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	……2019 (second semester) - 2020 (first semester)……………………….……
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 ……………………….……
Principal Investigator(s):	…… Stefano Federico …………………….……
	………………………………………………………….……
Affiliation:	ISAC-CNR (Institute for Atmospheric Sciences and Climate - National Research Council)……………………….……
Name of ECMWF scientist(s) collaborating to the project (if applicable)	………………………………………………………….…… ………………………………………………………….……
Start date of the project:	……1 January 2018…………..……
Expected end date:	… 31 December 2020…………………………..……

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)	6,000,000	9,000,000 (an extension was approved)	6,000,000	5,200,000
Data storage capacity	(Gbytes)	7 TB	7 TB	9 TB	10 TB

Summary of project objectives (10 lines max)

The aim of this project is to test several configurations of the RAMS model for one-day precipitation forecast and for the lightning forecast. During the project the objectives were mainly focused towards the impact of lightning on the Very Short Range precipitation forecast (VSF_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) was considered, even if with minor emphasis. Case studies are useful to understand the impact of lightning data assimilation for challenging forecasts. Nevertheless, during the project, it emerged the necessity 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 summarised in a chapter of a book.

Summary of problems encountered (10 lines max)

During the last semester of 2019, there was a need to do an additional (long) numerical experiment, which was not planned at the starting of the project. We assessed the impact of lightning data assimilation for a whole year (1 September 2018 – 31 August 2019). There was a request for additional 3.000.000 SBU that were granted by ECMWF.

A very annoying connection problem happened during the last semester caused by some apps of a device that the PI of this project used to connect to ecgate. The problem was resolved with the help of the service desk. Several people of ECMWF staff followed this issue, which was solved thanks to their help. However, Dominique Lucas, who is warmly acknowledged, was fundamental to solve the issue.

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

The PI of this special project is writing a chapter of a book on precipitation, published by Elsevier, and the results of the experiment ran in the second part of 2019, using the additional resources given to this project, will be used in this chapter. Also, sensitivity tests to parameters of lightning data assimilation are requested in this chapter. These tests are currently under way. In this last semester the focus will be on the publication of the book chapter stated above.

It would be interesting to return to the problem of lightning forecast implementing a (second) diagnostic scheme for lightning forecast in RAMS model. This is planned for the last three months of this year if resources will be available. For this purpose, additional SBU will be requested this summer to be allocated to this project.

List of publications/reports from the project with complete references

Already reported in the previous progress report:
Elenio Avolio, Stefano Federico, WRF simulations for a heavy rainfall event in southern Italy: Verification and sensitivity tests, Atmospheric Research, Volume 209, 2018, Pages 14-35, ISSN 0169-8095, https://doi.org/10.1016/j.atmosres.2018.03.009.

Mascitelli, Alessandra; Federico, Stefano; Fortunato, Marco; Avolio, Elenio; Torcasio, Rosa Claudia; Realini, Eugenio; Mazzoni, Augusto; Transerici, Claudio; Crespi, Mattia; Dietrich, Stefano: Data assimilation of GPS-ZTD into the RAMS model through 3D-Var: preliminary results at the regional scale. Meas. Sci. Technol. 30 (2019) 055801 (14pp). https://doi.org/10.1088/1361-6501/ab0b87

New:
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.

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

Torcasio, R.C.; Federico, S.; Puca, S.; Vulpiani, G.; Prat, A.C.; Dietrich, S. Application of Lightning Data Assimilation for the 10 October 2018 Case Study over Sardinia. *Atmosphere* 2020, *11*, 541.

There also two articles under review:
Albert Comellas Prat, Stefano Federico, Rosa Claudia Torcasio, Alex O. Fierro, Stefano Dietrich: Lightning data assimilation in the WRF-ARW model for short-term rainfall forecasts of three severe storm cases in Italy.

A. Mascitelli, S. Federico, R.C. Torcasio, S. Dietrich: Assimilation of GNSS single-frequency receivers data in RAMS NWP model: Impact studies over central Italy.

It is worth remembering that ECMWF and this project are explicitly acknowledged in all these publications.

Summary of results

Introduction
In this period several experiments on lightning, radar reflectivity and, with minor emphasis, GPS-ZTD data assimilation were performed with RAMS@ISAC (Regional Atmospheric Modeling System at the Institute for Atmospheric Sciences and Climate). Among the case studies two are worth mentioning and were used for specific assessments: the Livorno case, occurred on 9-10 September 2017 over Tuscany, Italy, and the Sardinia case, occurred over Sardinia island on 10 October 2018. The first case study is well known because heavy precipitation occurred not only in Italy but in several countries of the Mediterranean. The case studied caused 9 casualties in Italy and important damages to infrastructures; the case study of 10 October 2018 is challenging to forecast because two heavy precipitation spots were recorded over the Sardinia island, few tens of kilometres apart, with small-moderate rain between the two spots.

Lightning data assimilation
At the moment of writing, two techniques can be used to assimilate lightning in RAMS@ISAC: nudging and 3D-Var. Both these techniques are well documented in Federico et al. (2019). In both cases a pseudo-profile of saturated mixing ratio of water vapour is generated. This profile is saturated

between the LCL (Lifting Condensation Level) or 0°C isotherm, depending on the data assimilation setting, and the -25°C isotherm. The profile is assumed with no-data outside this vertical domain. Then, the pseudo profile is assimilated into RAMS@ISAC using 3D-Var or nudging.
In the following we show two phases of the two storms introduced above to show the relevant impact of lightning and radar reflectivity data assimilation on the precipitation forecast. Also, we consider the sensitivity of predicted rainfall to relevant settings of the model and data assimilation. The discussion of the two phases is taken from two papers published with the computational resources of this special project.

Results for lightning data assimilation
Most of the comments and figures used in this section are taken from:

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.

for the Livorno case and from:

Torcasio, R.C.; Federico, S.; Puca, S.; Vulpiani, G.; Prat, A.C.; Dietrich, S. Application of Lightning Data Assimilation for the 10 October 2018 Case Study over Sardinia. *Atmosphere* 2020, *11*, 541.

for the Sardinia case.

Sardinia case: Phase 03-06 UTC on 10 October 2018

Definitions:
VSF_3h: is a forecast where flashes are assimilated for 6h, then follows a free forecast of 3h. The horizontal resolution is 3 km. The vertical levels are unevenly spaced and covers the troposphere and the lower stratosphere.
VSF_1h: is a forecast where flashes are assimilated for 6h, then follows a free forecast of 1h. The horizontal resolution is 3 km. The vertical levels are unevenly spaced and covers the troposphere and the lower stratosphere.
VSF_2km: is a forecast where flashes are assimilated for 6h, then a free forecast of 1h follows at 2km horizontal resolution. The vertical levels are unevenly spaced and covers the troposphere and the lower stratosphere.

The precipitation of the phase 03-06 UTC was very intense in the eastern part of Sardinia where 142 mm/3h were recorded in Tertenia and 67 mm/3h were recorded in Flumini Uri a San Vito. More than 47 mm/3h were observed in the central part of southern Sardinia (Figure 1).

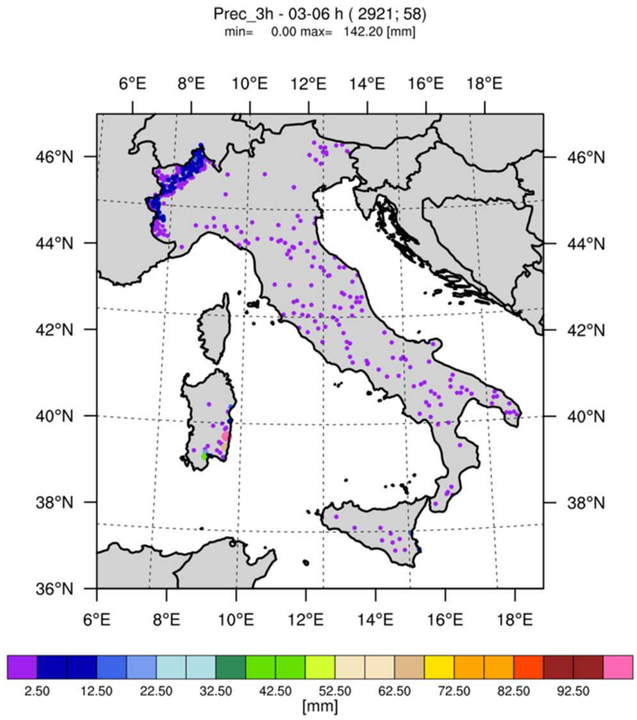


Figure 1: Rainfall observed by the Italian raingauge network between 03 and 06 UTC on 10 October.

The large precipitation of this phase was not simulated by CTRL (Figure 2a), which missed the forecast. The VSF_3h (Figure 2b) did a much better forecast, simulating more than 60 mm/3h over eastern Sardinia and 25 mm/3h in the southern part of the Island. <

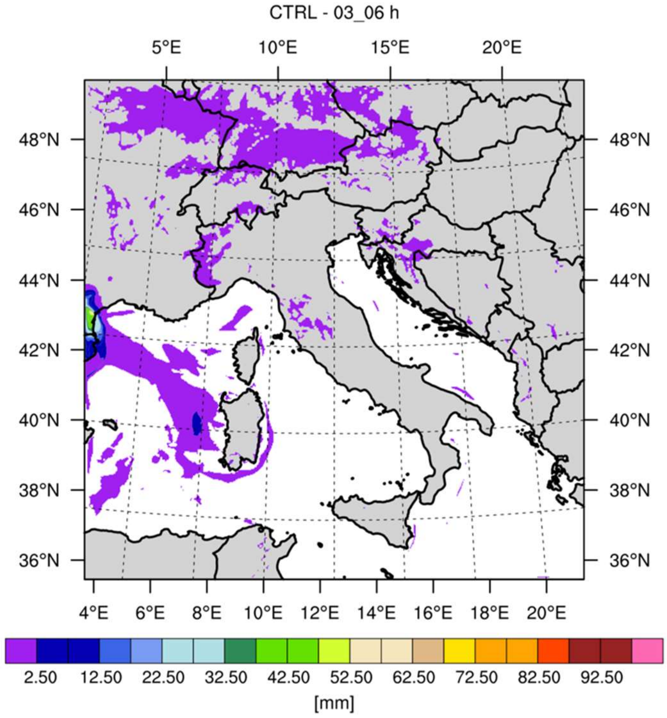
While VSF_3h improves substantially the forecast of the intense precipitation of this phase when compared to CTRL, the precipitation amount is underestimated.

VSF_1h gives a considerable improvement to the rainfall forecast of VSF_3h (Figure 2c). The maximum rainfall over eastern Sardinia is 130mm/3h and the maximum over southern Sardinia is 70 mm/3h. In both cases, the precipitation amount is in good agreement with observations.

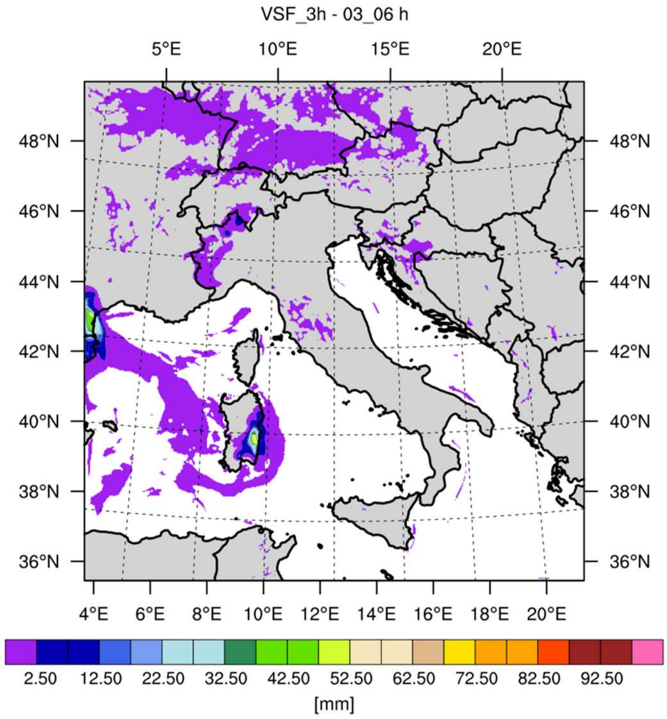
The increase of model resolution (Figure 2d) has also a significant impact on the precipitation forecast. The precipitation is reduced, compared to VSF_1h, both in eastern and southern Sardinia (100 mm/3h and 50 mm/3h, respectively).

The precipitation amounts simulated by VSF_1h and VSF_2km are in well agreement with observations while VSF_3h underestimates the rainfall prediction. While this result is expected because the 1h forecast assimilates more frequently the flashes and follows better the time evolution of the storm, the important difference between the rainfall prediction of VSF_3h and that of VSF_1h (or VSF_2km) is, at least in part, caused by the inability of the RAMS@ISAC model to simulate and sustain the convection for this specific time period of the storm evolution. This is shown by: a) the very low precipitation simulated by CTRL; b) the fact that once convection is forced by lightning data assimilation, like in VSF_3h, it decays rapidly, as shown by the much smaller amount of precipitation forecast by VSF_3h compared to VSF_1h and VSF_2km.

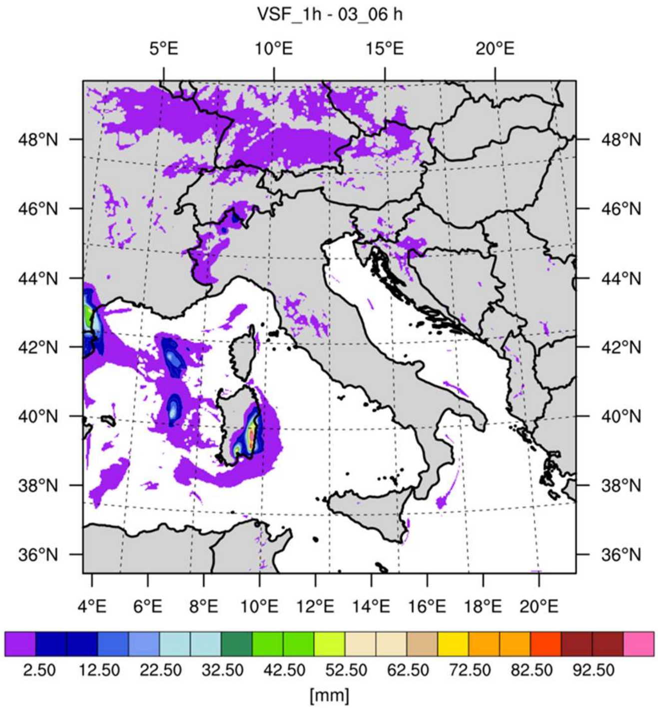
a)


CTRL - 03_06 h
5°E
10°E
15°E
20°E
48°N
46°N
44°N
42°N
40°N
38°N
36°N
4°E
6°E
8°E
10°E
12°E
14°E
16°E
18°E
20°E
2.50
12.50
22.50
32.50
42.50
52.50
62.50
72.50
82.50
92.50
[mm]

b)


VSF_3h - 03_06 h
5°E
10°E
15°E
20°E
48°N
46°N
44°N
42°N
40°N
38°N
36°N
4°E
6°E
8°E
10°E
12°E
14°E
16°E
18°E
20°E
2.50
12.50
22.50
32.50
42.50
52.50
62.50
72.50
82.50
92.50
[mm]

c)



d)

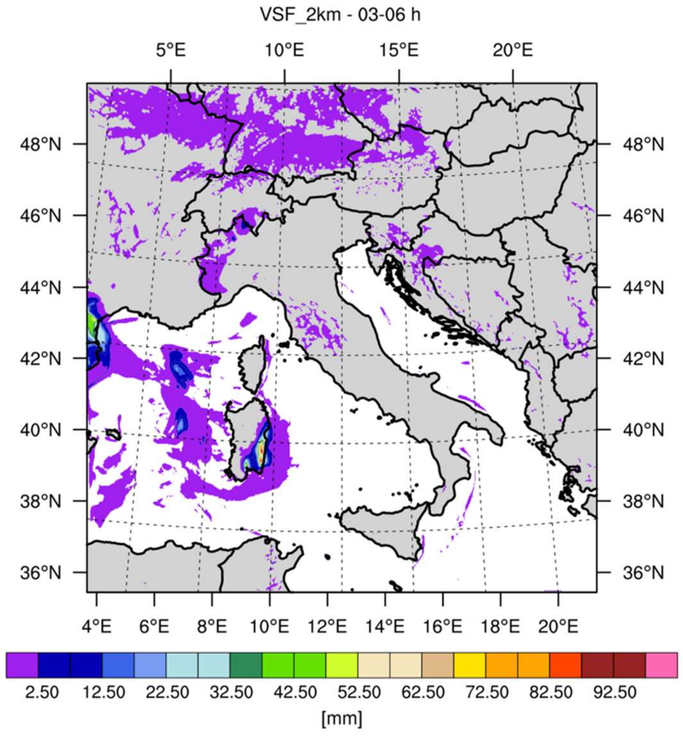


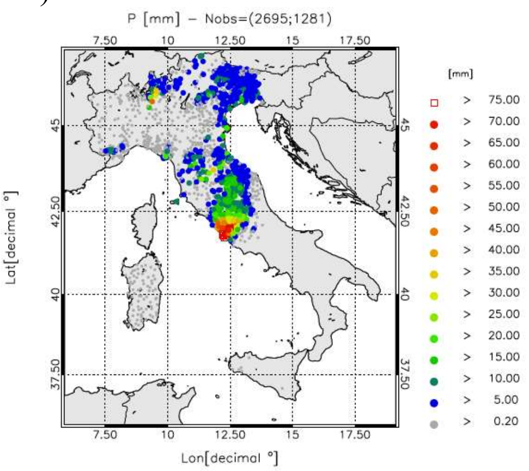
Figure 2: Accumulated precipitation between 03 UTC and 06 UTC on 10 October 2018 for: (**a**) CTRL; (**b**) VSF_3h; (**c**) VSF_1h; (**d**) VSF_2km. For VSF_1h and VSF_2km the precipitation is given by the sum of the three very short term forecast of 1h between 03 and 06 UTC. From Torcasio et al., 2020.

The above discussion is confirmed by the scores for the simulated reflectivity computed at 04 UTC for three different reflectivity values (0, 5, 15 dBz) and for three heights (2, 3, 5km, which were the heights of available CAPPI for this case study). These statistics can be found in Table 2 of Torcasio et al. (2020). The comparison between observed and simulated reflectivity shows that lightning data assimilation improves substantially the radar reflectivity simulated by RAMS@ISAC at all levels. Also, doing a very update cycle every 1h (VSF_1h) instead of 3h (VSF_3h) is important for predicting both the maximum over eastern Sardinia and that over southern Sardinia. Finally, refining the horizontal resolution (VSF_2km) had an important role because improved the already satisfactory VSF_1h forecast by reducing the false alarms.

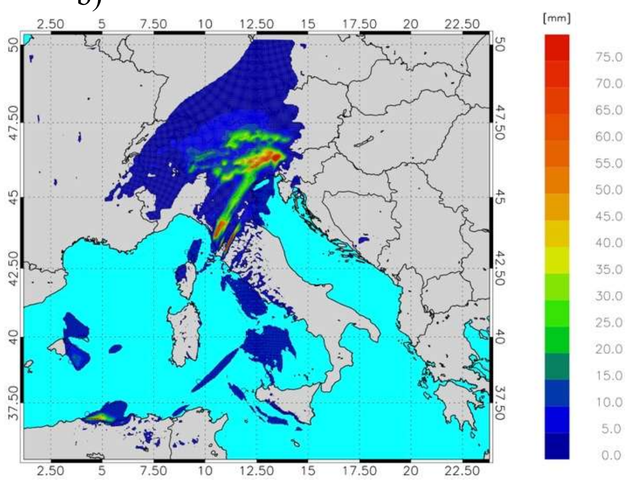
Results of radar reflectivity data assimilation – 10 September 2017phase 06-09 UTC

Definitions:
CTRL: control run, without lightning or radar data assimilation. Duration 9h, horizontal resolution 4 km. Unevenly spaced vertical levels covering the troposphere and lower stratosphere.
LIGHT: simulation with lightning data assimilation. Duration 9h, horizontal resolution 4 km. The first six hours are used for lightning data assimilation. Unevenly spaced vertical levels covering the troposphere and lower stratosphere.
RAD: simulation with radar reflectivity data assimilation. Duration 9h, horizontal resolution 4 km. The first six hours are used for radar reflectivity data assimilation. Unevenly spaced vertical levels covering the troposphere and lower stratosphere.
RADLI: simulation with both lightning and radar reflectivity data assimilation. Duration 9h, horizontal resolution 4 km. The first six hours are used for data assimilation. Unevenly spaced vertical levels covering the troposphere and lower stratosphere.

a)

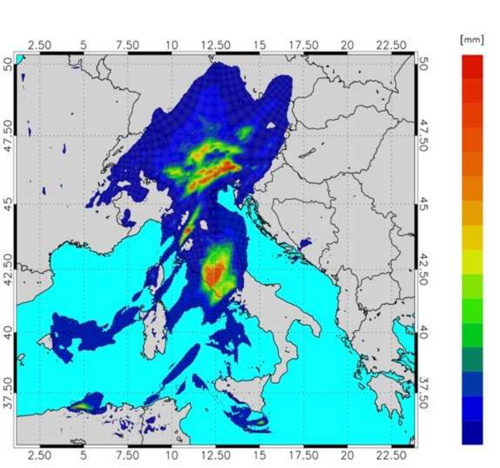


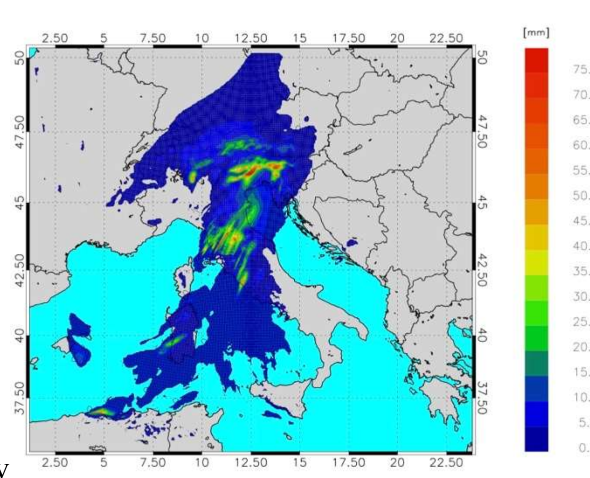
b)



c)

d)

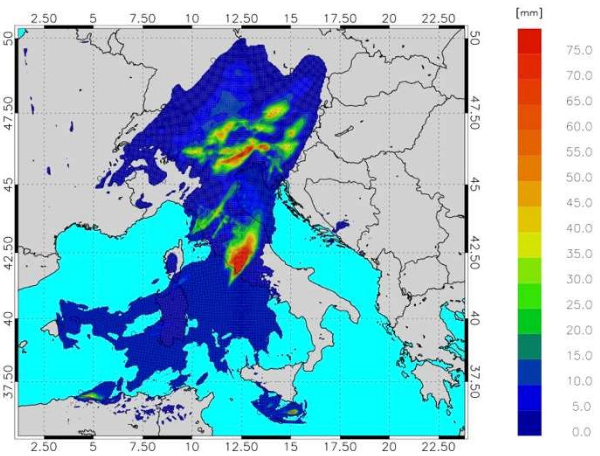


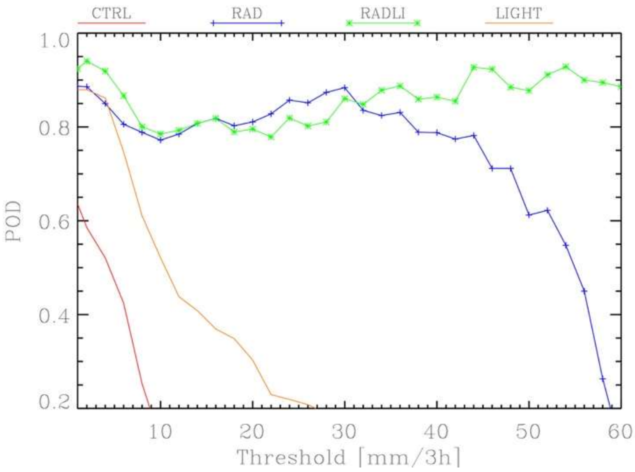


v

e)

f)





g)

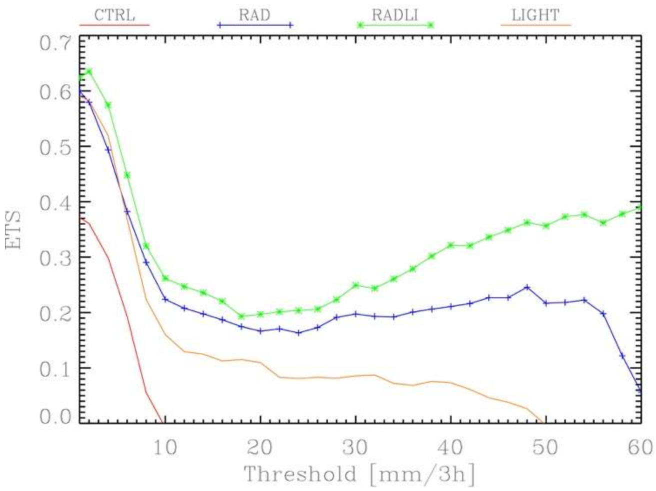


Figure 3: a) rainfall reported by raingauges between 06 - 09 UTC on 10 September 2017. For this time period 2695 raingauges reported valid observations in the domain, however only stations reporting at least 0.2 mm/3h are shown The first number in the title represents the number of raingauges available over the domain, while the second number shows those observing at least 0.2 mm/3h; b) as in a) for the CTRL forecast; c) as in a) for the RAD forecast; d) as in a) for the LIGHT forecast; g) as in a) for the RADLI forecast; f) POD score for the period 06-09 UTC on 10 September; e) as in f) for the ETS score. POD and ETS scores are computed over the domain of Figure 3a-c. From Federico et al. (2019).

In this period of the Livorno flood, the most intense phase of the precipitation occurred over Central Italy, specifically over the coastal part of Lazio (Figure 3a). More in detail, among the 2695 raingauges reporting valid data over the domain of Figure 3a, 307 reported more than 10 mm/3h, 132 more than 20 mm/3h, 86 more than 30 mm/3h, 66 more than 40 mm/3h, 49 more than 50 mm/3h and 35 more than 60 mm/3h. Among the 35 raingauges measuring more than 60 mm/3h, 33 were over the Lazio, showing the heavy rainfall occurred over the Region.

Some precipitation persisted over Tuscany, but the rainfall is much lower compared to previous 6h over this region. Other notable precipitation areas are over the NE of Italy (moderate to low amounts), over Central Alps (moderate values) and over the whole Sardinia (small amounts).

Figure 3b shows the rainfall simulated by CTRL. The forecast is unsatisfactory, mainly for the following two reasons: a) heavy precipitation is simulated over Tuscany (> 75 mm/3h), also close to the Livorno area; b) small precipitation is forecast over Central Italy. The rainfall over NE Italy is well represented in space but overestimated. The small precipitation over Sardinia is not forecast by CTRL.

Considering the evolution of CTRL rainfall forecast for the different phases of the storm, we conclude that CTRL was able to predict abundant rain over Livorno (Tuscany), but this was delayed compared to the real event.

The rainfall simulated by RAD (Figure 3c) clearly improves the forecast compared to CTRL. First, the precipitation over Lazio is well predicted and the rainfall values are larger than 40 mm/3h (up to

65 mm/3h), so the RAD forecast represents the main precipitation spot over Italy for this time period. Second, the precipitation over Tuscany is lower than CTRL, showing the ability of radar reflectivity factor data assimilation to dry the model when it predicts rain that is not observed. Third, the precipitation over Central Alps is represented, even if located about 30 km to the East.
There are also aspects of the rainfall forecast that are less satisfactory: the small precipitation over Sardinia is not represented by RAD; the precipitation over NE Italy is well represented in space but overestimated.
LIGHT forecast, Figure 3d, shows a worse performance compared to RAD for this period. The precipitation forecast is mainly over Tuscany, where it is overestimated, with a small precipitation spot over Lazio. There are, however, three improvements compared to CTRL and RAD: a) the small precipitation over Sardinia is well represented in LIGHT; b) the precipitation over Central Alps is well predicted; c) the rainfall forecast over NE Italy is overestimated by LIGHT but to a less extent compared to RAD.
The precipitation forecast of RADLI, Figure 3f, represents very well the precipitation over Lazio, and the rainfall amount is better predicted compared to RAD. The precipitation over Sardinia is well represented by RADLI as well as the precipitation over Central Alps, giving the best results among all forecasts.
The POD score confirms the above analysis. All the experiments with data assimilation outperform the CTRL forecast, and RAD performs better than LIGHT. RADLI shows the best POD among all configurations because it represents better the amount of rainfall over Lazio.
Similar considerations apply to ETS; it is worth noting the high value of ETS for thresholds larger than 50 mm/3h, which represent heavy rainfall. A forecast that was missed by CTRL is correctly represented in both space and time by the assimilation of radar reflectivity factor and lightning.
It is important to note that even if for the specific period considered in this section the assimilation of radar reflectivity gave a larger improvement compared to lightning data assimilation, more in general both data contribute to the improvement of precipitation forecast, and an assessment of which type of data is more effective for the precipitation forecast in RAMS@ISAC has not been yet assessed.

Conclusions

In this year several additional numerical experiments were performed with lightning and radar reflectivity data assimilation, with minor emphasis on GPS-ZTD data assimilation (see the paper Mascitelli et al. (2019) for a discussion of the status of the assimilation of GPS-ZTD in RAMS@ISAC). In particular, the case studies of Sardinia and Livorno gave the possibility to explore several aspects of lightning and radar reflectivity data assimilation.
The experiment of Sardinia showed the importance of both the forecast duration and the model horizontal resolution on the precipitation forecast. The Livorno case study showed the notable impact of radar reflectivity data assimilation on the RAMS@ISAC precipitation forecast. Further research is necessary to better assess the impact of lightning and radar reflectivity data assimilation on the RAMS@ISAC precipitation forecast.
Starting from the first numerical experiments on lightning data assimilation (Federico et al. 2017), we gained a much clearer idea of the potential of lightning data assimilation on the precipitation forecast with RAMS@ISAC. Also, in the years, the setting of lightning data assimilation has been revised and tuned to have a better precipitation forecast over Italy. For these reasons it is the right time to do a systematic experiment to evaluate the different factors that may have a substantial impact on lightning data assimilation. This will be explored in the last part of this project by requesting additional computing time to be allocated for this project. In particular, the sensitivity of the precipitation forecast to the profile of water vapour assimilated and the impact of the forecast length on the precipitation forecast will be explored.

References

Federico, S., Petracca, M., Panegrossi, G., and Dietrich, S.: Improvement of RAMS precipitation forecast at the short-range through lightning data assimilation, Nat. Hazards Earth Syst. Sci., 17, 61-76, doi:10.5194/nhess-17-61-2017, 2017.

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.

Torcasio, R.C.; Federico, S.; Puca, S.; Vulpiani, G.; Prat, A.C.; Dietrich, S. Application of Lightning Data Assimilation for the 10 October 2018 Case Study over Sardinia. *Atmosphere* 2020, *11*, 541.