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	……………2022/2023……………………………..……
Project Title:	Improvement of very-short term forecast using lightning and radar data assimilation
Computer Project Account:	…………SPITFEDE………………………………..……
Principal Investigator(s):	……Stefano Federico……………………….……
	……………………………………………………….……
Affiliation:	………… CNR-ISAC ……………………..……
Name of ECMWF scientist(s) collaborating to the project (if applicable)	…Claudio Transerici (cmn)……………………..…… …Rosa Claudia Torcasio (it85) ……..……
Start date of the project:	………1 January 2021………………………………..……
Expected end date:	…… 31 December 2023…………………..……

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)			20000000	17300000
Data storage capacity	(Gbytes)			35 TB	88 TB

Summary of project objectives (10 lines max)

The general objective of the project is to evaluate the impact of lightning data assimilation (LDA) and radar reflectivity data assimilation (RDA) on the very-short term forecast over Italy, with emphasis on high precipitation events. This objective was focused on specific goals that can be tackled in the framework of this special project.

The data assimilation is mainly based on lightning and radar reflectivity data, even if some additional data from GNSS-ZTD receivers were tested. Verification was done for the following parameters, depending on the application: precipitation, flashes density, total precipitable water and GNSS-ZTD.

Summary of problems encountered (10 lines max)

No significant problems were encountered during the project. The disk quota of 35 TB is full and additional space was used on ECFS. Should this cause problems, we will transfer some of the datasets elsewhere. The ability to post-process the model output on the Atos computer with the IDL software gave the possibility to leave the dataset on this computer, increasing the amount of disk space required for data storage. The CPU quota is almost exhausted because 17300000 SBU of the total 20.000.000 SBU have been already used (at 10 June 2023). This was caused by the many numerical experiments that were done in the first part of the year at high-horizontal resolution (2-3 km) over Italy. A request for additional resources will be prepared in the next days.

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

In the remainder of the project the focus will be on the assessment of the role of radar reflectivity data assimilation (RDA) and lightning data assimilation (LDA) on the improvement of the Very Short-Term precipitation forecast over Italy (up to 6h). The suppression of negative spurious convection by lightning data assimilation will be also considered. Finally, if additional resources will be provided, the impact of wind data assimilation will be considered for a specific case.

List of publications/reports from the project with complete references

Published papers

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 and Predictability of a Summer Convective Thunderstorm in Southern Italy. Atmosphere 2021, 12, 958. https://doi.org/10.3390/atmos12080958

Rosa Claudia Torcasio; Stefano Federico; Albert Comellas Prat; Giulia Panegrossi; LeoPio D'Adderio; Stefano Dietrich. Impact of Lightning Data Assimilation on the Short-Term Precipitation Forecast over the Central Mediterranean Sea. Remote Sensing 2021, 13, 682.

Federico, S.; Torcasio, R.C.; Lagasio, M.; Lynn, B.H.; Puca, S.; Dietrich, S. A Year-Long Total 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 month https://www.mdpi.com/2072-4292/14/14.

Conference proceeding

Federico, S., Torcasio, R.C., Mascitelli, A., Del Frate, F., Dietrich, S. (2022). Preliminary Results of the AEROMET Project on the Assimilation of the Rain-Rate from Satellite Observations. In: Gervasi, O., Murgante, B., Misra, S., Rocha, A.M.A.C., Garau, C. (eds) Computational Science and Its Applications – ICCSA 2022 Workshops. ICCSA 2022. Lecture Notes in Computer Science, vol 13380. Springer, Cham. https://doi.org/10.1007/978-3-031-10542-5_36

Papers under review

A paper is currently under review on NHESS (https://nhess.copernicus.org/preprints/nhess-2023-18/#discussion).

Torcasio, R. C., Mascitelli, A., Realini, E., Barindelli, S., Tagliaferro, G., Puca, S., Dietrich, S., and Federico, S.: The impact of GNSS Zenith Total Delay data assimilation on the short-term precipitable water vapor and

precipitation forecast over Italy using the WRF model, Nat. Hazards Earth Syst. Sci. Discuss. [preprint], https://doi.org/10.5194/nhess-2023-18, in review, 2023.

Finally, a paper, assessing the impact of the LDA on the lightning forecast is under preparation.

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.

1. **WRF model**

The WRF numerical model is used in this project with Advanced WRF dynamic (WRF-ARW), version 4.1.3. The simulations use one domain, with 635 grid points in the WE and SN directions and 50 unevenly spaced vertical levels with a model top at 50 hPa. The model domain covers the Central Mediterranean and the whole Italian territory. It has a horizontal grid spacing of 3 km. A second version of the model with 850 grid points in both WE and SN directions at 2km horizontal resolution was used for some experiments. The first configuration was used in most of cases and in particular for results in sections 4, 5, 6 and 7.
The physical schemes employed include the Thompson microphysics scheme, the Mellor-Yamada-Janjic scheme, using a one-dimensional prognostic turbulent kinetic energy scheme with local vertical mixing, the 5-layer thermal diffusion for land surface processes scheme, the Monin-Obukhov (Janjic Eta) scheme for surface layer physics, the Dudhia scheme for the short-wavelength radiative scheme, and the Rapid Radiative Transfer Model (RRTM) for the longwave radiative scheme. No cumulus parameterization was used as the simulations of this project are convection-allowing.
Initial and boundary conditions for the simulations are provided by the Integrated Forecasting System (IFS) global model of the European Centre for Medium-Range Weather Forecasts (ECMWF), with few exceptions with the Global Forecasting System. Specifically, we use the analysis-forecast cycle issued at 12 UTC on the day before the actual day to forecast. Data are downloaded at 0.25° horizontal resolution.

2. **Lightning and radar reflectivity data assimilation**

Lightning data assimilation is done in the project with two different techniques: nudging and 3D-Var. Radar reflectivity data assimilation is done by 3D-Var. When lightning data assimilation is made by nudging we follow the scheme of Fierro et al. (2012). Lightning data assimilation made by 3D-Var is performed through pseudo-profiles of saturated relative humidity between the Lifting Condensation Level (LCL) and the -25°C isotherm and then assimilated through WRFDA. The radar reflectivity data assimilation is done using the indirect method in WRFDA accounting for snow and graupel mixing ratio in addition to the rainwater mixing ratio. A saturated mixing ratio, at the model temperature, is assimilated inside the cloud (Gao and Stensrud, 2012).

3. **Forecast verification**

For lightning data assimilation and forecast verification we used the Lightning Detection Network (LINET) data (Betz et al., 2009). This network, which is composed by more than 200 sensors over Europe, observes both Intra Cloud (IC) and Cloud to Ground (CG) strokes, making use of the Time of Arrival (TOA) method. LINET provides the time of occurrence, the amperage and the position for each stroke, and the heights for IC strokes. For data assimilation, only the information regarding the date and time (in milliseconds) and the position (latitude and longitude) of each stroke are used. Furthermore, all strokes recorded in a time range of 1 s and in a spatial range of 10 km are considered as a single flash.
For rainfall verification we used precipitation data from the Italian rain gauge network. This network accounts for about 4000 rain gauges widespread over the Italian territory. Data come from the regional administrations and are collected nationwide from the Department of Civil Protection. The map of the raingauges was shown in the report of the last year.

4. **Results for lightning and radar reflectivity data assimilation**

Up to now the project showed the important and positive contribution of lightning and radar reflectivity data assimilation on the precipitation forecast over Italy. This was assessed mainly on a case studies approach using different data assimilation methods (for example nudging and 3D-Var for lightning). Despite the differences among the methods, data assimilation gives a substantial improvement to the precipitation forecast. For this reason, we implemented an operational version of the WRF model with both lightning and radar reflectivity data assimilation. The forecast uses a very short-term approach in which a 6h data assimilation phase is followed by a 6h forecast. The figure below shows the Equitable Threat Score for the control simulation (red curve, also BCKG), without data assimilation, and for the simulation RL with lightning and radar reflectivity data assimilation (blue curve, also RL) for a period of five months (September 2022-January 2023).

a) b)

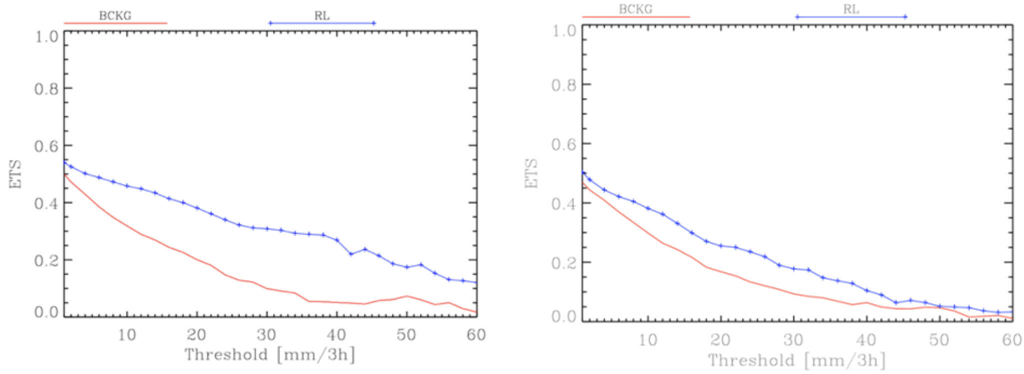


Figure 1: Equitable Threat score for the first 3h after the end of the assimilation period (panel a, also 0-3h forecast period) and between 3 and 6h after the forecast phase (panel b, also 3-6h forecast period).

It is apparent the improvement of the RL simulations compared to the control forecast. While the model performance decreases with the forecasting time because the ETS of the forecast period 3-6h is lower than the corresponding value of the 0-3h phase, the positive impact of LDA and RDA data assimilation lasts at least 6h.

5. GNSS-ZTD data assimilation

The attention was not limited to the lightning and radar reflectivity data assimilation and we considered the impact of the GNSS-ZTD data assimilation on the short-term precipitation forecast over Italy. The analysis considered the month of October 2019 and we used the WRF model at 3km horizontal resolution over Italy. The forecast approach is the very short-term at 6h in which a 3D-Var data assimilation is done every 1h for 6h (seven analysis including the initial time) and then follows a 6h forecast. Four simulations are needed to forecast a whole day. A total of 388 receivers, rather homogeneously distributed over Italy, is considered for data assimilation.

A paper was prepared for this experiment and was submitted for open discussion on NHESS: Torcasio, R. C., Mascitelli, A., Realini, E., Barindelli, S., Tagliaferro, G., Puca, S., Dietrich, S., and Federico, S.: The impact of GNSS Zenith Total Delay data assimilation on the short-term precipitable water vapor and precipitation forecast over Italy using the WRF model, Nat. Hazards Earth Syst. Sci. Discuss. [preprint], https://doi.org/10.5194/nhess-2023-18, in review, 2023. Currently the open discussion in closed and the paper needs major revisions.

Here we just report the main conclusions of the study. The comparison between first guess and ZTD observations showed that the forecast without data assimilation underestimates the water vapor content for the period. The GNSS-ZTD data assimilation partially compensates for this underestimation increasing the water vapor content in the atmosphere. The data assimilation roughly halves both the BIAS and the RMSE statistics for the ZTD. The analysis over the Italian territory shows a general reduction of BIAS and RMSE of the precipitable water vapour thanks to the rather homogeneous and widespread coverage of GNSS receivers.

The precipitation forecast analysis was divided in two time ranges: the first 3h (0-3h) and the second 3h (3-6h) after the last analysis. Results show that the forecast was improved for both time ranges and that the improvement was statistically significant up to the 30mm/3h threshold, which is representative of moderate-intense precipitation.

6. **Lightning prediction**

Lightning prediction is an important task for several applications. It is also a necessary step to implement a spurious convection suppression by lightning data assimilation.

In the second year of the project, the electrification scheme of Lynn et al. (2012) was tested over Italy for 162 cases occurred between 1 March 2020 and 28 February 2021. The cases span the four seasons and reflect the seasonal behavior of lightning: 69 cases occurred in summer, 46 in fall, 18 in winter and 29 in spring.

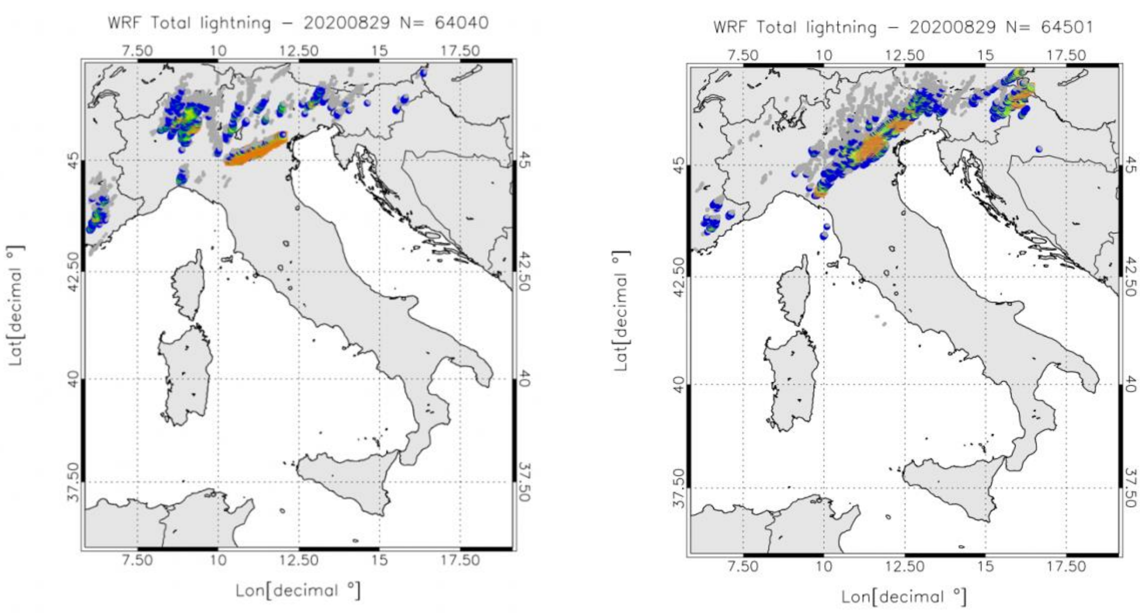
Three different configurations of the lightning dynamic scheme are considered: L50, L75 and L100.

These configurations differ for the key parameter of assumed charge transferred in one second within the convective and stratiform clouds. They are, respectively, $0.5*10^{-4}$ C, $0.74*10^{-4}$ C and $1.0*10^{-4}$C.

The results of this experiment were published in the paper: Federico, S.; Torcasio, R.C.; Lagasio, M.; Lynn, B.H.; Puca, S.; Dietrich, S. A Year-Long Total 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 month https://www.mdpi.com/2072-4292/14/14.

The results of this experiment open the possibility for an operational implementation of lightning forecast. In addition, we started to study the impact of lightning data assimilation on the lightning forecast. This activity started in the second year of this special project and the work is still in progress in this direction. In particular, we are running two seasons (summer 2020 and fall 2021) using two WRF configurations: the control without lightning data assimilation and the simulations with lightning data assimilation. The target is the verification of the lightning forecast at the short-range (0-3h, and 3h-6h). Results will be available in the final report of this project. Here we limit out attention to the result of a case study.

a) b)



c)

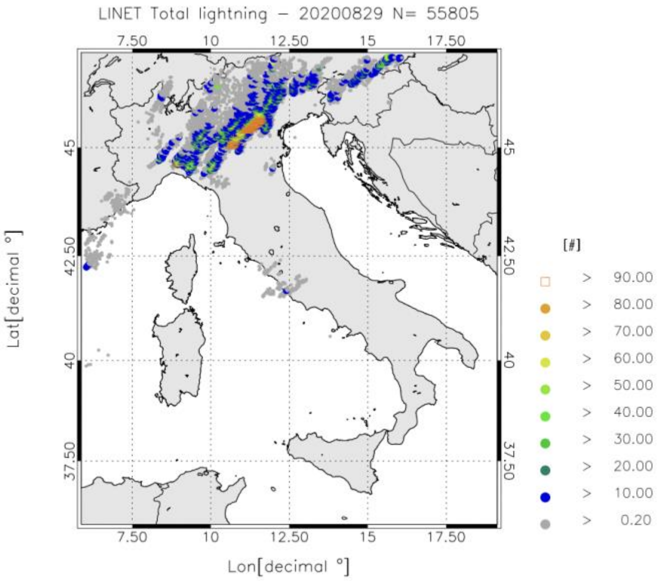


Figure 2: strokes density (number of strokes in the 3h between 09 and 12 UTC on 29 August 2020 for: a) control forecast, without LDA; b) the forecast with LDA, and; c) LINET observations.

Figure 2 shows the strokes density for the 29 of August 2020 between 09 and 12 UTC. The control simulation, without LDA, shows scattered convection over northern Italy. Compared to observations, Figure 2c, the simulated lightning density is concentrated in smaller patterns, even if the amount of lightning simulated is comparable with that observed. The simulation with lightning data assimilation, Figure 2b, shows a lightning density closer to that observed both for position and for the pattern covered by lightning. The number of strokes simulated in good agreement 3h the observations. The result of Figure 2 shows that LDA can improver substantially the lightning forecast. As stated above, this work is in progress and the results will be presented in the final report.

7. **Rain-rate data assimilation**

In the framework of the AEROMET (AEROspatial data assimilation for METeorological weather prediction) project the rain-rate estimated by the geostationary satellite MSG (Meteosat Second Generation) was assimilated in the WRF model. Preliminary results of this work were published in the proceeding of the ICCSA conference. The paper is: Federico, S., Torcasio, R.C., Mascitelli, A., Del Frate, F., Dietrich, S. (2022). Preliminary Results of the AEROMET Project on the Assimilation of the Rain-Rate from Satellite Observations. In: Gervasi, O., Murgante, B., Misra, S., Rocha, A.M.A.C., Garau, C. (eds) Computational Science and Its Applications – ICCSA 2022 Workshops. ICCSA 2022. Lecture Notes in Computer Science, vol 13380. Springer, Cham. https://doi.org/10.1007/978-3-031-10542-5_36.
In this paper we showed the methodology and the result for two cases of the AEROMET project. The project aims at assimilating the rain-rate estimated by meteorological satellites using a simple cloud model and a 3DVar data assimilation scheme. We showed the results for two winter case studies, occurred in winter 2021-2022. The forecast approach is the very short term forecast at 6h, in which a 6h data assimilation phase is followed by a 6h forecast. Four simulations are required to forecast a whole day.
In the first case, a storm acting over the southern Tyrrhenian Sea, was advected towards southern Italy affecting Calabria and Campania regions. In the second case, the storm acted over Liguria with precipitation mainly in the eastern part of the region.
Results show some improvements of the precipitation forecast at the short-range over southern Italy for the first case, and a better representation of the precipitation field for the second case. While the case studies considered in this work are well representative of what AEROMET aims to investigate, because it considers meteorological system over the sea that are advected over the land, a much larger number of cases needs to be investigated in different seasons to quantify the impact of the method.

8. **Conclusions**

This project showed the positive impact of lightning and radar reflectivity data assimilation for the precipitation forecast over Italy. This was the basis to implement an operational forecast using the data assimilation of both data sources. The results for a period of five months using this operational forecast were shown in this report. Lightning forecast was set-up in this project and its potential for an operational implementation was shown in a recent paper.
The assimilation of GNSS-ZTD was performed for a month of intense precipitation over northwestern Italy using a dense network of receivers distributed rather homogeneously over the country. Results are promising because they show the ability of GNSS-ZTD data assimilation to improve the precipitation forecast at the short-term (0-6h) for moderate to intense precipitation (10-30 mm/3h). This subject requires further investigation in future studies.

9. **Future perspectives**

The impact of lightning and radar reflectivity data assimilation on the precipitation forecast will be further explored extending the comparison of the operational forecast with or without data assimilation to a longer period. Part of these simulations will be done using the computing resources of this special project.
Because now we have tools to assimilate and predict lightning, a study on the impact of lightning data assimilation on the lightning forecast will be considered. This study is in progress within this project.
An OSSE (Observing System Simulation Experiments) will be conducted in this project for the wind data assimilation for WIVERN (WInd VElocity Radar Nephoscope). This OSSE will use an ensemble approach for the Medicane Ianos case study. This experiment will enlarge the types of observations used in the special project, and will be performed if additional resources will be dedicated to this project.

References

Betz, H.D.; Schmidt, K.; Laroche, P.; Blanchet, P.; Oettinger, W.P.; Defer, E.; Dziewit, Z.; Konarski, J. LINET—An international lightning detection network in Europe. Atmos. Res. 2009, 91, 564–573

Fierro, A. O., E. R. Mansell, C. L. Ziegler, and D. R. MacGorman (2012). Application of a lightning data assimilation technique in the WRF-ARW Model at cloud-resolving scales for the tornado outbreak of 24 May 2011. Mon. Wea. Rev., 140, 2609–2627, doi:10.1175/MWR-D-11-00299.1.

Gao, J., and Stensrud, D. J. (2012). Assimilation of Reflectivity Data in a Convective-Scale, Cycled 3DVAR Framework with Hydrometeor Classification. *Journal of the Atmospheric Sciences* 69, 3, 1054-1065, available from: <https://doi.org/10.1175/JAS-D-11-0162.1>

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