Preliminary Results of the AEROMET Project on the Assimilation of the Rain-Rate from Satellite Observations

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Abstract. The regions close to the sea are often hit by meteorological systems that generate over the sea and then are advected towards the land. These systems impact the activities over the sea and is it important to predict their occurrence for the safety of the people as well as for the best prediction of ship-routes. The lower number of meteorological observations over the sea compared to the land and the absence of the orographic triggering mechanism, makes prediction of these storms difficult. Satellite observations are very important in this framework because they provide data over both land and sea that can help the prediction of convective storms.

The AEROMET project (AEROspatial data assimilation for METeorological weather prediction) aims to assimilate the rain-rate estimated from satellite observations into the Numerical Weather Prediction (NWP) Weather Research and Forecasting (WRF) model to improve the prediction of convective meteorological systems, especially those originating over the sea. The method to assimilate the rain-rate is straightforward: given the best estimate of the rain-rate, it is assimilated in the model through 3D-Var with a simple cloud model. Two examples, occurred on 10 December 2021 and on 15 February 2022, show the feasibility of the method, nevertheless many cases must be studied to quantify the impact of the assimilation of satellite observed rain-rate on the precipitation forecast.

Keywords: Satellite derived rain-rate · Data assimilation · WRF model

1 Introduction

The Mediterranean is a hot spot for climate change [1] and it is often struck by severe meteorological events that cause flood and flash flood in the area. The

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impact of these events is amplified by the presence of a warm sea, which feeds the storm with huge amounts of water vapor, and the complex orography of the Basin which triggers, amplifies, and focuses the rainfall over specific areas [2–4]. These events are difficult to predict because of the many spatial and temporal scales involved [5]. Numerical weather prediction (NWP) models using convection permitting horizontal resolutions (<= 3 km) can represent the occurrence of heavy precipitation, nevertheless their precision in the representation of the convective rainfall in space, time, and amount is still challenging [6]. One of the reasons for the difficulty of precisely representing the convection in NWP is the lack of information at the local scale in the initial conditions.

Data assimilation is a powerful tool to improve the initial conditions of NWP models at the local scale as reported in many studies [7,8]. The data assimilation in the Mediterranean area is challenging when convective meteorological systems develop in the open sea, where radar observations aren't available. Lightning data assimilation has proven to be a powerful tool to predict convective storms over the land and the sea [9,10], nevertheless lightning is very few in winter and spring and are not always available, even if the launch of the new MTG (Meteosat Third Generation) satellites, with the MTG-LI (Lightning Imager) onboard will ensure the availability of lightning data.

Satellites are an important source of data over the sea and can be successfully exploited to improve the convection prediction by NWP models. The AEROMET project, funded by the regional government of Lazio, aims to explore the assimilation of the rain-rate estimated by meteorological satellites in convective environments. Specifically, the assimilation of the rain-rate is made through a simple cloud model, which is activated when rain-rate estimated by satellites is over a threshold (here 3 mm/h). It is very important to select a threshold representative of convective rainfall, to avoid an over addition of water vapor in the model. Preliminary results of the AEROMET project are shown in this paper. We show the methodology followed to assimilate the rain-rate, and the results for two case studies.

The paper is divided as follows: the WRF model settings and the 3D-Var method are introduced in Sect. 2; in this section we also introduce the dataset used in this work. Section 3 shows the results for the 10 December 2021 and 15 February 2022 case studies, while conclusions are given in Sect. 4.

2 Data and Methods

2.1 WRF Model Configuration and Experiment Description

The meteorological model used in this study is the Weather Research and Forecast (WRF) model with advanced WRF dynamic (WRF-ARW), version 4.1.3 [11]. We considered one grid with a horizontal grid spacing of 3 km and 635×635 grid points in both NS and OE directions. The vertical grid has 50 unevenly spaced levels, extending from the surface to 50 hPa. Model grid parameters are reported in Table 1. The domain (Fig. 1) covers the Italian territory, the Central Mediterranean and Central Europe.

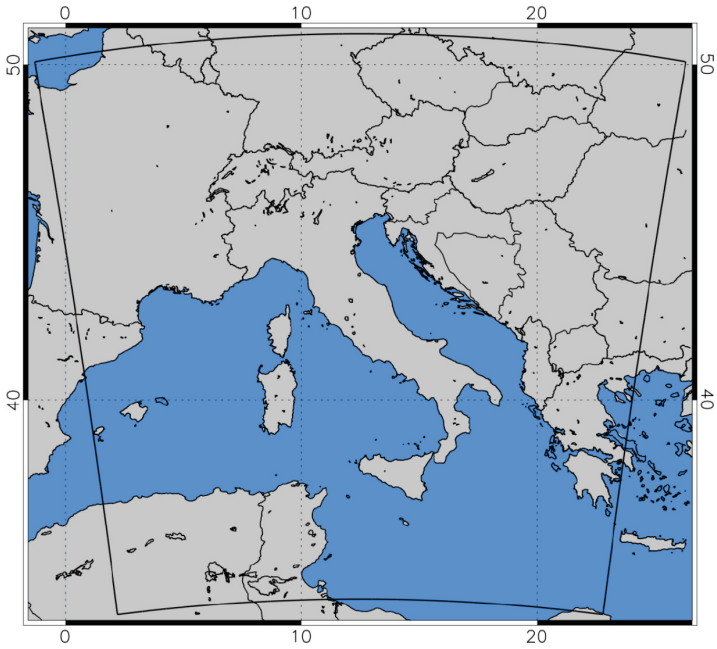


Fig. 1. The WRF domain.

Table 1. WRF model grid parameters. NNXP and NNYP are model grid points in WE and SN directions, respectively. NNZP is the number of vertical levels considered. DX and DY are the grid spatial dimensions in the WE and SN directions, respectively. Lx and Ly represent the domain extension in WE and SN directions, while Lz represents the vertical model extension. CENTLON and CENTLAT are the coordinates of the grid center.

NNXP	635
NNYP	635
NNZP	50
Lx(km)	1905
Ly(km)	1905
Lz(hPa)	50
DX(km)	3
DY(km)	3
CENTLAT	43N
CENTLON	12.5E

The main physical characteristics of the model include the new Thompson microphysics scheme [12], the Mellor-Yamada-Janjic turbulence kinetic energy scheme for the boundary layer [13], the Monin-Obukhov-Janjic scheme for surface layer physics, the five-layer thermal diffusion for land surface processes, the Dudhia scheme [14], and the rapid radiative transfer model (RRTM) [15] for shortwave and longwave radiative schemes, respectively. Radiative scheme is used every 10 min. The time step is 12 s.

Using WRF model with the configuration described above, we analyzed several case studies occurred in winter 2021–2022. For these days, we ran WRF model simulations in two different modes:

- BCKG, a background configuration, which does not assimilate satellite derived rain-rate;
- 3DV, a simulation which assimilate rain-rate data by 3DVar

WRF model was initialized using initial and boundary conditions from European Centre for Medium range Weather Forecast (ECMWF) analysis/forecast available at a horizontal grid spacing of 0.25°. The analysis/forecast cycle issued at 12 UTC on the day before the actual day to forecast were used for initialization.

The forecasts were performed using a Very Short-term Forecast (VSF) approach. More in detail, we ran 4 simulations in order to cover the whole day. Each run lasted 12 h. The first 6 h of the run are used for spin-up the model and for data assimilation in the configuration assimilating the rain-rate, while the last 6 h were used as forecast period. The assimilation scheme is shown in Fig. 2.

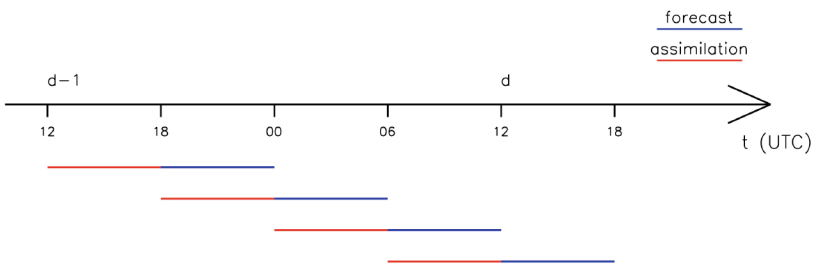


Fig. 2. Assimilation scheme. The red lines represent the assimilation phase, while the blue lines represent the forecast phase. (Color figure online)

In this paper, we focus on two case studies, in order to show the impact of rain-rate assimilation on the precipitation forecast at the short time. In particular, we will describe the period between 00 and 03 UTC on 10 December 2021 and the period between 00 and 03 UTC on 15 February 2022.

2.2 Satellite and MCM Dataset

We assimilated rain-rate estimated by satellites. More specifically we used the dataset H03B distributed by HSAF (EUMETSAT Satellite Application Facility on Support to Operational Hydrology and Water Management). The H03B product is based on a blended MicroWave - InfraRed (MW-IR) technique. The IR images come from the SEVIRI instrument on board the Meteosat satellites, while MW data come mainly from SSMIS, AMSU-A and MHS [16].

It is a near real-time product providing precipitation rate at regular time intervals of 15 min with a spatial coverage from 60° S to 67.5° N and from 80° W to 80° E [16]. The resolution varies from 3 km to 8 km over the full disk and it is consistent with the SEVIRI pixel. On the area considered in this study a spatial resolution of about 5 km is available. At each 15-min interval a calibration procedure is applied to provide one precipitation rate estimate in each grid-box. For assimilation we used the instantaneous rain-rate estimate at the 3DVar time (see next subsection for details).

The model precipitation outputs, both with and without assimilation, were compared with MCM dataset. The Modified Conditional Merging (MCM) technique permits to integrate precipitation measures coming from different instruments, in order to define a better precipitation field both in terms of positioning and amount. This method is based on the methodology, named Conditional Merging, described in [17]. Two kind of data are used as input: raingauges measurements, which give a direct indication of precipitation amount in different points of the domain, and radar estimates, which give information on the spatial structure of the precipitation field. MCM data are available every half an hour, providing the precipitation accumulated in the last hour. For comparison, we used model and MCM precipitation data, accumulated over a 3 h period.

2.3 Assimilation Method

For rain-rate assimilation we used a 3DVar technique. In particular, we used a 3DVar package developed at CNR-ISAC [18], which was employed for many assimilation experiments with RAMS@ISAC model, assimilating data from different sources, going from radar reflectivity and lightning data [2,7,19] to GPS-ZTD data [20]) and which is now applied to the WRF model.

In the AEROMET project a simple cloud model to assimilate the rain-rate is proposed in the 3D-Var framework: for grid points where the rain-rate is larger than a given threshold (3 mm/h was selected as a first threshold through trial and errors), the atmospheric column is saturated from the LCL (Lifting Condensation Level) to the −25 °C isotherm. The LCL is estimated from the model output and because the cloud top is at −25 °C. With this setting, we are assuming a convective cloud developing, with high vertical extension. For this reason, a minimum threshold of rain-rate must be considered to avoid an excessive addition of water vapor to the model that could result in too many false alarms of the predicted rainfall. After inspection of the rain-rate of the dataset

H03B for several cases and few simulations for tuning the method, a minimum threshold of 3 mm/h was adopted.

To further explore this point, we consider the results of the rain-rate data assimilation on the 10 December 2021 at 18 UTC (Fig. 3), one of the two cases considered in this paper. Figure 3a shows the rain-rate of the H03B dataset; the whole southern Italy is interested by a storm with rain-rates up to 10 mm/h. Convection occurs both over the land and over the sea. Figure 3b and Fig. 3c show the innovations at 1270 a.s.l. for the rain-rate thresholds of 3 mm/h and 5 mm/h. The innovations are represented for the mixing ratio of the water vapor, instead of relative humidity. As stated above, the model dependent variable is the water vapor mixing ratio and innovations must be converted from relative humidity to mixing ratio before being used by WRF. Interestingly, the innovations on the west side of the Italian peninsula are larger than those on the eastern side. This is caused by the fact that the background is comparatively more humid on the east side of Italy for this specific case.

Comparing Fig. 3b and Fig. 3c it is apparent that the amount of water vapor assimilated into WRF using the 3 mm/h threshold, is much more extended and representative of the observed rainfall occurring over the area compared to the 5 mm/h threshold. The subjective inspection of other cases led to the same result, and it was decided to adopt the 3 mm/h thresholds for the winter season.

It is finally noticed that, as the cloud model assumes a saturated profile from LCL to −25 °C isotherm, the innovations are always positive.

The above method was applied only when the rain-rate estimated by the H03B dataset is larger than 3 mm/h. In a future development of the AEROMET project, a neural network approach will be adopted to discriminate a threshold for the data assimilation of the rain-rate.

Rain-rate assimilation is done by generating a relative humidity pseudo-profile where the estimated rain-rate is higher than 3 mm/h, both over sea and over land. As said, this pseudo-profile is saturated between LCL and the −25 °C layer, with no data elsewhere (i.e. for heights lower than LCL and higher than −25 °C). The parameter assimilated by the model is the water vapor mixing ratio and, therefore, the relative humidity profile is converted to water vapor mixing ratio before being assimilated by the model. The 3DVar method consists in the minimization of a cost function, given by:

$$J(\boldsymbol{x}) = \frac{1}{2}(\boldsymbol{x} - \boldsymbol{x}_b)^T B^{-1}(\boldsymbol{x} - \boldsymbol{x}_b) + \frac{1}{2}(H(\boldsymbol{x}) - \boldsymbol{y}_o)^T R^{-1}(H(\boldsymbol{x}) - \boldsymbol{y}_o) \quad (1)$$

where $\mathbf{x}$ represents the state vector, $\mathbf{B}$ and $\mathbf{R}$ are the background error matrix and the observation error matrix, respectively, y_o are the water vapor mixing ratio pseudo-profiles and H is the observation operator, which is used to obtain the water vapor mixing ratio profiles in correspondence of the pseudo-observations.

The cost function is calculated by means of the conjugate gradient method. The background error matrix used for the experiment is calculated by NMC method [21] on a period representative of the season in which the case study

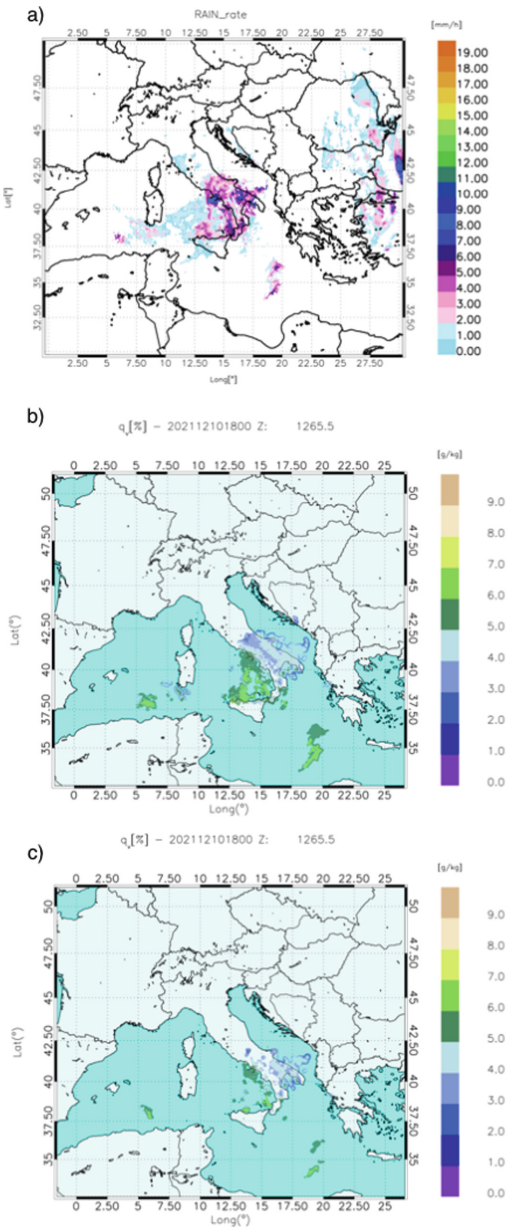


Fig. 3. (a) rain-rate from H03B at 18 UTC on 10 December 2021, (b) innovations of water vapour mixing ratio at 1270 m a.s.l. for 3 mm/h threshold, (c) as in (b) for 5 mm/h.

occurred. As said, we performed an assimilation phase of 6 h. For this phase, we ran the 3DVar every one hour.

3 Results

In this section we consider the results of the application of the method for the 10 December 2021 in the period 00-03 UTC and for the 15 February 2022 between 00 and 03 UTC.

The first period refers to the simulation started at 18 UTC on 09 December 2021 and the 00-03 UTC forecast is at the end of the assimilation period (between 18 UTC on 09 December 2021 and 00 UTC on 10 December 2021). The observations and the innovations (i.e. the difference between the analysis and background field) of the last analysis assimilated in the WRF model is shown in Fig. 4. For the innovations we consider the relative humidity field at 2830 m a.s.l., nevertheless innovations are found at all vertical levels of the WRF model, through the application of the 3D-Var method. Figure 4a shows the rain-rate derived from METEOSAT observations, which are the input of the 3D-Var in AEROMET. As stated, we consider only the grid-points with the rain-rate above 3 mm/h. There are few precipitating cells over the southern Tyrrhenian Sea and over Calabria. Other areas of precipitation are over the France, the Balkans and the Adriatic Sea. Figure 4b shows the innovations of relative humidity at about 2830 m a.s.l. The relative humidity increases by more than 20% over the southern Tyrrhenian Sea, showing several convective cells developing over the area.

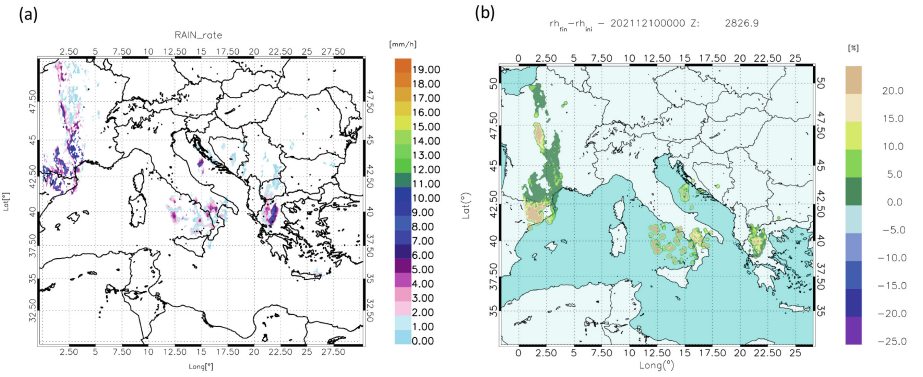


Fig. 4. (a) Rain rate estimated by H03B "copyright (2022) EUMETSAT", (b) Relative humidity field innovation at 2830 m a.s.l.

The impact of the rain-rate assimilation on the precipitation forecast between 00 and 03 UTC on 10 December 2021 is shown in Fig. 5. Comparing the precipitation forecast of the background (Fig. 5a) and of the analysis (Fig. 5b) few differences arise: the precipitation over Calabria (the southernmost tip of Italy)

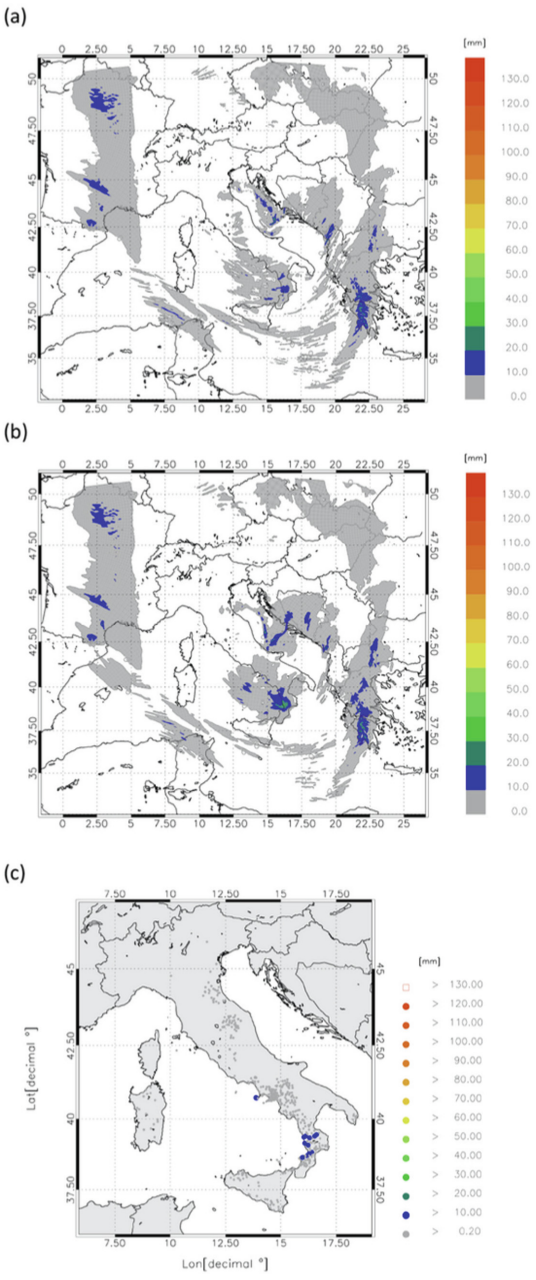


Fig. 5. Precipitation between 00 and 03 UTC on 10 December 2021 for (a) Background model (BCKG), (b) model with rain-rate assimilation (3DV), (c) MCM dataset observations.

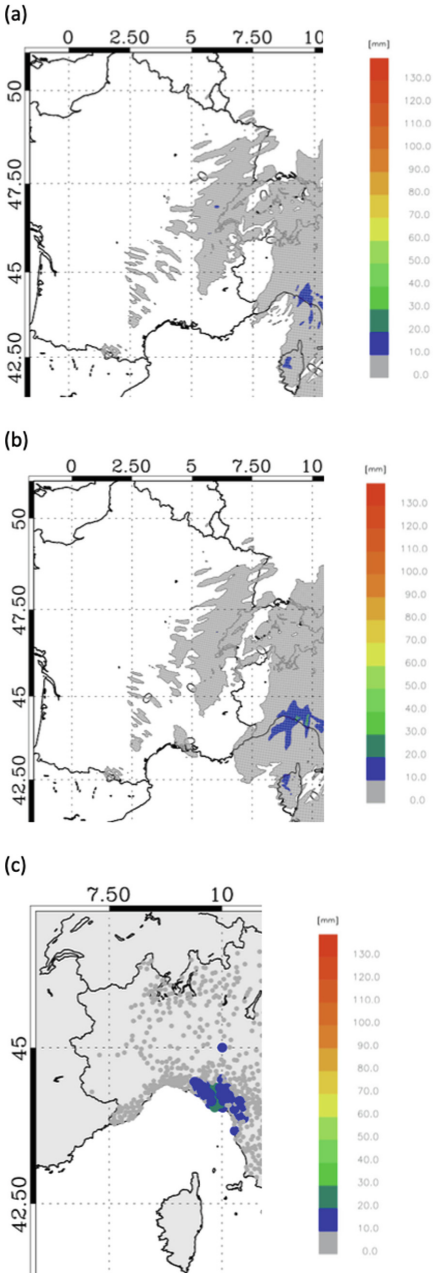


Fig. 6. Precipitation between 00 and 03 UTC on 15 February 2022 for (a) Background model (BCKG), (b) model with rain-rate assimilation (3DV), (c) MCM dataset observations. Only the northwest area of the domain is shown for clearness

is larger in the forecast with rain-rate data assimilation compared to the background, in better agreement with observations (Fig. 5c); the rainfall over Campania, underestimated by the background is correctly simulated by the forecast assimilating the rain rate.

Interestingly, the impact of data assimilation over France is reduced because the innovations are smaller (most of times <5%, Fig. 4b). There are some aspects of the forecast that are less satisfactory as the decrease of the precipitation in some parts of the Central Italy, which are better predicted by the background. It is finally noticed that rainfall increases over the sea for the simulation with data assimilation, for example over the southern Tyrrhenian Sea or north of the Balearic Islands. The impact of the rain-rate data assimilation on the precipitation forecast over the sea will be also considered in AEROMET.

A second case study refers to the 15 February 2022, between 00 and 03 UTC and affected the eastern part of the Liguria region, in the northwest of Italy. The analysis at 00UTC (not shown), which is the last analysis assimilated by the simulation, shows high water vapour innovations (>20%) in the eastern part of Liguria, west Piedmont region and southern France. Figure 6 shows the impact of data assimilation on the precipitation between 00 and 03 UTC. The domain is zoomed over the NW of Italy for clearness. Rainfall observations (Fig. 6c) show moderate precipitation over Liguria with a maxima in the range 20–30 mm/3 h. The background forecast (Fig. 6a) shows an amount between 10 and 20 mm/3 h and the precipitation area is smaller than observed. The forecast with the assimilation of the rain-rate has a better performance compared to the background: first, the observed precipitation area above 10 mm/3 h is better represented; second, the precipitation amount predicted is between 20 and 30 mm/3 h, in good agreement with observations, and the positioning of the largest precipitation amount is very satisfactory.

4 Conclusions

This paper shows 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. 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 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. Moreover, the verification of the rainfall over the sea it is another problem that AEROMET will assess.

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