Heavy Rain Forecasting by Model Initialization With LAPS: A Case Study

Alessandro Tiesi, Mario Marcello Miglietta, Dario Conte, Oxana Drofa, Silvio Davolio,
Piero Malguzzi, and Andrea Buzzi

***Abstract*—Results of the assimilation of high-density data to initialize the high-resolution meteorological model MOLOCH (CNR-ISAC) are described. The local analysis and prediction system (LAPS), a mesoscale data assimilation system developed at NOAA, is applied to modeling a case study of heavy precipitation that occurred over Liguria, north-western Italy, on November 4, 2011, causing severe flood in the city of Genoa. This case is representative of some episodes that affected the region in the last few years, where the coastal orography, besides enhancing the convective uplift, contributed to the formation of convergence lines over the sea, responsible for the onset of convective cells. The present work aims at the implementation of a model-based operational short-range prediction system, with particular focus on quantitative precipitation forecasting in a time range up to 12–24 h. The use of LAPS analysis as initial condition for the MOLOCH model shows a positive impact on the intensity and distribution of the simulated precipitation with respect to the simulations where only large-scale analyses are employed as initial conditions. Effects on the models simulations are due to the assimilation of surface network data, radio-sounding profiles, radar and satellite (SEVIRI/MSG) data.**

***Index Terms*—Data analysis, high-resolution weather forecast, model initialization.**

I. INTRODUCTION

THE NUMERICAL weather prediction (NWP) of intense meteorological events is a difficult task, mainly due to the chaotic nature of the atmosphere. Particularly in the presence of strong small-scale instabilities, like convective instability, which is very often responsible of local-scale severe weather and heavy precipitation, errors in model initial conditions may grow with time very rapidly [1]. Forecast errors originate both from uncertainties in the initial conditions, mainly due to the lack of sufficiently dense data sources resolving mesoscale features, and from deficiencies in NWP models, due to the approximate numerical methods used in solving the equations and, in particular, to the physical parameterizations representing sub-grid processes [2].

In spite of the above limitations, for forecasting times exceeding a couple of hours, the prediction of atmospheric convective events and of quantitative precipitation can rely almost exclusively upon numerical models. Therefore, mesoscale data assimilation (DA), aimed at defining suitable initial conditions for high-resolution meteorological models, is an essential step to properly simulate severe weather phenomena. Available mesoscale data from both local measurements and high-resolution remote sensing retrievals can have an important impact on high resolution forecasts aimed at resolving the convective scales.

The local analysis and prediction system (LAPS, https://laps.noaa.gov/) is a numerical tool designed at the National Oceanic and Atmospheric Administration (NOAA, USA) for the generation of mesoscale analyses. LAPS analyses, based on the Barnes recursive approach [3], can be used as initial conditions for limited-area meteorological models as well as a tool to construct consistent 3-D atmospheric fields suitable for nowcasting applications [4]–[7]. LAPS allows the exploitation of meteorological data coming from any sort of conventional and nonconventional sources, including remotely sensed data.

The LAPS system has been recently implemented to initialize the two meteorological models developed at CNR-ISAC (hereafter ISAC), BOLAM and MOLOCH. BOLAM is a hydrostatic limited area model, appropriate for grid spacing of the order of 10 km [8], [9]. MOLOCH is a nonhydrostatic model that allows an explicit representation of atmospheric deep convection (“convection permitting model”) and is appropriate for simulations with grid spacing of the order of 1 km [10]–[12]. More details on the above models are provided in Section III. In the configuration implemented at ISAC (http://www.isac.cnr.it/dinamica/projects/forecasts/index.html), BOLAM forecasts are used to provide initial and boundary conditions (IC/BC) to MOLOCH, so as to bridge the gap between coarse time-space scales of global analyses/forecasts and a convection-resolving grid.

In this paper, LAPS analyses, exploiting mesoscale data assimilation, are used to provide initial conditions to both BOLAM and MOLOCH models. The assimilation and forecasting experiments presented here are based on a heavy rain episode, which affected the town of Genoa and the surrounding area on November 4, 2011. The amount of precipitation of this event exceeded 500 mm in 24 h. The consequent flooding caused several casualties and widespread damages. The limited

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A. Tiesi, O. Drofa, S. Davolio, P. Malguzzi, and A. Buzzi are with the National Research Council of Italy (CNR), Institute of Atmospheric Sciences and Climate (ISAC), I-40129 Bologna, Italy (e-mail: a.tiesi@isac.cnr.it; o.drofa@isac.cnr.it; s.davolio@isac.cnr.it; p.malguzzi@isac.cnr.it; a.buzzi@isac.cnr.it).

M. M. Miglietta is with the National Research Council of Italy (CNR), Institute of Atmospheric Sciences and Climate (ISAC), I-73100 Lecce, Italy (e-mail: m.miglietta@isac.cnr.it).

D. Conte is with Euro-Mediterranean Center on Climate Changes (CMCC), I-73100 Lecce, Italy (e-mail: d.conte@gmail.com).

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area models BOLAM and MOLOCH, initialized with global model analyses (ECMWF-IFS or NOAA-GFS) in the absence of mesoscale assimilation, underestimated the rainfall amount for this event [12]. Thus, the use of LAPS analysis as initial conditions for both models, in particular for MOLOCH, is expected to improve the quantitative precipitation forecast (QPF) at convection-permitting resolution. The final purpose of the present study is a possible operational implementation of the modeling chain LAPS-BOLAM-MOLOCH, in order to help releasing timely and more accurate warnings in case of significant and severe events.

This paper is organized as follows. Section II provides a short description of the case study and of the typical problems associated with the numerical modeling of small-scale phenomena. Sections III and IV briefly depict the tools used here, namely the meteorological models and the LAPS system, the software interfaces designed for coupling LAPS with BOLAM and MOLOCH, as well as the observational data entering the analysis/assimilation procedure. Section V describes the results of the assimilation and forecasting exercise, evaluating the benefits induced by the assimilation itself on the forecast, in particular on QPF. Conclusion is drawn in Section VI.

II. Genoa Flooding Episode and Its Meteorological Modeling

Precipitation in coastal areas of the Mediterranean Sea can reach significant intensity and amounts due to a combination of dynamical factors, ranging from cyclogenesis and cyclones to local convection [13], [14]; which can be enhanced and maintained quasi-stationary by the presence of steep orography [15]. Also, particularly in the fall season, the temperature difference between the sea surface and the atmosphere enhances sensible and latent heat fluxes, which constitute an important source of energy for precipitating systems [16].

Northwestern Italy is characterized by a complex topography, as the Maritime Alps and the northern Apennines face the Ligurian Sea and the northern Tyrrhenian Sea. Such mountain chains, besides directly forcing vertical motions, possibly triggering and maintaining deep moist convection, may also favor the formation of mesoscale low-level flows and of convergence lines between air masses of different thermodynamic characteristics [12]. This effect can result in the development of quasi-stationary convective cells over the Ligurian Sea. The convective cells regenerate over the sea, migrate slowly toward the coast and reinforce over the orographic slopes, ending up in very intense precipitation episodes [12], [17], [18]. Thus, these coastal areas appear particularly exposed to the risk of floods and flash floods [17].

A typical Mediterranean episode of this kind occurred over Genoa on November 4, 2011. Heavy precipitation caused floods of small river basins, provoking six casualties and significant damages to local infrastructures. A detailed description of the meteorological and hydrological situation characterizing the episode is reported in [17] and [19]. Buzzi *et al.* [12] presented a modeling-based study of this episode, showing a comparison with observations, for different model configurations and grid spacing. In particular, they showed that the use of a horizontal grid spacing in the range between 1.0 and 1.5 km in the numerical meteorological model MOLOCH allows simulating the rain quantity close to the observed records. Thus, a very high-resolution of the nonhydrostatic model is required for an accurate description of the convection dynamics and of their feedback on the density current triggering the formation of new cells. However, high-resolution modeling is a necessary but not sufficient condition for an adequate QPF if the initial state of the atmosphere does not represent the relevant small scales of motion. Such scales can be introduced into the initial condition only by means of a proper model initialization, i.e., applying a high-resolution analysis tool capable of assimilating dense mesoscale data.

III. BOLAM and MOLOCH Models

As anticipated in Section I, BOLAM and MOLOCH are numerical meteorological models developed at ISAC. BOLAM is a limited area hydrostatic model ([8], [9]); in the present study, it is implemented to produce simulations for a domain extending over the entire European continent, part of North Africa and the Eastern Atlantic Ocean. The horizontal grid spacing is 8.3 km (522×394 longitude–latitude grid points), with 50 vertical levels (plus 7 soil layers). Atmospheric convection is parameterized using a modified version of the Kain–Fritsch scheme [20]. Initial and boundary conditions are provided by 3-h ECMWF-IFS global model analyses/forecasts sampled at the resolution of 0.25° in latitude and longitude.

The BOLAM hourly forecasts are used to define the initial and boundary conditions for the nested high-resolution model MOLOCH [10]–[12]. MOLOCH solves explicitly the equations for a fully compressible and nonhydrostatic atmosphere, including microphysical and soil processes. The nested domain (see Fig. 1), centered over Liguria, covers the northwest of Italy with a grid spacing of 1.5 km (514×514 longitude–latitude grid points), 50 vertical levels, and 7 soil layers. Both BOLAM and MOLOCH use grids in a rotated coordinate system, which assures mesh isotropy at the centre of the domain. In the numerical experiments described here, the MOLOCH simulations start at 00:00 UTC, the same initial time of the BOLAM forecasts, and run for 24 h. This means that in practice the MOLOCH initial condition is a higher-resolution downscaling of the BOLAM fields. The model starting times are set coincident for both models, allowing for an assessment of the net impact of the use of the same analysis as initial condition for each model.

IV. Implementation of LAPS Data Analysis for the Meteorological Models

As mentioned above, local scale information must enter the initial conditions of nonhydrostatic, high-resolution numerical models, such as MOLOCH, if convective scales related to QPF in the (very) short range have to be explicitly simulated. The local scale information can be obtained by exploiting local meteorological data (typically surface mesoscale networks, aircraft data, etc.) and remotely sensed data (from radars and satellites). While surface data are available over land in highly

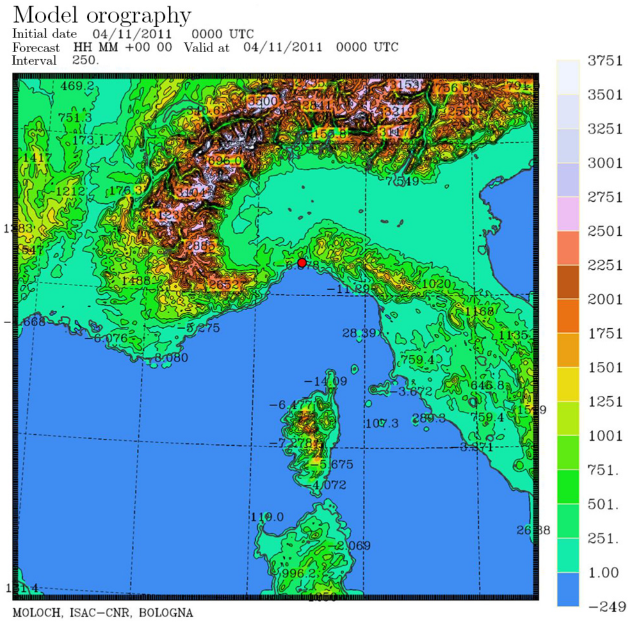

Fig. 1. Domain and topography (contour interval 250 m) of the high-resolution model MOLOCH characterized by the steep orography due to the Alps and the Apennines. The red spot marks the position of Genoa.

populated geographical zones (at least over Europe), remotely sensed data (in practice satellite data) may help in filling gaps over oceans and deserts.

LAPS is a tool designed to perform meteorological data analysis at the mesoscale. LAPS has been developed at the Earth System Research Laboratory (ESRL) of NOAA [4]–[7], [21], [22]. LAPS has been designed to perform 3-D analyses on a limited domain by ingesting and harmonizing data recorded by a variety of sources and platforms: surface stations, radio-soundings, wind profilers, instrumented and commercial aircraft, and meteorological radars and satellites.

LAPS analyses are performed by means of separated customizable modules for winds, temperature, moisture, and cloud content of ice and water. The modules are based on different approaches: the interpolation method implemented in the early versions is based on the recursive Barnes scheme [3]. However, more recent versions are migrating toward an implementation of the variational approach (3DVAR and 4DVAR) with the perspective of application to the Ensemble Kalman filter (EnKF) [23]–[25]. The LAPS version used to produce the analyses for the model initialization shown in this paper is the 0-46-1, and implements a mixed approach (Barnes and 3DVAR). Developments are due to ongoing collaboration of NOAA with several worldwide institutions, including ISAC [26], [27].

LAPS performs analyses of data by modifying a background field (typically a gridded coarse analysis or a model forecast) to produce gridded analyzed fields. Backgrounds fields are created by the LAPS ingestion module (see details in Section IV-B), while the SEVIRI/MSG data are provided by a module developed at ISAC to ingest the European geostationary satellite data in the LAPS analyses [26], [27]. Suitable interfaces between the ISAC models and LAPS have been created and inserted into the LAPS ingestion module in order to provide LAPS with the background fields derived from model analyses or forecasts, consistent with ISAC model grids, orography, coordinates, and variables (see also Section IV-A).

The sequential assimilation scheme starts with the wind analysis near the surface and in the free atmosphere. Then the surface module provides near-surface analyses of temperature and humidity. The free atmosphere analysis of temperature, cloud condensate, and moisture are then performed in sequence and merged with the surface analysis. A final module processes the analyzed fields for the interfaces constructed to return the analyzed gridded fields to the ISAC models.

Several preliminary tests have been made to check and eventually modify several parameter values of the LAPS modules. For example, some parameters have been tuned to the data density and topographic characteristic of the area of interest.

In the present study, LAPS provides the initial conditions for both BOLAM and MOLOCH, assimilating meteorological data from surface observations (METAR and SYNOP), atmospheric soundings (RAOB), meteorological radar reflectivity and radiances recorded by the geostationary satellite sensor SEVIRI, on board of the Meteosat Second Generation (MSG).

A. LAPS Interfaces With BOLAM and MOLOCH

The interfaces needed to couple LAPS with BOLAM and MOLOCH were not available and had to be developed and implemented at ISAC. Actually, double-directional interfaces (one for each model) are needed to operate LAPS in combination with a meteorological prognostic model. The input interface provides the suitable (model) background fields to LAPS, as it converts the meteorological fields defined in the prognostic model format/grid (analysis or forecast) to the LAPS format, preserving the specific horizontal coordinates and topography of the model but interpolating from the model vertical coordinate to constant pressure levels required by LAPS (see below). The output interface converts back the LAPS analysis into the model grid and format (including vertical interpolation from pressure to model hybrid coordinates), to be used as model initial condition. For this purpose, it was necessary to modify substantially the LAPS module that defines the horizontal domain. Since ISAC models operate on latitude-longitude rotated coordinate system, not natively available in LAPS, the option of rotated geographical grid was coded and added to the existing options (polar stereographic, Lambert conformal, and Mercator). In this way, horizontal interpolation is not needed, preventing the introduction of large errors in areas with steep orography, as the one represented in Fig. 1.

Concerning the vertical coordinates, interpolation cannot be avoided, since LAPS works only on pre-defined constant pressure levels, while ISAC models use different hybrid terrain-following vertical coordinates (BOLAM uses a scaled pressure, while MOLOCH uses a scaled height). In the vertical interpolation procedures implemented in the LAPS interfaces, the number of LAPS pressure levels has been set to 150. Such high number of levels was necessary in order to minimize the interpolation error in both the input and output interfaces. Preliminary numerical tests were performed in order to test whether LAPS pseudo-analyses (i.e., analyses without

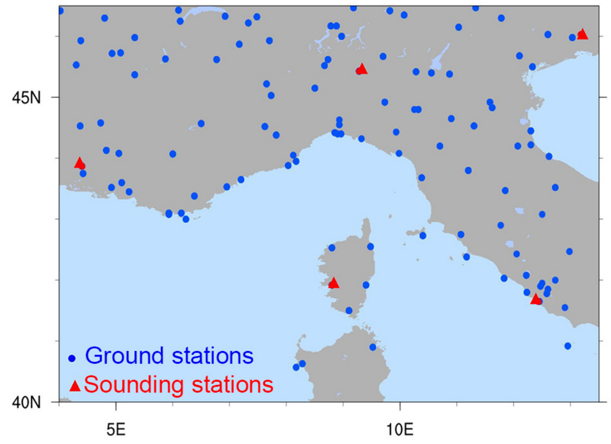

Fig. 2. Map of surface meteorological stations (blue points) and radio-sounding locations (red triangles) available inside the geographic domain used for the present case study.

data ingestion) appreciably modified the background fields. Actually, this test turned out to be crucial and allowed to spot and improve several critical aspects of LAPS. Application of all the above measures assured that the application of LAPS in the absence of data to be assimilated did not modify appreciably the model forecasts.

B. Data Sources

Four different kinds of data are assimilated in the present study: surface observations, upper air soundings, satellite radiances, and radar reflectivity. All assimilated data derive from observations made in the time interval between 23:30 UTC of November 3, 2011 and 0:30 UTC of the following day, nominally referred to 00:00 UTC of the November 4, 2011. For each set of data, it has been necessary to implement some *ad hoc* data conversion interfaces in order to adapt the individual data formats to the LAPS ingestion modules.

1) Surface Observation Data: Surface data have been provided by the Regional Environmental Protection Agency of the Liguria Region (ARPAL). The set of meteorological surface data includes the METAR and SYNOP reports collected over a large European domain (used for BOLAM) and the Liguria Region network. Within the MOLOCH domain, the number of surface stations is in total 124 (see Fig. 2). Surface data provide information on pressure, wind, temperature, and humidity. The measuring frequency of stations ranges from 15 min to 1 h. For the surface data analysis implemented here, all data recorded within a 60-min time window centered on the analysis instant have been used.

2) Sounding Data: The sounding data have been provided by ARPAL (triangles in Fig. 2). The stations used for the analysis cover Europe and North Africa.

3) Satellite Data: The module performing the ingestion of SEVIRI/MSG data into LAPS has been developed at ISAC, since LAPS originally did not consider the assimilation of the European geostationary satellite data [26], [27]. Five SEVIRI/MSG channels are used by LAPS analysis: the visible VIS006, the infrared channel IR_039, the water vapor WV_062, and the thermal infrared IR_108 and IR_120. Preliminary tests performed at ISAC have shown a substantial impact of the satellite data on cloud and humidity analysis, especially in the lower atmosphere (not shown). However, such impact has a minor effect on model simulations.

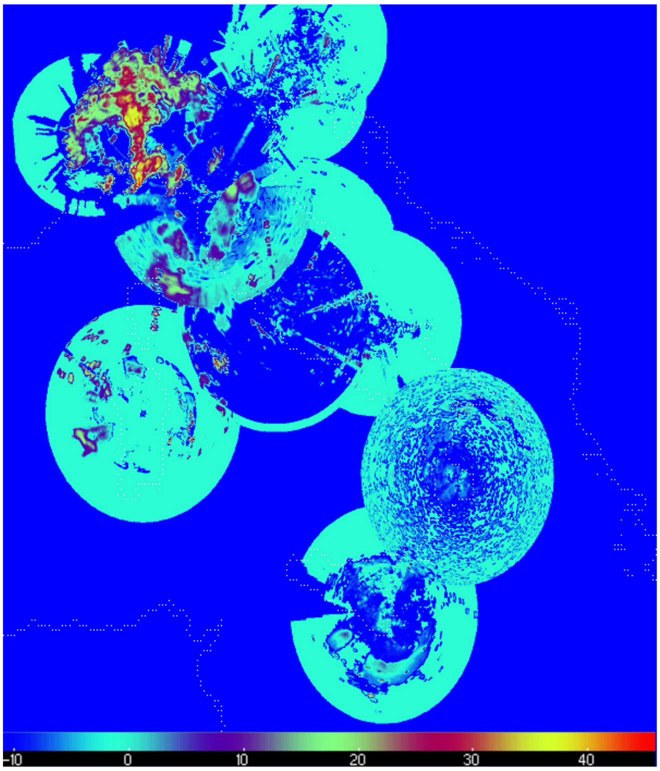

Fig. 3. Mosaic of radar reflectivity (dBZ) covering Italy at 1-km resolution and 2-km height at 00:00 of November 4, 2011.

Another issue concerned the analysis for large domains extending to high latitudes. In such cases, due to the observation geometry and the low height of the sun on the horizon, the resulting visible albedo cannot be defined (twilight effect) and the analysis may affect negatively the cloud cover field at high latitudes. However, this problem does not affect the present simulations at much lower latitudes.

4) Radar Reflectivity Data: The radar reflectivity composite over Italy is provided by the National Civil Protection Department and by the International Centre on Environmental Monitoring (CIMA). The reflectivity data used in LAPS are at constant altitude plan position indicator (CAPPI). The CAPPI reflectivity at the heights of 2, 3, and 5 km all over Italy, with 1-km horizontal resolution, is ingested into LAPS at 00:00 UTC of November 4, 2011 (Fig. 3 shows the data at 2-km height).

V. CASE STUDY: THE GENOA FLOOD

Genoa is a densely populated town with a high anthropic impact, being confined into a narrow coastal area comprised between the Liguria Sea and the Apennines Mountains surrounding the Gulf of Genoa (see Fig. 1). Several creeks crossing the urban area can overflow when intense precipitation occurs locally or in the upper portions of the catchments. Fig. 4 reports

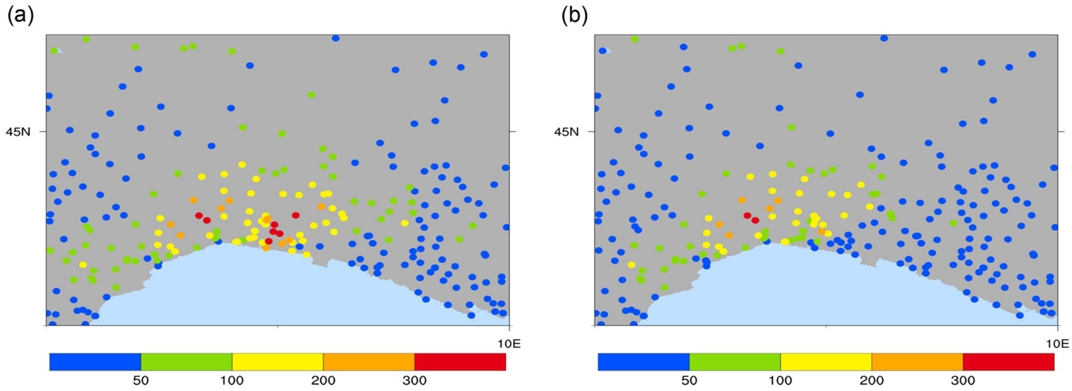

Fig. 4. Accumulated precipitation (kgm^{-2}) in (a) 24 and (b) 12 h, for the period ending at 00:00 UTC of November 5, 2011.

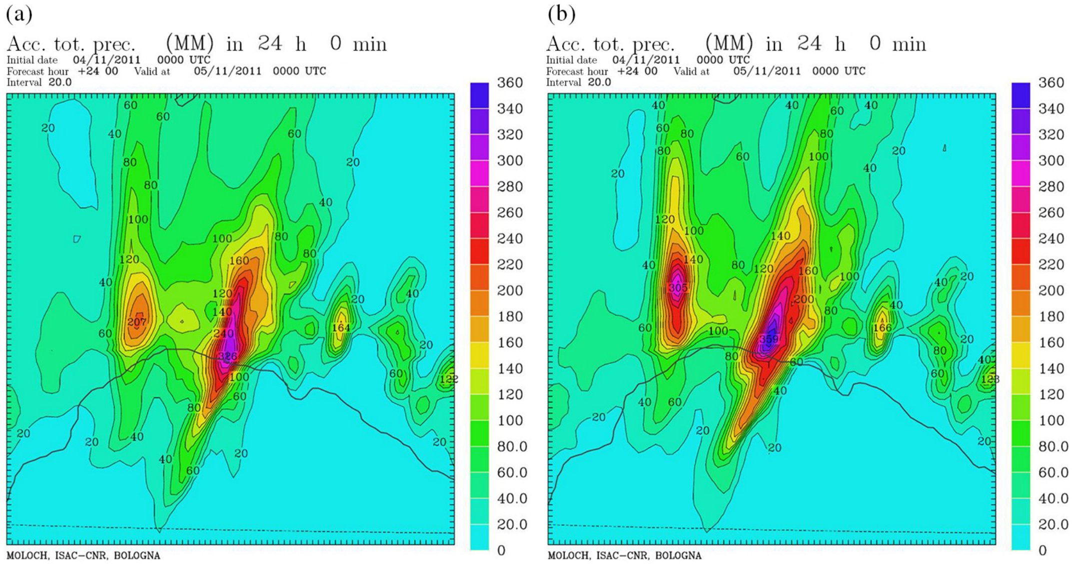

Fig. 5. 24-h accumulated precipitation simulated by MOLOCH (a) without LAPS and (b) with LAPS assimilation. The integration ends at 00:00 UTC of November 5, 2011. (a) Ctrl MOLOCH. (b) LAPS + MOLOCH.

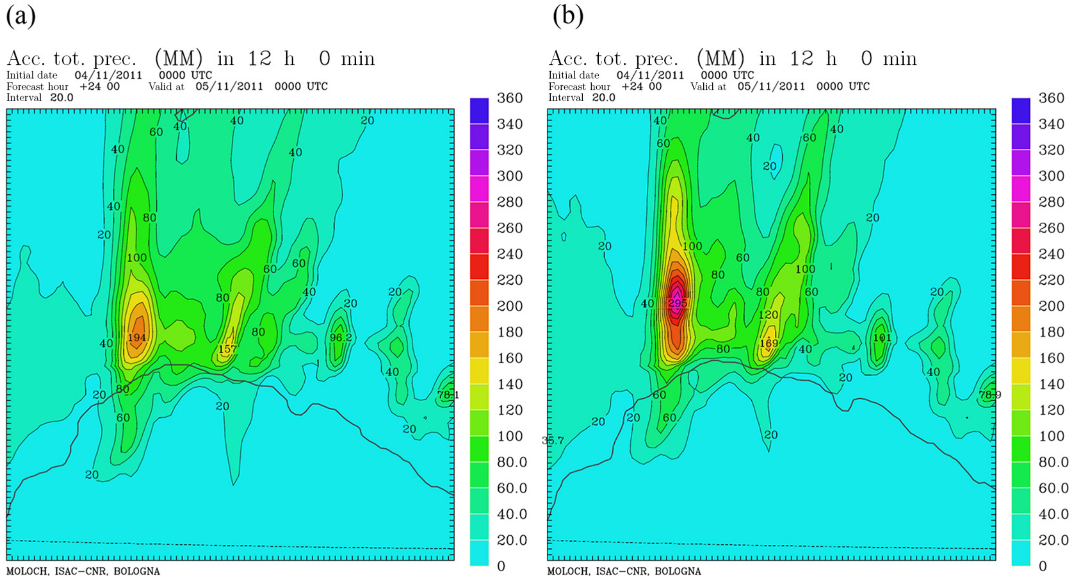

Fig. 6. Same as Fig. 5 but for 12-h-accumulated precipitation. Integration interval starts at 12:00 UTC of November 4, 2011. (a) Ctrl MOLOCH. (b) LAPS + MOLOCH.

the accumulated precipitation in 24 h (a) and in 12 h (b), ending at 00:00 UTC of the 5th of November, as observed by the local rain gauge network. The most intense spell of precipitation started in the late morning over Genoa and the adjacent hills, where small river catchments are located, and lasted for several hours. Accumulated values locally exceeded 450 mm in 24 h. Intense precipitation continued until the evening, but affected an area to the west of Genoa.

With the model set up described in Sections III and IV, two numerical experiments were performed: a preliminary run using only the BOLAM model, in order to evaluate the impact of the LAPS analysis at intermediate spatial scale; a second experiment with the MOLOCH model, whose boundary conditions are provided by BOLAM. In both cases, the initial condition was modified by assimilating the available observations at 00:00 UTC of the 4th of November with LAPS.

The simulations were compared with the BOLAM and MOLOCH control runs, obtained starting from the unmodified initial states (large scale analysis). The experiment involving BOLAM alone exhibited a weak effect of the LAPS assimilation on the precipitation forecast, in spite of the fact that some significant but local modifications of the initial conditions were introduced by LAPS, mainly into the low-level wind and humidity fields (not shown). Fig. 5(a) and (b) shows the MOLOCH accumulated precipitation over 24 h, obtained without (left) and with (right) LAPS assimilation, respectively. In contrast with the BOLAM experiment, the initialization using the LAPS analysis determines significant differences in the forecasts. The larger sensitivity to the initial condition of MOLOCH is expected, due to the growth of convective instabilities at the high resolution of a convection-permitting model. The precipitation maximum changes from 326 mm [Fig. 5(a)] to 359 mm [Fig. 5(b)], while the secondary peak to the west of Genoa increases from 207 mm [Fig. 5(a)] to a more realistic value of 305 mm [Fig. 5(b); also compare it with Fig. 4(a)].

The forecast improvement, especially of the western precipitation maximum, is also confirmed by inspection of Fig. 6, where the accumulated precipitation in the last 12 h of the simulation is shown. The comparison with Fig. 4(b) indicates that precipitation timing is correctly predicted for both the control and the LAPS case, but the simulated maximum is closer to the observations when LAPS initialization is used.

The qualitative interpretation based on the results shown in Figs. 5 and 6 is corroborated by a “statistical” analysis, based on contingency tables (occurrence or not of precipitation above prescribed thresholds), aimed at comparing observations and model simulations of precipitation. Several indices were calculated by considering the observations from 1598 rain gauges distributed over the whole MOLOCH domain and precipitation accumulated at individual model grid points.

The bias and the root-mean-square error (RMSE) are defined as follows:

$$Bias = \frac{1}{N}\sum_{i=1}^{N}\left(IP_i^{sim} - IP_i^{obs}\right)$$

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(IP_i^{sim} - IP_i^{obs}\right)^2}$$

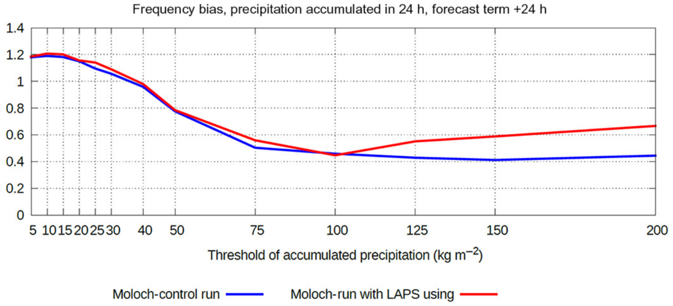

Fig. 7. FB for different thresholds of accumulated precipitation.

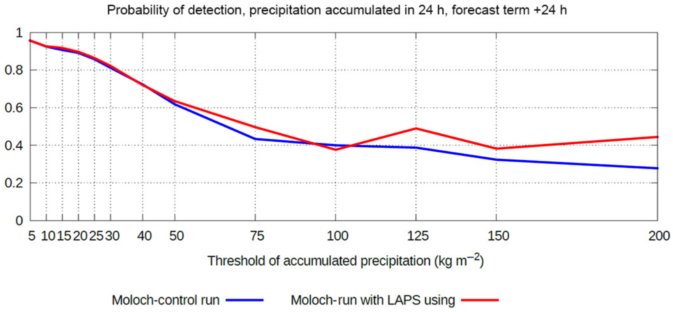

Fig. 8. POD for different thresholds of accumulated precipitation.

where N is the total number of reports from the rain gauge stations (1598), and IP_i^{sim} and IP_i^{obs} are the model simulated and the observed time integrated precipitation, respectively. The bias and the RMSE are shown in Table I for both the time integration periods of 12 and 24 h ending at 00:00 UTC of November 5, 2011. Although such indices have a statistical significance only if applied to a sufficiently long time interval or to many episodes, a non-negligible improvement due to the LAPS assimilation can be deduced for both time windows. In addition, for the 24-h-integrated precipitation, Figs. 7 and 8 show the frequency bias (FB) and the probability of detection (POD) indices versus the threshold of accumulated precipitation [28]. In practice:

$$FB = \frac{A + C}{A + B}$$

$$POD = \frac{A}{A + B}$$

for each threshold of accumulated precipitation, A is the hit rate, B is the miss rate (forecast underestimation of precipitation), and C is the false alarm rate (forecast overestimation of the precipitation).

Figs. 7 and 8 show that the MOLOCH simulation initialized by the LAPS analysis exhibits both FB and POD values closer to the ideal unity value for rain thresholds higher than 100 mm. For lower precipitation thresholds, the impact of LAPS initialization seems still relevant until 50 mm, while it is negligible for smaller thresholds. Such results confirm that the improvement of the high-resolution forecast in case of assimilation is related to the simulation of convective precipitation, which is associated with high precipitation rates. Of course, drawing more general conclusion requires the application of the above evaluation methods to a larger number of cases.

TABLE I
BIAS AND RMSE OF THE INTEGRATED PRECIPITATION, COMPUTED OVER 1598 RAIN GAUGE STATIONS DISTRIBUTED OVER THE WHOLE MOLOCH DOMAIN

Integration time (h)	Bias ($\mathrm{kg\ m^{-2}}$)	RMSE ($\mathrm{kg\ m^{-2}}$)	Simulation
12	–1.78	19.47	Ctrl MOLOCH
12	–1.59	18.63	LAPS+MOLOCH
24	–2.50	25.00	Ctrl MOLOCH
24	–1.63	23.97	LAPS+MOLOCH

VI. CONCLUSION

The implementation of the LAPS system for initializing the ISAC meteorological models has been presented. Such implementation required the development of new interfaces, capable of handling rotated latitudinal–longitudinal coordinates, as well as the development of a specific module for the ingestion of radar data.

Preliminary application of the LAPS analysis to the BOLAM-MOLOCH modeling chain indicates a significant impact on the quantitative precipitation forecast at high resolution. The case study considered here (the Genoa flood of November 2011) highlights the effect of local data assimilation when convective scales are involved. The low-level temperature and wind fields, as well as the humidity distribution in the entire troposphere, appear to be mostly affected by the high-resolution data assimilation allowed by the LAPS system.

Preliminary sensitivity experiments, not discussed in detail here, have shown the effect of including a single data source at a time. In particular, the assimilation of surface stations introduces changes in the low-level wind, temperature, and humidity that can directly affect the onset of convection and its location, by changing the characteristics of a moist and warm low-level jet, interacting with the orography, which is often responsible for the triggering of convection in this kind of events. Sensitivity simulations show also that the assimilation of SEVIRI/MSG satellite data can play a key role in filling conventional data void regions, especially over the sea, thus having an important impact on the humidity and condensate distribution, especially where clouds are detected.

Finally, in the particular case considered here, meteorological radar data, though entering the assimilation, exhibit a small impact, probably due to the limited number of levels ingested and to the low values of reflectivity at the time of model initialization, since at that time convective activity over the area monitored by the Italian radar network was weak.

The accumulated precipitation simulated when the LAPS analysis is applied to the MOLOCH initial condition shows a better agreement with rain gauge observations, as shown by precipitation maps and by various "statistical" indices base on contingency tables. However, a statistically significant approach based on the simulation of many cases is a necessary step in order to confirm the promising results presented in this work, which should be regarded as a demonstration of the feasibility of data assimilation of a variety of meteorological data platforms with LAPS.

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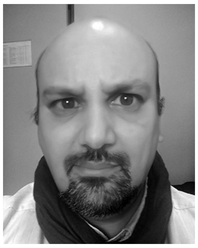


Alessandro Tiesi received the degree in physics from the University of Calabria, Rende, Italy, in 1997, and the Ph.D. degree in physics and astronomy from the University of Glasgow, Glasgow, U.K., in 2003.

In 2003, he started to work as a Postdoc with CNR-ISAC, Bologna, Italy, in several projects involving the modeling of the dispersion of aerosol in the atmosphere, the turbulent diffusion in the atmospheric boundary layer, and the remote sensing of atmospheric gas and aerosol. Currently, he is working on the analysis of the meteorological data for the initialization of high-resolution meteorological models. From 2008 to 2012, he has collaborated with CGS S.p.A. (OHB), Bologna, Italy, hosted at CNR-ISAC headquarter in the remote sensing of gas and aerosol of the atmosphere, and participated to the model development of an interferometer focusing on the issue of the air quality.

Mario Marcello Miglietta received the degree (Hons.) in physics from the University of Lecce, Lecce, Italy, in 1993, and the Ph.D. degree in physics, in 1999.

From 1993 to 2001, he was a Weather Forecaster with the Italian Air Force Meteorological Service. Since December 2001, he has been with CNR-ISAC. He has been a Visiting Scientist at different research institutions (including a total of 19 months at the National Center for Atmospheric Research (NCAR), Boulder, CO, USA). He has an experience of more than 20 years in meteorology. He has coauthored more than 100 papers, 48 of which published in ISI-listed journals. He is a Visiting Scientist with the European Commission, Joint Research Center, Institute for Energy and Transport, Ispra, Varese.

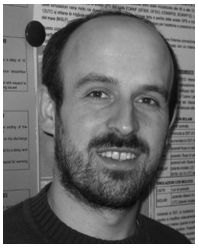
Dr. Miglietta has been an Associate/Guest Editor for different journals, including, e.g., *Atmospheric Research*, *Advances in Science and Research*, *Meteorologische Zeitschrift*, and *Advances in Meteorology*. Since 2007, he has been a Convener of a session on “Coastal Meteorology and Oceanography” with the European Meteorological Society (EMS) Annual Meeting, and a member of the steering committee with the International Conference on Alpine Meteorology (ICAM) since 2013. He received the Habilitation as Associate Professor in “Earth Science Physics” and in “Geophysics.”

Dario Conte received the degree in computer science engineering from the University of Lecce, Lecce, Italy, in 2003, and the Ph.D. degree in information and communication engineering from the University of Salento, Lecce, Italy, in 2007.

Since 2003, he has multiple job contracts with: ISAC-CNR, Bologna, Italy; the University of Salento, Lecce, Italy; CMCC (EuroMediterranean Centre on Climate Changes), Lecce, Italy; and ARPA-Puglia, Bari, Italy. During this period, he has dealt mainly with high-performance computing, grid computing, management and processing of geographic data on behalf to regional weather and air quality models. He is working for CMCC on: regional climate modeling; dynamical downscaling; regional scale climate projections, in particular in the Mediterranean area; extreme storm surges along the Mediterranean coast. He participated in several research projects and presented his results by means of several international research journal and conferences.

Oxana Drofa received the degree (*cum laude*) in meteorology and climatology from Moscow State University, Moscow, Russia, in 1994, and the Ph.D. degree in physical and mathematical sciences with specialization in meteorology from Hydrometeorological Centre of Russia, Moscow, Russia, in 1998.

From 1995 to 1999, during the Postgraduate course, she worked as a permanent position of Meteorologist with Hydrometeorological Centre of Russia. From 1999 to 2011, she worked with various contracts of temporary position in ISAC (former ISAO) of CNR, Bologna, Italy, where she has been a Researcher with a permanent position in ISAC-CNR, Bologna, Italy, since 2011. Her research interests include: parameterization of microphysical processes, parameterization of the hydro-thermal processes in the soil and vegetation cover and at the surface, application and development of geophysical datasets for NWM models, assimilation of satellite and radar data in NWP models, coupling of NWP models with a hydrological numerical model for hydrological forecast, application of NWP models for operational meteorological forecast, application of the radiative transfer model RTTOV (SAF of Eumetsat) with simulated data of NWP models, parameterization of microphysical processes for a numerical hydro-dynamical model of the atmosphere, assimilation of satellite and radar data in a NWP model, development of numerical schemes of dynamical atmospheric processes, development of various components of NWP models, objective verification of NWP model results, application of NWP models for the study of atmospheric phenomena, practical application of NWP models for meteorological forecast.



Silvio Davolio was born in Reggio Emilia, Italy, in 1972. He received the degree (Hons.) in physics from the University of Modena, Modena, Italy, in 1997.

Since 2008, he has been a Permanent Research Scientist with CNR-ISAC, Bologna, Italy. From 2007 to 2012, he was a Guest Professor of Atmospheric Physics with the Department of Physics, Università Cattolica of Brescia, Brescia, Italy. He has authored/coauthored over 30 publications. His research interests include mesoscale meteorology, atmospheric dynamics, data assimilation, and NWP.

Dr. Davolio is a member of the International Scientific Steering Committee of the HyMeX program and PI for the modeling activity of CNR-ISAC in the RITMARE CNR Flagship Project. He has been an Associate Editor for the Quarterly Journal of the *Royal Meteorological Society* since 2010.

Piero Malguzzi received the B.S. degree in physics from the University of Bologna, Bologna, Italy, and the Ph.D. degree in meteorology from Massachusetts Institute of Technology, Cambridge, MA, USA, in 1978 and 1984, respectively.

Currently, he is a Senior Research Scientist with CNR-ISAC, Bologna, Italy, with 30-year research experience in dynamic meteorology and numerical modeling, where he has been the Head of the Modeling Division since 2014. His research interests include the study of convective phenomena, interaction of atmospheric mesoscale flows with orography, low-frequency variability of the general circulation of the atmosphere and atmospheric blocking, development of dynamical/physical schemes of meteorological models, and implementation on parallel architectures.

Andrea Buzzi was born in Mantova, Italy, on April 27, 1949. He received the degree (Hons.) in physics from the University of Bologna, Bologna, Italy, in 1972.

Currently, he is an Associate Senior Scientist with ISAC-CNR (Institute for Atmospheric Sciences and Climate of the National Research Council of Italy), Bologna, Italy. He was a Senior Research Scientist with ISAC until 2014, and a Contract Professor of Dynamic Meteorology with the Department of Physics, University of Bologna, Bologna, Italy, from 2005 to 2015. He was responsible for the Dynamic Meteorology Division, ISAC (2002–2009). He was a Visiting Scientist at different universities and research institutions (including 2 years at the Imperial College, London, U.K.). He was a Contract Professor of Dynamic Meteorology with different universities in Italy. He has a 40-year research experience in synoptic and dynamic meteorology, meteorological numerical modeling, analysis, and assimilation of meteorological data. He was a Principal Investigator in many nationally and internationally based research contracts on the research themes listed above, including Environment and Climate EU projects. He is participating in national and international research projects in dynamic and synoptic meteorology, geophysical fluid dynamics, climatology, including ALPEX (ICSU-WMO), MAP, MEDEX, and MAP-DPHASE (WWRP-WMO).

Prof. Buzzi was a member of several international scientific committees and many scientific organizing committees of scientific meetings and schools in meteorology. He was an Associate Editor of the *Quarterly Journal of the Royal Meteorological Society* (2002–2007).