SPECIAL PROJECT FINAL REPORT

All the following mandatory information needs to be provided.

Project Title:	Improvement of very-short term forecast using lightning and radar data assimilation
Computer Project Account:	spitfede
Start Year - End Year :	2021- 2023
Principal Investigator(s)	Stefano Federico
Affiliation/Address:	CNR-ISAC (National Research Council – Institute of Atmospheric Sciences and Climate), via del Fosso del Cavaliere 100, 00133 Rome
Other Researchers (Name/Affiliation):	Claudio Transerici (cmn) CNR-ISAC, via del Fosso del Cavaliere 100, 00133 Rome Rosa Claudia Torcasio (it85) CNR-ISAC, via del Fosso del Cavaliere 100, 00133 Rome

The following should cover the entire project duration.

Summary of project objectives

(10 lines max)

The general objective of the project is to evaluate the impact of data assimilation on the very-short term forecast over Italy, with emphasis on high precipitation and convective events. This objective is vast and needs to be focused on specific goals that can be tackled in the framework of this special project. Specifically, in this project we considered the problem of assimilation of lightning, radar reflectivity, GNSS-ZTD data using two different meteorological models (RAMS@ISAC and WRF) and predicting two different parameters (precipitation and lightning). In all cases we had a substantial improvement of the convection forecast (both precipitation and lightning) at the short-range and more details are provided below. Five open-access papers and a conference proceeding were published in this project.

Summary of problems encountered

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

No specific problems were encountered during this special project. Additional resources were request for the three years 2021 (4 millions), 2022 (4 millions) and 2023 (9 millions SBU) and these additional resources were always agreed.

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 more then 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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This project explored the possibility to assimilate several datatypes in a Rapid Update analysis/forecast Cycle (RUC) of a Numerical Weather Prediction (NWP) and evaluated the impact of the data assimilation on the prediction of the convection. The latter is quantified by the lightning and intense precipitation (> 10 mm/1h) occurrence. We used two different models RAMS@ISAC (Regional Atmospheric Modeling System at the Institute of Atmospheric Sciences and Climate) and the WRF (Weather Research and Forecasting) model.

Different data types were considered: lightning, radar reflectivity, satellite derived rain-rate and GNSS-ZTD (Zenit Total Delay). Five publications were published in the framework of this project and we will give the summary of the results of the project by considering the main results of each of those papers.

The paper [1] considers the analysis of a very localized and heavy thunderstorm over Palermo, the main city of Sicily, occurred in the afternoon of the 15 July 2020. More than 120 mm/3h fell over the city in just 3h (between 14 and 17 UTC) and the densely populated city was flooded, causing lot of damages. The previous day forecast issued alerts for Catania, another city of Sicily, located quite far from Palermo (about 200 km to the southeast of Palermo), so it missed the forecast.

We investigated the possibility to improve the forecast through lightning and radar reflectivity data assimilation. The assimilation of both datatypes was done through 3DVAR following the method detailed in [1] and we used the RAMS@ISAC model. Figure 1 shows the precipitation forecast by different model configurations between 14 and 17 UTC on 15 July 2020.

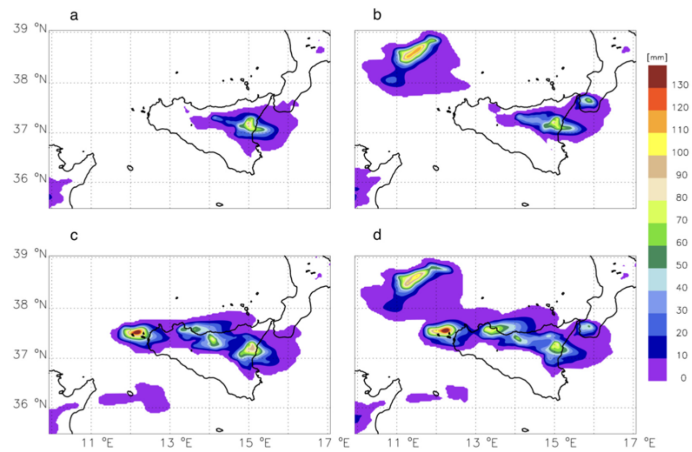


Figure 1: the precipitation simulated by RAMS@ISAC between 14 and 17 UTC on 15 July 2020. The upper left panel is the control simulation, the upper right is the simulation with radar reflectivity data assimilation, the lower-left panel is for the simulation with lightning data assimilation, the lower-right panel is for the simulation assimilating both radar and lightning. From Federico et al. (2021).

From Figure 1, it follows the important role played by the lightning data assimilation in triggering the storm at the correct position. More than 50 mm/3h were predicted in correspondence of Palermo for the simulation assimilating lightning. Assimilating radar reflectivity did not improve much the control forecast forecasting a rainfall less than 10 mm in the 3h. However, assimilating both lightning and radar reflectivity had a substantial impact on the rainfall forecast. Indeed, more than 90 mm/3h were simulated in correspondence of Palermo, well simulating the 120 mm/3h observed. For this case study, the lightning and radar reflectivity data assimilation acted synergistically to improve the event forecast.

Another point that was considered in this work is the time availability of the forecast. The performance of Figure 1 for the simulation assimilating radar and lightning is very good. Nevertheless, this forecast could be issued at 14:30 UTC, when the event already started in Palermo, even if well before its most intense phase (between 15 and 16 UTC). Three additional experiments were performed to explore this issue. In the first experiment the assimilation was done until 13:30 UTC (the forecast could be issued at 14:00 UTC); in the second experiment the assimilation is done up to 13:00 UTC (the forecast could be issued at 13:30 UTC), and in the third experiment the assimilation was done until the 12:30 UTC (the forecast could be issued at 13:00 UTC). We recall that the event started at 14:00 UTC and lasted until 17:00 UTC. Results show reasonable results for these three experiments with a precipitation

between 50 and 60 mm/3h in correspondence of the Palermo. These results show the need for a very short-term precipitation forecast for Italy, especially in summer.
The paper [2] investigates the performance of lightning forecast over Italy for a total of 162 case studies. We show the performance of the "dynamic lightning scheme" for next-day total strokes forecast (Lynn et al., 2012). The predictions were compared against strokes recorded by a ground observational network for a forecast period spanning one year and considering a total of 162 case studies between 1 March 2020 and 28 February 2021. The events considered were characterized by at least 3000 observed strokes over Italy. The events span a broad range of lightning intensity from about 3000 to 600,000 strokes in one day: 69 cases occurred in summer, 46 in fall, 18 in winter, and 29 in spring. The meteorological driver was the Weather Research and Forecasting (WRF) model (version 4.1) and we focused on the next-day forecast. Strokes were simulated by adding three extra variables to WRF, namely, the potential energies for positive and negative cloud to ground flashes and intracloud strokes. Each potential energy is advected by WRF, it is built by the electrification processes occurring into the cloud, and it is dissipated by lightning. Observed strokes were remapped onto the WRF model grid with a 3 km horizontal resolution for comparison with the strokes forecast. Results are discussed for the whole year and for different seasons. Moreover, statistics are presented for the land and the sea. In general, the results of this study show that lightning forecast with the dynamic lightning scheme and WRF model can be successful for Italy; nevertheless, a careful inspection of forecast performance is necessary for tuning the scheme. This tuning is dependent on the season. A numerical experiment changing the microphysics scheme used in WRF shows the sensitivity of the results according to the choice of the microphysics scheme.
The most important results of paper [2] is that lightning forecast can be done with success over Italy for the next day, nevertheless the model output must be upscaled to larger grid size than the native WRF grid (3km). It was determined that 24 km grid upscaling is the best compromise between the forecast performance and adopting a spatial resolution compatible with the alerting areas used by the Department of Civil Protection for alerting the population for adverse weather conditions (Figure 2).

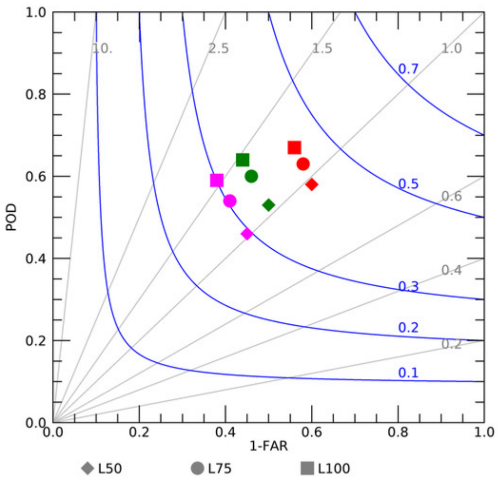
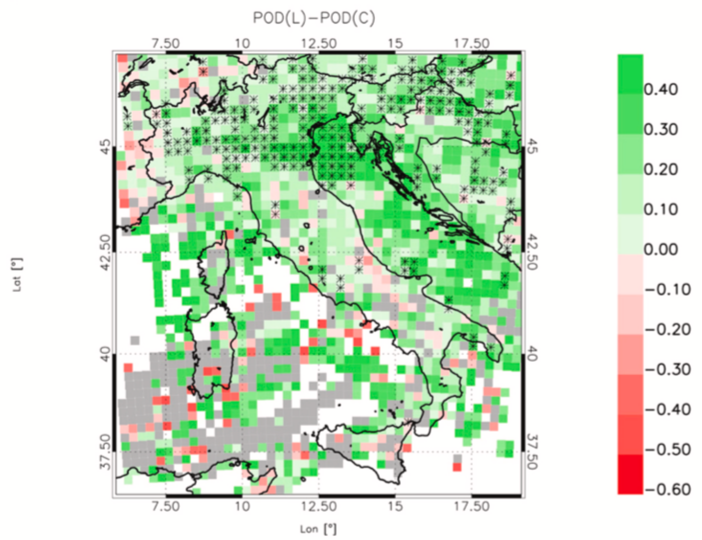


Figure 2: performance diagram for lightning forecast for three different settings of the dynamic lightning scheme (L50, L75, L100) for a total of 162 cases over Italy. From [2].

In the paper [3] we further explored the problem of lightning forecast using lightning data assimilation (LDA) to improve the lightning forecast. We use the Weather Research and Forecasting (WRF) model coupled with the Dynamic Lightning Scheme (DLS) at convection allowing horizontal resolution (3km). We carried out a two-seasons experiment (summer 2020 and fall 2021) providing the forecast of lightning and precipitation for the next 6 h (nowcasting), considering two sub-periods (0-3 h and 3-6 h) for verification. It is shown that LDA can trigger convection missed by the control forecast, without LDA, and/or can redistribute the strokes predicted to be more consistent with observations.
LDA has a positive impact on strokes forecast, improving correct forecasts and reducing false alarms. This improvement is however confined to the first three-hours of forecast with negligible to negative impact for longer time ranges, in line with other studies.

Interestingly, it was shown that the improvement pattern is different in summer and fall, depending on the convection development. In summer the improvement occurs mainly over the land where convection develops vigorously and most of the lightning are assimilated. In fall the convection develops mainly over the sea. As a consequence, lightning are mostly assimilated over the land in summer and over the sea in fall and the following forecast is improved mainly over the land in summer and over the sea in fall. An example for the POD score is shown in Figure 3.

a)



b)

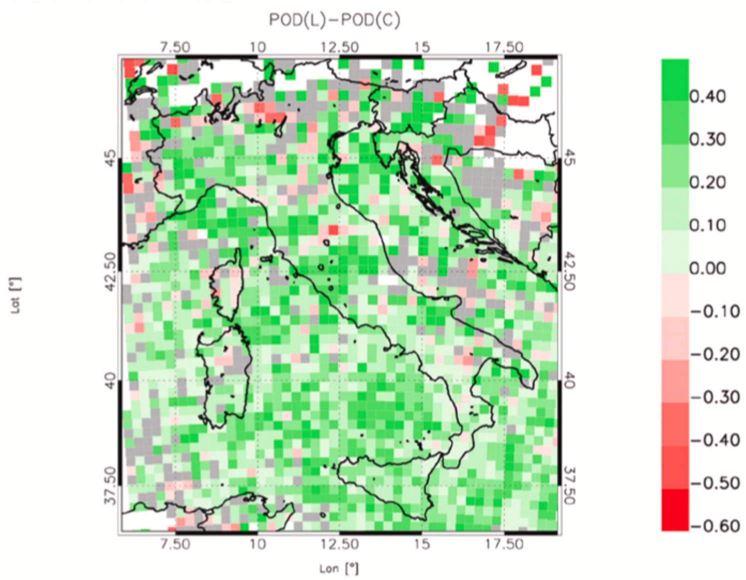


Figure 3. Difference of the scores between the forecast with LDA and the control forecast (in this order): a) POD for summer 2020; b) POD for fall 2021. Greenish colors are positive values, reddish colors are negative values. Grey colors represent grid cells with the same score values for forecasts with or without LDA. The differences are computed for all simulations in each season, considering the first 3 h of forecast and the threshold of 1 stroke per grid cell (24*24 km) per 3 h. Asterisks show grid cells where the statistical significance of the difference of the scores is larger than 90%. From [3].

The paper [4] shows the impact of GNSS-ZTD data assimilation on the precipitable water vapor (PWV) and precipitation forecast. The WRF model is used and GNSS-ZTD data of 388 receivers distributed over the Italian territory are assimilated using the 3D-Var tool distributed with WRF. The experiment considers a period of one month (October 2019) with four simulations per day lasting 12 hours each. In the first 6h, the GNSS-ZTD data assimilation takes place, with a total of seven analyses, i.e. the initial time and the following 6h. The second 6h are used for verification and compared with a control model,

without GNSS-ZTD data assimilation. For precipitation verification a dataset of about 3000 rain gauges distributed over Italy is considered.
PWV is verified hourly, for the hours from 1 to 6 after assimilation, while precipitation is verified on two 3h periods, namely the first and the second 3 hours after assimilation. Results show that precipitation forecast is improved up to 6h. Frequency Bias (FBIAS) and Probability of Detection (POD) increase when data assimilation is performed. However, simulations with data assimilation register a higher False Alarm Rate (FAR) compared to control simulations and this influenced the results for the Equitable Threat Score (ETS), which is also improved by data assimilation but with a reduced impact caused by false alarms. As regards PWV, statistics show a clear improvement of simulations with data assimilation compared to control, with PWV Root Mean Square error (RMSE) almost saved for the first hour forecasting time. As expected, the improvement decreases with forecasting time. Finally, two sensitivity tests are performed. The first test considers a data thinning experiment over a 16-days period, divided into two sub-periods, the days 14-23 October, when heavy and widespread precipitation occurred in the Northwestern Italy and the days 5-10 October, characterized by moderate to intense precipitation. A distance (in this case 20km), at which observation errors become uncorrelated is calculated at a first step. Small differences resulted between this test and the original experiment, even if the experiment with data thinning is worse than the original one for precipitation thresholds lower than 40 mm/3h. In the second test we compared the results of simulations with or without bias removal for the 10-days period 14-23 October finding small differences between the two, but with a slightly better performance when bias removal is applied.
The paper [5] studies the impact of lightning data assimilation (LDA) on the prediction of a thunderstorm occurred on 15 September 2022 over Marche Region, which caused casualties and damages.
Again, the WRF model is used, but in this case with a 3D-Var package developed at CNR-ISAC and already presented above, discussing the paper [1]. Four 3h phases of the events are analysed, using a very short-term (VSF) forecasting approach. Two different model configurations are considered: a configuration (ANL) where lightning data are assimilated until the beginning of the forecasting period, and a configuration (ANL-1H) which assimilates lightning until one hour before the forecasting period. Results are compared with a control simulation, without LDA, which represents the previous day forecast. Both configurations with assimilation calculate three analyses at three consecutive hours. Moreover, a sensitivity test (ANL-1H_4) is performed, considering data assimilation until one hour before the end of the forecasting period, but starting to assimilate lightning data one hour before compared to ANL-1H, with a total of four analyses in this case. Lightning forecast is also studied for all 3h forecasting phases and strokes prediction is performed through the Lynn method (Lynn et al., 2012).
Results show that the previous day forecast of intense convective events can be improved by LDA, giving a better representation both of the intensity and of the location of the event.
Simulations ANL and ANL-1H improved the control performances both for precipitation and for strokes forecast, even if a decrease of the LDA impact is observed for high strokes intensities. The main drawback is that these simulations in VSF are available shortly before the event. The ANL-1H is available before the ANL, but its performance is worse than ANL. For this reason, the ANL-1H_4 sensitivity test was analysed. The ANL-1h_4 simulation is available at the same time of ANL-1H, and results show a substantial improvement for the ANL-1H_4 compared to the ANL-1H, revealing the importance of an additional analysis time.
All in all, for strokes forecast, ANL simulations have a larger POD and a lower FAR compared to ANL-1H simulations, while for precipitation forecast ANL has both a larger POD and a larger FAR than ANL-1H.

References

Lynn, B.H.; Yair, Y.; Price, C.; Kelman, G.; Clark, A.J. Predicting cloud-to-ground and intracloud lightning in weather forecast models. Weather Forecast. 2012, 27, 1470–1488.

List of publications/reports from the project with complete references

Five papers have been published in the framework of this special project.

[1] Federico, S.; Torcasio, R.C.; Puca, S.; Vulpiani, G.; Comellas Prat, A.; Dietrich, S.; Avolio, E Impact of Radar Reflectivity and Lightning Data Assimilation on the Rainfall Forecast an Predictability of a Summer Convective Thunderstorm in Southern Italy. Atmosphere 2021, 12, 958 https://doi.org/10.3390/atmos12080958

[2] Federico, S.; Torcasio, R.C.; Lagasio, M.; Lynn, B.H.; Puca, S.; Dietrich, S. A Year-Long Tota Lightning Forecast over Italy with a Dynamic Lightning Scheme and WRF. Remote Sens. 2022, 14 3244. https://doi.org/10.3390/rs14143244. This paper received the cover of the journal for the mont https://www.mdpi.com/2072-4292/14/14.

[3] Stefano Federico, Rosa Claudia Torcasio, Jana Popova, Zbyněk Sokol, Lukáš Pop, Martina Lagasio, Barry H. Lynn, Silvia Puca, Stefano Dietrich, Improving the lightning forecast with the WR model and lightning data assimilation: Results of a two-seasons numerical experiment over Italy Atmospheric Research, Volume 304, 2024, 107382, ISSN 0169- 809 https://doi.org/10.1016/j.atmosres.2024.107382.

[4] Torcasio, R. C., Mascitelli, A., Realini, E., Barindelli, S., Tagliaferro, G., Puca, S., Dietrich, S., an Federico, S.: The impact of global navigation satellite system (GNSS) zenith total delay dat assimilation on the short-term precipitable water vapor and precipitation forecast over Italy using th Weather Research and Forecasting (WRF) model, Nat. Hazards Earth Syst. Sci., 23, 3319–333 https://doi.org/10.5194/nhess-23-3319-2023, 2023.

[5] Torcasio, R.C.; Papa, M.; Del Frate, F.; Dietrich, S.; Toffah, F.E.; Federico, S. Study of the Intense Meteorological Event Occurred in September 2022 over the Marche Region with WRF Mode Impact of Lightning Data Assimilation on Rainfall and Lightning Prediction. Atmosphere2023,14,1152 https:// doi.org/10.3390/atmos14071152

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.)

We will continue to explore the impact of different data sources on the forecast of deep convective events over Italy and the central Mediterranean. In particular, the special project "Improvement of NWP prediction at the short-range for high impact meteorological events" was approved for the years 2024-2026. In this project, in addition to other observations as radar reflectivity and lightning, the pseudo-observations of the WInd VElocity Radar Nephoscope (Wivern) will be considered (Illingworth, 2018). Wivern will use a Polarimetric Doppler radar at 94 GHz with a conic scan, the first of this type, for the observation of the winds inside the clouds following a cycloid pattern. The assimilation of these winds for specific case studies will be considered in the special project.

Reference:

Illingworth, A. J., and Coauthors, 2018: WIVERN: A New Satellite Concept to Provide Global In-Cloud Winds, Precipitation, and Cloud Properties. Bull. Amer. Meteor. Soc., 99, 1669–1687, https://doi.org/10.1175/BAMS-D-16-0047.1.