The first point is shown by comparing the integrated water vapour simulated at an independent station (the geodetic receiver ROUN) when the integrated water vapour is assimilated to the other stations (see Figure 7 of the paper). The second point is shown verifying the rainfall forecast by the model with or without integrated water vapour data assimilation against raingauge observations over Lazio and Abruzzo regions. To show this impact, an hindcast of the month of October 2019 is done. The assimilation IWV data assimilation is done continuously during the simulation. The whole period is integrated by 30 simulations. Each simulation starts at 12 UTC on a day and last 36 h . The first 12 h are considered as spin-up and are discarded from the analysis. The horizontal resolution of the model is 3 km, while the vertical domain span the whole troposphere. Results shown a positive impact of integrated water vapour data assimilation on the precipitation forecast. As in Mascitelli et al. (2019) the impact is mainly on the reduction of false alarms than in the increase oh hits.

References

Fierro, A. O., Mansell, E., Ziegler, C., and MacGorman, D.: Application of a lightning data assimilation technique in the WRFARW model at cloud-resolving scales for the tornado outbreak of 24 May 2011, Mon. Weather Rev., 140, 2609–2627, 2012.

Caumont, O., Ducrocq, V., Wattrelot, E., Jaubert, G., and Pradier-Vabre, S.: 1D + 3DVar assimilation of radar reflectivity data: a proof of concept, Tellus A, 62, 173–187, https://doi.org/10.1111/j.1600-0870.2009.00430.x, 2010.

List of publications/reports from the project with complete references

A total of five papers were published on international peer-reviewed journals with most of the computing resources given by this project. The publication list with acknowledgments to this special project is reported below:

1) Marra, A.C.; Federico, S.; Montopoli, M.; Avolio, E.; Baldini, L.; Casella, D.; D'Adderio, L.P.; Dietrich, S.; Sanò, P.; Torcasio, R.C.; Panegrossi, G. The Precipitation Structure of the Mediterranean Tropical-Like Cyclone Numa: Analysis of GPM Observations and Numerical Weather Prediction Model Simulations. *Remote Sens.* 2019, *11*, 1690. https://doi.org/10.3390/rs11141690

2) Federico, S., Torcasio, R. C., Avolio, E., Caumont, O., Montopoli, M., Baldini, L., Vulpiani, G., and Dietrich, S.: The impact of lightning and radar reflectivity factor data assimilation on the very short-term rainfall forecasts of RAMS@ISAC: application to two case studies in Italy, *Nat. Hazards Earth Syst. Sci.*, 19, 1839–1864, https://doi.org/10.5194/nhess-19-1839-2019, 2019.

3) Mascitelli, A., Federico, S., Fortunato, M., Avolio, E., Torcasio, R.C., Realini, E., Mazzoni, A., Transerici, C., Crespi, M, Dietrich, S.: Data assimilation of GPS-ZTD into the RAMS model through 3D-Var: preliminary results at the regional scale, *Meas. Sci. Technol.* 30 (2019) 055801. https://doi.org/10.1088/1361-6501/ab0b87

4) Torcasio, R.C.; Federico, S.; Puca, S.; Vulpiani, G.; Comellas Prat, A.; Dietrich, S. Application of Lightning Data Assimilation for the 10 October 2018 Case Study over Sardinia. *Atmosphere* 2020, *11*, 541. https://doi.org/10.3390/atmos11050541

5) Mascitelli, A.; Federico, S.; Torcasio, R.C.; Dietrich, S.: Assimilation of GPS Zenith Total Delay estimates in RAMS NWP model: Impact studies over central Italy, Advances in Space Research, in press, https://doi.org/10.1016/j.asr.2020.08.031, 2020.

In addition, the material of an extended numerical experiment of one-year showing the impact of LDA on the very short-term precipitation forecast (3h) will be published in a book published by the Elsevier. I cannot give the reference at the time of writing.

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.)

The impact of lightning and radar data assimilation on the precipitation forecast over Italy is very important, as shown in this project and other applications over Italy. However, the impact of LDA, RDA and other sources of data on the rainfall forecast needs to be considered more in detail to assess their impact on alert systems at the short-range. In addition, there are scientific points that must be considered in detail, as the impact (and the reduction) of false alarms in weather forecasts assimilating data at the local scale.
To investigate these points, I submitted a special project for years 2021-2023 at the ECMWF entitled "Improvement of very-short term forecast using lightning and radar data assimilation". The project started in January 2021.
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