Large-scale EXecution for Industry & Society

Deliverable D7.9

Final Report (KPI Included) on Demonstration and Validation of the Weather & Climate Test-bed Applied to Selected Cases

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GLOSSARY

ACRONYM	DESCRIPTION
ADMS	Atmospheric Dispersion Modelling System
API	Application Programming Interface
COAU	Unified Air Operations Centre
ERDS	Extreme Rainfall Detection System
FSS	Fractions Skill Score
GFS	Global Forecast System
GPM	Global Precipitation Measurement
HPC	High Performance Computing
IFS	Integrated Forecasting System of ECMWF
IMERG	Integrated Multi-satellitE Retrievals for GPM IR Infrared
JAXA	Japan Aerospace Exploration Agency
KPI	Key Performance Indicator
MB	Mean Bias
MODE	Method for Object-Based Evaluation
NASA	National Aeronautics and Space Administration
NCEP	National Centers for Environmental Prediction
OL	Open Loop
QPE	Quantitative Precipitation Estimation
QPF	Quantitative Precipitation Forecast
RISICO	RISchio Incendi e COordinamento
RMSE	Root Mean Squared Error
WCDA	Weather and Climate Data API
WRF	Weather Research and Forecasting
WPS	WRF Preprocessing System

TABLE OF PARTNERS

ACRONYM	PARTNER
Avio Aero	GE AVIO SRL
Atos	BULL SAS
AWI	ALFRED WEGENER INSTITUT HELMHOLTZ ZENTRUM FUR POLAR UND MEERESFORSCHUNG
BLABS	BAYNCORE LABS LIMITED
CEA	COMMISSARIAT A L ENERGIE ATOMIQUE ET AUX ENERGIES ALTERNATIVES
CIMA	CENTRO INTERNAZIONALE IN MONITORAGGIO AMBIENTALE - FONDAZIONE CIMA
CYC	CYCLOPS LABS GMBH
ECMWF	EUROPEAN CENTRE FOR MEDIUM-RANGE WEATHER FORECASTS
EURAXENT	MARC DERQUENNES
GFZ	HELMHOLTZ ZENTRUM POTSDAM DEUTSCHESGEOFORSCHUNGSZENTRUM GFZ
ICHEC	NATIONAL UNIVERSITY OF IRELAND GALWAY / Irish Centre for High-End Computing
IT4I	VYSOKA SKOLA BANSKA - TECHNICKA UNIVERZITA OSTRAVA / IT4Innovations National Supercomputing Centre
ITHACA	ASSOCIAZIONE ITHACA
LINKS	FONDAZIONE LINKS / ISTITUTO SUPERIORE MARIO BOELLA ISMB
LRZ	BAYERISCHE AKADEMIE DER WISSENSCHAFTEN / Leibniz Rechenzentrum der BAdW
NUM	NUMTECH
O24	OUTPOST 24 FRANCE
TESEO	TESEO SPA TECNOLOGIE E SISTEMI ELETTRONICI ED OTTICI

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EXECUTIVE SUMMARY

The goal of the LEXIS (Large-scale Execution for Industry & Society) project is to design and implement a platform for executing complex workflows in which HPC, Big Data and Cloud domains will converge. Such a platform takes advantage of the large-scale, geographically distributed resources exposed by HPC centres through their respective infrastructures.

The LEXIS project relies on three large-scale pilot use cases to validate and deploy its technology and infrastructure improvements, assigning to each pilot its own work package. Specifically, the WP7 has delivered a system for prediction of water-air-quality-food nexus phenomena and their associated socio-economic impacts whose demonstration and validation are provided in this deliverable. This deliverable reports and assesses the modelling results related to multiple and interconnected layers:

- WRF model, including data assimilation of Italian weather radar data and in situ 2 m temperature from Weather Underground network, and Continuum for flash-flood prediction,
- WRF model, including data assimilation of Italian weather radar data and in situ 2 m temperature from Weather Underground network, and RISICO for forest fire risk prediction,
- WRF model, including data assimilation of French weather radar data and in situ 2 m temperature from Weather Underground network, and ADMS model for air quality,
- WRF model, including data assimilation of Italian weather radar data, and ERDS system for extreme rainfall phenomena detection.

Position of the deliverable in the whole project context

Deliverable D7.9 is a product of the WP7 (Weather and Climate Large-scale Pilot), and is related to Task 7.3 entitled "Regional Weather and Climate: Assimilation of Local in-situ Unstructured Observations in High-Resolution Downscaling of Global Forecast", Task 7.4 entitled "Cloud-Based Domain Specific Application Modelling, Forced by Regional Forecasts and Environmental Observations", Task 7.5 entitled "Cloud-Based Socio-Economic Impact Modelling Based on Exposure Information and Environmental Forecasts" and Task 7.6 entitled "Full Test-beds Integration, from Global Models to Socio-Economic Impact". This document is an update and final version of the Deliverable D7.4 [1], Deliverable D7.6 [2] and Deliverable D7.8 [3].

As depicted in Figure 1, WP7 with its weather and climate models is one of the primary sources, together with WP5 and WP6, for setting the foundations and testing capabilities of the LEXIS platform, and specifically of the orchestrator. Conversely, WP2 provides the main inputs concerning requirements and specifications, as well as ensuring that development done in WP7 is aligned with the general requirements for the LEXIS platform. WP3 is in charge of developing the LEXIS storage solution on which workflows and the orchestrator rely on to ensure capability of storing data. WP4 lays the foundations for the orchestration of application workflows during their whole lifetime (from the definition to the execution and completion), security aspects and monitoring of used resources. WP8 is focused on creation of the portal and analysing monitoring data for billing purposes.

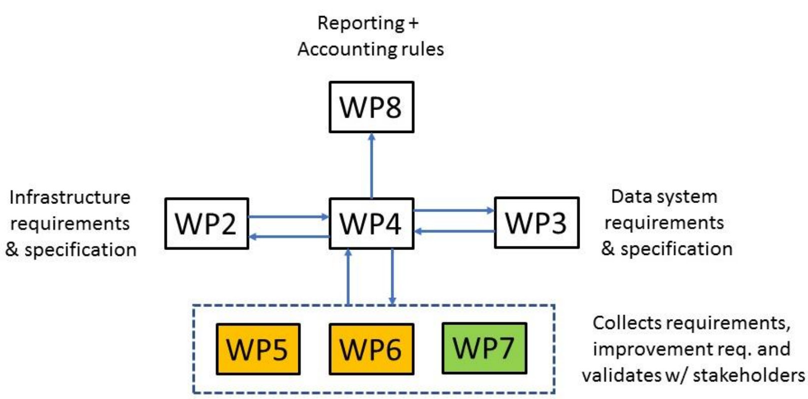

Figure 1 Position of WP7 in the LEXIS project

Description of the deliverable

This deliverable presents the most updated description of each WP7's application use cases and the results achieved by them after their final deployment on the LEXIS platform. The main purpose of this document is to illustrate the KPIs associated to and the possible impacts of LEXIS.

Contributors for the deliverable content are:

- CIMA as the leader of WP7,
- CIMA as the responsible for the activities concerning WRF and the applications with Continuum and RISICO models,
- ITHACA as the responsible for the applications with ERDS model, and responsible for the preparation of this document,
- NUM as the responsible for the applications with ADMS and ADMS Urban models.

1 INTRODUCTION

1.1 LEXIS WP7

In the WP7 "Weather and Climate Large-scale Pilot ", various use cases in terms of application, domain size, etc. were tested by the LEXIS platform and connected federated infrastructure.

Figure 2 presents these applications. We can notice two elements from this figure that:

- The simulated domain goes from global to local,
- The use cases are not independent and interact with each other (e.g. IFS weather forecast of ECMWF will be used as an input of CIMA WRF regional forecast, which will be used as an input of NUM urban air-quality forecast).

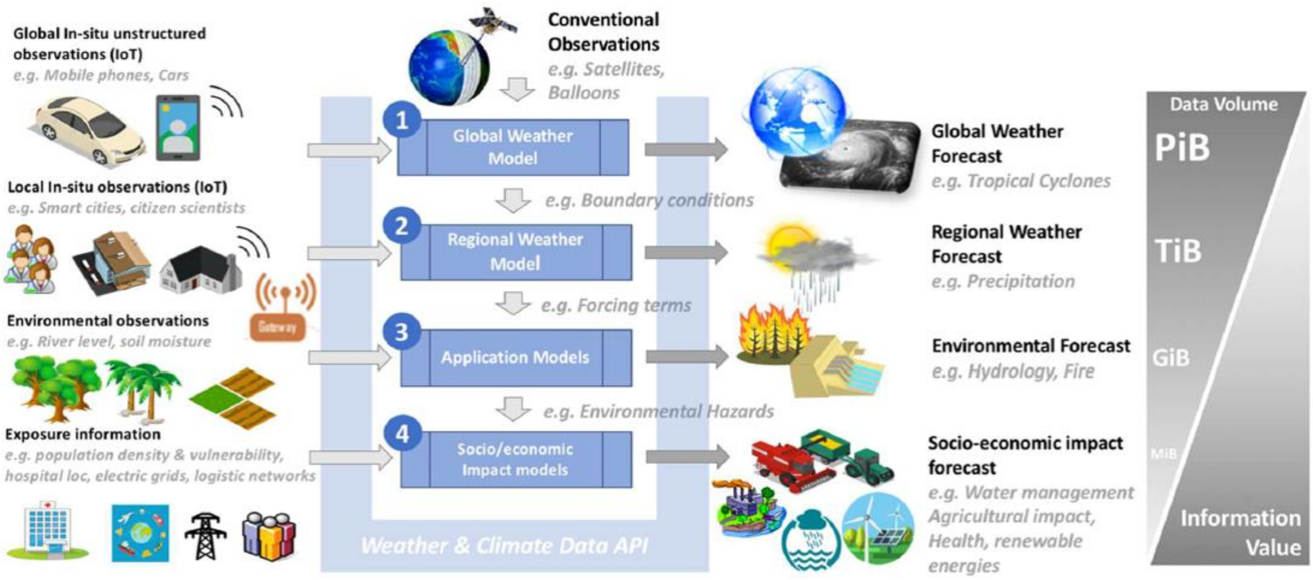

Figure 2 List of the different WP7 applications

One of the key points of WP7 is the exchange and handling of datasets from one application to another. The deployment of each application into the LEXIS platform and connected federated infrastructure is not only the porting of each model on HPC/Cloud clusters, but also the interaction between applications, as well as the visibility of the final outputs on the LEXIS portal. As a consequence, the deployment of WP7 applications rely on generic LEXIS components and on specific WP7 components.

2 DESCRIPTION OF THE CASE STUDIES AND RESULTS FOR WRF MODEL

2.1 VERIFICATION OF WRF MODEL

2.1.1 Introduction

The analysis will be conducted checking the Fractions Skill Score, or FSS [4] (as far as the precipitation is concerned), while for the 2 m temperature we use classical scores such as Mean Bias and Root Mean Square Error. The observations come from the National Department of Civil Protection.

The FSS is a method that has been used to analyse the skill of convective-allowing models at forecasting precipitation on a spatial scale. The FFS is a neighbourhood group method and it does not require the identification of features, as others do, so can run through data without human input. The method is designed to show how the skill varies with neighbourhood size, and determine the smallest scale at which the forecasts are deemed useful.

In the case of high-resolution forecasts, traditional verification methods tend to overemphasize errors on small spatial scales, leading to an unfair double penalty effect [4]. Taking into account more than one grid point helps to reduce this double penalty effect. Neighbourhood verification assesses forecast skill scores for different spatial windows and thresholds, allowing for the identification of the scales and thresholds where model quality reaches the highest values. In [5], the main neighbourhood verification methods are summarized. They represent different decision models to assess the usefulness of a forecast. The FSS is well suited for the verification of high-resolution forecasts [6] and evaluates the simulated fraction exceeding/falling below a certain threshold. In order to assess precipitation, the thresholds 0.1 mm/3 h, 0.2 mm/3 h, 0.5 mm/3 h, 1 mm/3 h, 2.5 mm/3 h, 5 mm/3 h, 7.5 mm/3 h, 10 mm/3 h, 12 mm/3 h and 15 mm/3 h have been used.

The FSS answers the question: what are the spatial scales at which the forecast resembles the observations? This approach directly compares the forecast and observed fractional coverage of grid-box events (rain exceeding a certain threshold) in spatial windows of increasing size. The FSS has the following properties:

- Range of 0 (complete mismatch) to 1 (perfect match),
- If either there are no events forecast and some occur, or some occur and none are forecast the score is always 0,
- As the size of the squares used to compute the fractions gets larger, the score will asymptote to a value that depends on the ratio between the forecast and observed frequencies of the event. The closer the asymptotic value is to 1, the smaller the forecast bias,
- The score is most sensitive to rare events (or for small rain areas).

2.1.2 The December 2020 case study

At the beginning of December 2020, the atmosphere over the central part of Europe is quite dynamic. There is no high pressure blocking cold air intrusions from the Atlantic or the Arctic, so there are cold fronts passing over Italy alternated with very short periods of stability. From a climatological point of view, the temperatures and the precipitation are aligned with the average of the period. The presence of precipitation sparse all over Italy for the first 10 days of December makes this time interval suitable for this kind of study.

The verification concerns the first 9 days of December and compares the LEXIS simulations with radar and ground IBM Weather Underground weather stations (the temperature at 2 m) data assimilation against the same set of simulations performed without assimilation (named Open Loop or OL).

In Figure 3 we show the FSS plots of LEXIS precipitation fields (left) and OL fields (right). As said, the check is performed on a 3-hourly threshold of precipitation (y-axis) and on different spatial scales (x-axis). The colour of the boxes indicates the value of FSS (palette on the right).

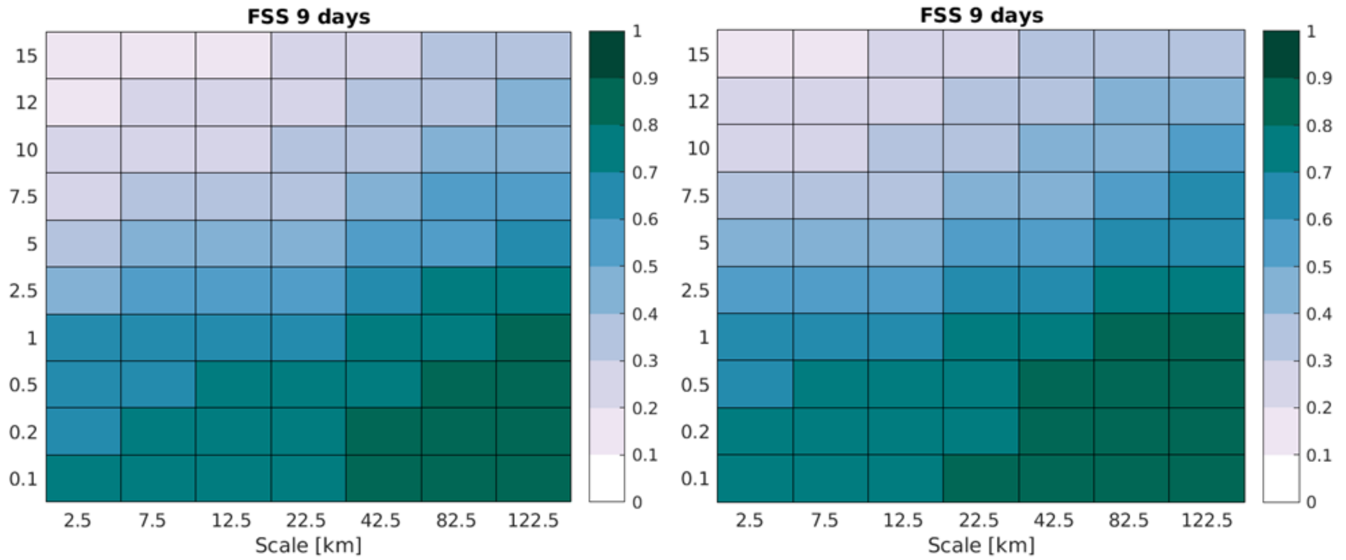

Figure 3 FSS for LEXIS simulations (left) and OL (right)

At a first glimpse, the two versions of the WRF model are very similar and the pattern is what we expect from a Limited Area Model. In fact, although we average over 9 days, the model has worse performances towards the higher thresholds where the FSS is lower. At the same time, the smaller scales get penalized by the well-known double penalty effect [7]. The detail is penalized unless exactly correct and higher resolution is indeed more detailed. An event might be predicted where it did not occur, but is very close to it. Nevertheless, since closeness is not rewarded, the model officially fails. This effect is emphasized by increasing the horizontal resolution and can be faced by using probabilistic forecasts.

The 2 m temperature verification was performed by using more than 2,200 stations of the National Department of Civil Protection all over Italy. In Figure 4 we show the average daily profile, the mean bias (MB), the root mean squared error (RMSE), and the correlation coefficient (r). Also, in this case, the two model versions share similar behaviour. The MB is quite low, basically between -0.5°C and 0.5°C. The LEXIS simulations are better in the central part of the day, with less overestimation with respect to OL version. The RMSEs are quite close to each other, between 2°C end 2.5°C. Eventually, the correlation coefficient is very high in both cases, being between 0.92 and 0.94.

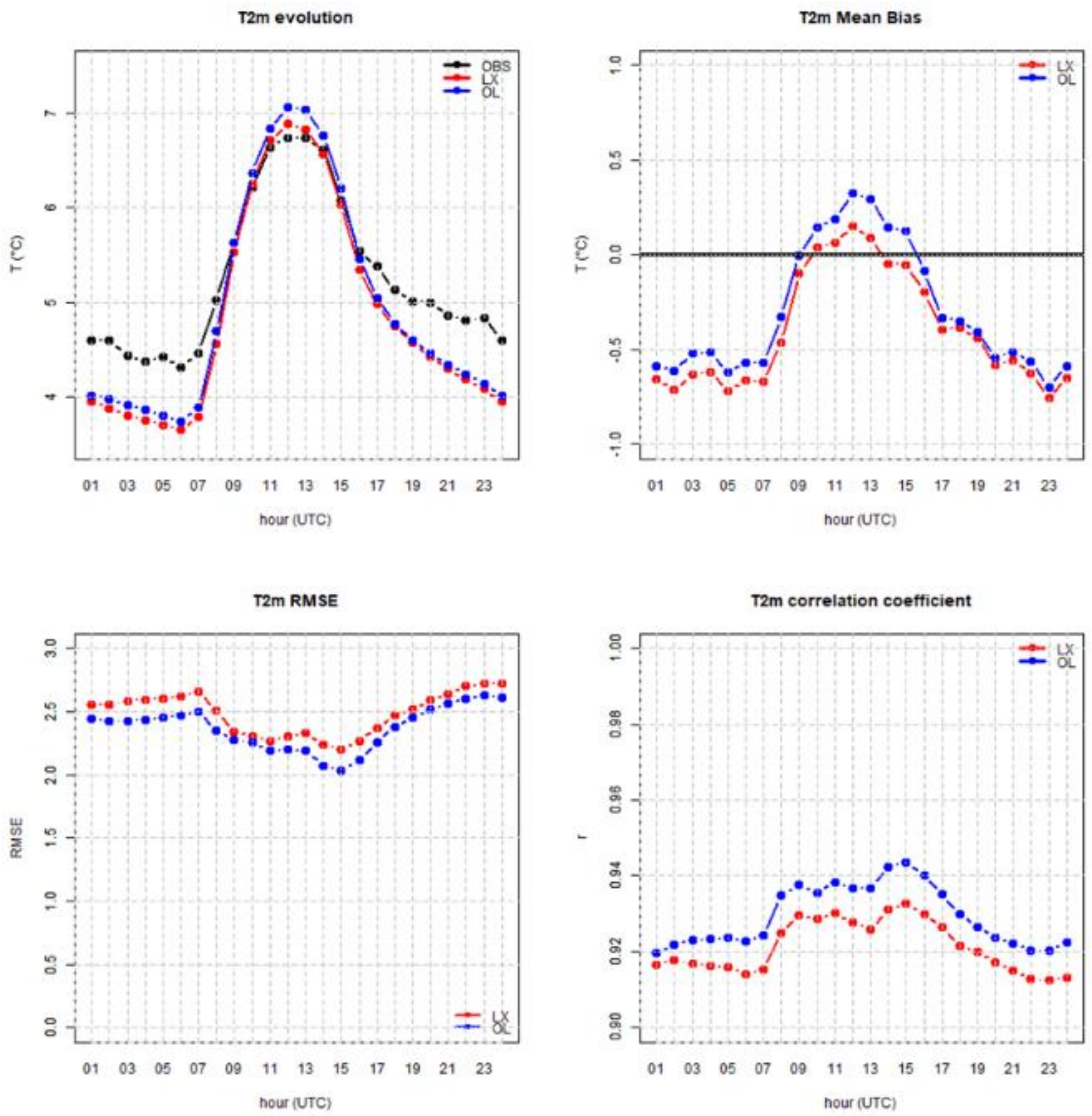

Figure 4 The 2 m temperature statistics for LEXIS simulations (red) and OL (blue). Mean daily profile (top left), Mean Bias (top right), RMSE (bottom left) and the correlation coefficient r (bottom right)

3 DESCRIPTION OF THE CASE STUDIES AND RESULTS FOR WRF-CONTINUUM WORKFLOW

3.1 VALIDATION OF THE WRF-CONTINUUM MODELLING EXPERIMENTS

To validate all the WRF-Continuum workflow experiments, the Method for Object-Based Evaluation (MODE) [8] is applied by comparing the Quantitative Precipitation Forecast (QPF) of WRF with the Quantitative Precipitation Estimation (QPE) offered by rain gauges and radar data.

MODE identifies precipitation structures in both forecast and observed fields and performs a spatial evaluation of the model capability of reproducing the identified observed objects.

Such validation method overcomes the so-called “double-penalty" issue, that traditional verification methods suffer from. This is particularly true when comparing high-resolution observational data analysis and cloud-resolving meteorological forecasts in the case of deep moist convective and highly localized phenomena.

Since traditional methods cannot provide a measure of spatial and temporal match between the forecast and the observed rainfall patterns, it is preferable to use feature-based verification techniques, such as MODE. In this project, different indices provided by MODE validation are considered. They include the following attributes: centroid distance, observed versus predicted areas, overlapping area, and total interest score, whose values range between zero (total disagreement between observed and predicted rainfall cluster) and one (high agreement).

3.2 CASE STUDIES

3.2.1 Emilia Romagna, 1-2 February 2019

In the days from 30 January 2019 to 2 February 2019, Northern Italy was affected by a depression that focused its effects on Emilia Romagna, initially with weak but widespread precipitation also of a snowy nature (30 - 31 January), and later (1 - 2 February) with more intense rains, which on the highest reliefs have determined the melting of the snows accumulated in the previous days. In the 48 hours of this second phase, rain gauges recorded rainfall values close to or greater than 300 mm (for example, 327 mm were recorded at Lake Scaffaiolo in the province of Modena, 286 mm at Bosco di Corniglio in the province of Parma, and 278.6 mm at Monteacuto delle Alpi in the province of Bologna).

The abundant rainfall, combined with the saturation effect of the soil, triggered floods on the entire Apennines hydrographic network (with emphasis on Reno, Panaro, Secchia, and Enza river basins). The most critical circumstance occurred on 2 February in the area of Castel Maggiore, where a break in the embankment caused the flooding of an area of about 27 km^2 with the consequent evacuation of almost 500 people in the territories of Castel Maggiore, Argelato, Calderara di Reno, Castello d'Argile, and Bologna (see Figure 5).

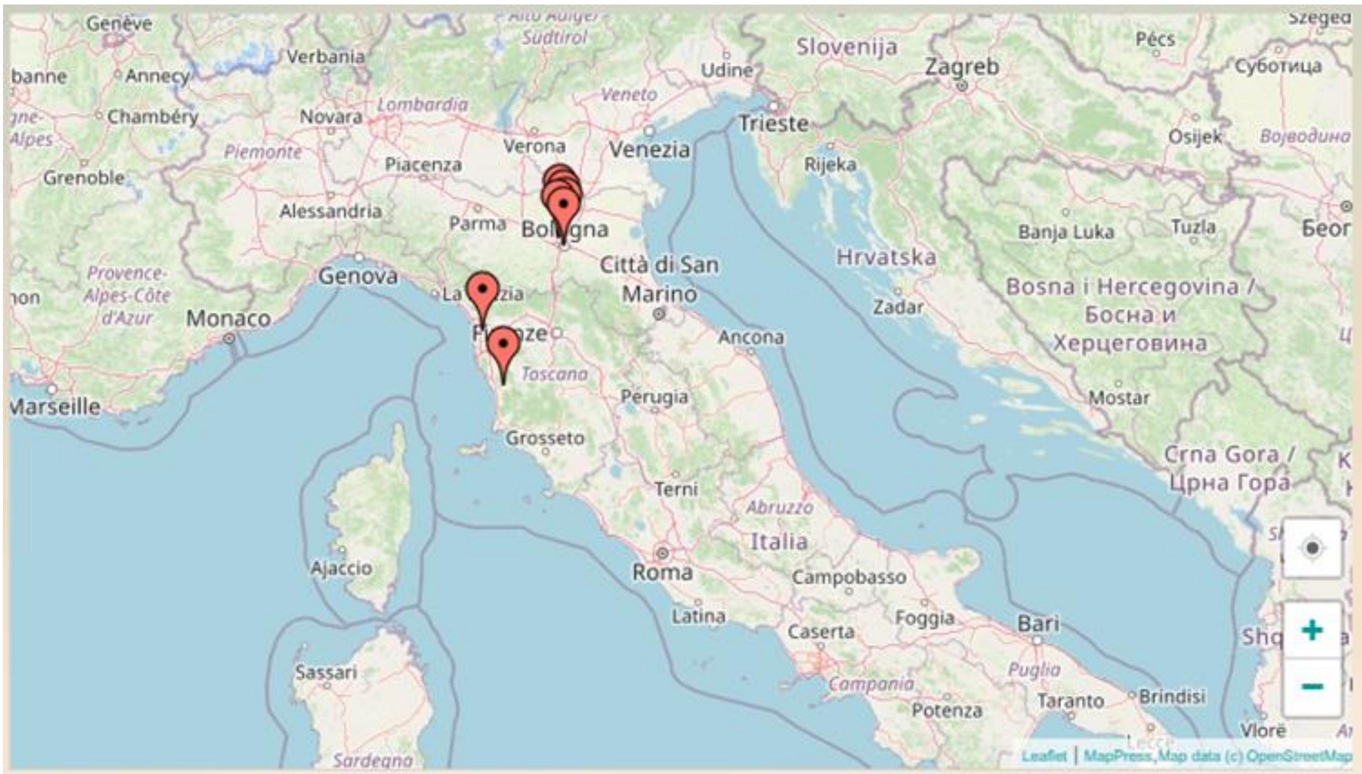

Figure 5 Affected areas during the event of the 1 - 2 February 2019

This event has been simulated by WRF at 2.5 km including the assimilation of radar data (reflectivity CAPPI at 2,000, 3,000, and 5,000 m) as well as the temperature at 2 m as provided by IBM Weather Underground stations (at 18, 21, and 00 UTC of the 30 January 2019). Figure 6 shows a very good agreement between the observed (upper panel) and predicted (lower panel) 48 hours rainfall depth (1 February 2019 00 UTC - 3 February 2019 00 UTC).

This statement is supported by the results of the MODE analysis (see Figure 7 and Table 1) for the 48 hours rainfall depth and threshold equal to 150 mm. Observed (blue) and forecast (red) clusters look very similar with a significant spatial overlapping and similar total extensions of the different convective structures detected in each cluster. Furthermore, both clusters 1 and 2 have centroid distances between observed and predicted fields below 15 km which is a rather small value (in the order of 4-5 times the grid spacing).

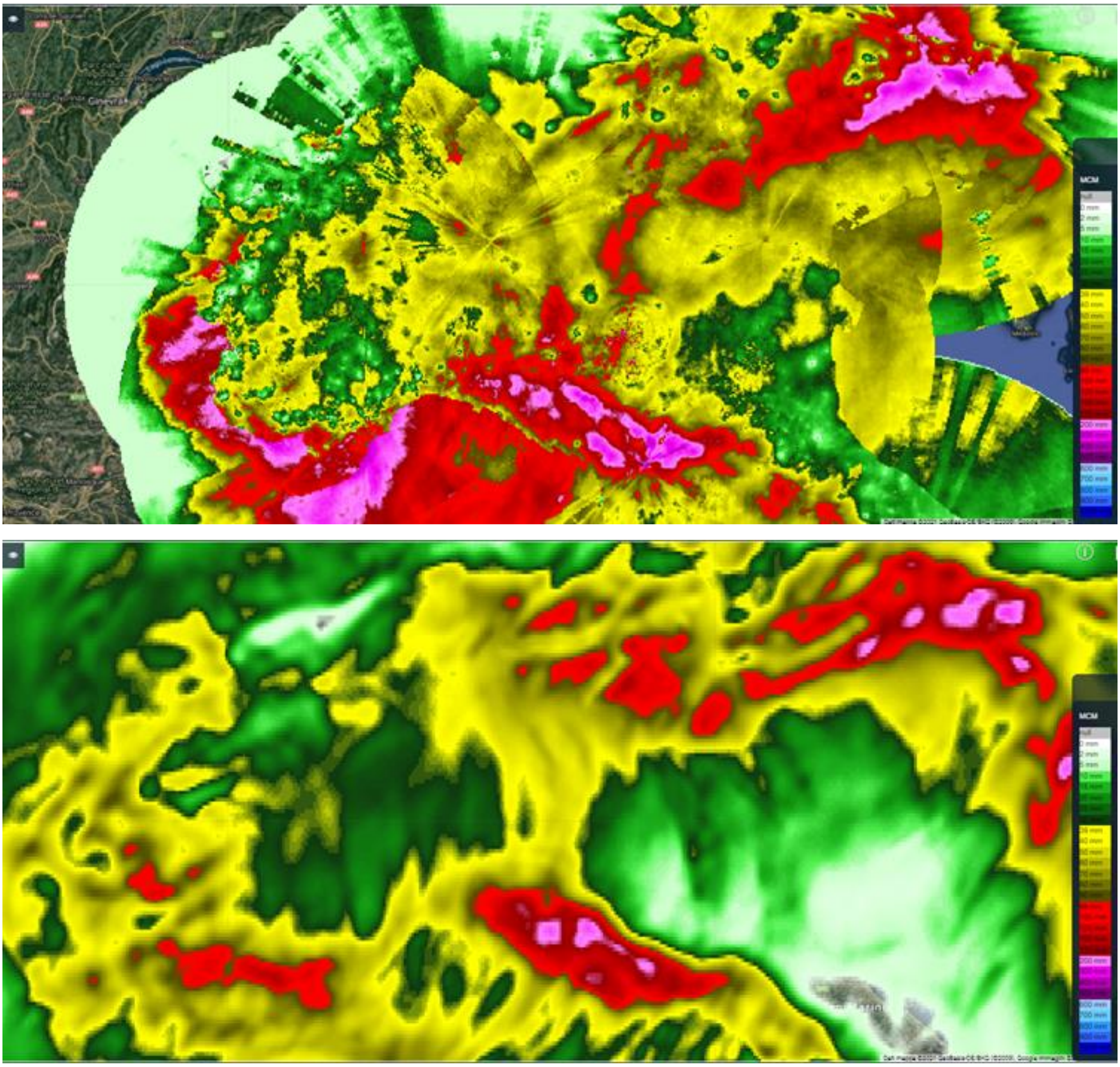

Figure 6 Observed (upper panel) and predicted (lower panel) rainfall depth (48 hours, 1 February 2019 00 UTC - 3 February 2019 00 UTC)

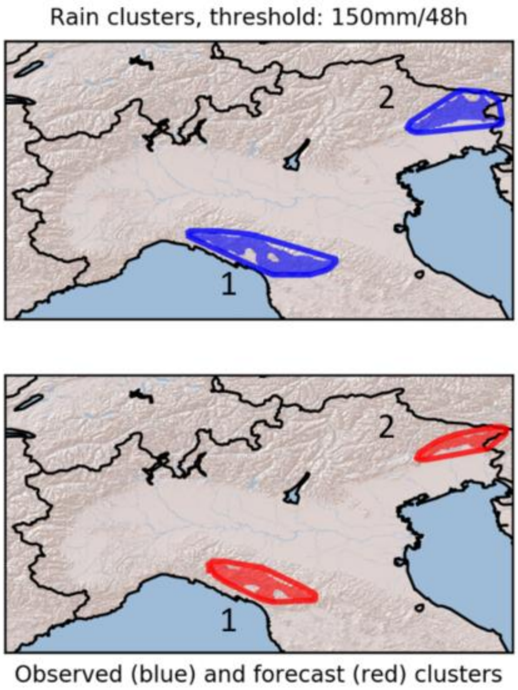

Figure 7 MODE analysis results of the event of the 1 - 2 February 2019

CLUSTER PAIR	CENTROID DISTANCE [km]	OBSERVED AREA [km^2]	FORECAST AREA [km^2]	INTERSECTION AREA [km^2]	FCST INT 90P [mm]	OBS INT 90P [mm]	TOTAL INTEREST
1	13.28	6,138	4,375	3,663	208.15	272.50	0.99
2	11.60	4,156	2,288	1,963	212.43	277.97	0.96

Table 1 MODE analysis results of the event of the 1 - 2 February 2019

From a hydrological point of view, the Continuum model results suggest severe discharge for a large portion of the Pianura Padana catchments with peak discharges above the red alert level (see Figure 8, upper panel), also in the area of the Reno catchment which caused many floods both in the lowland areas and in the mountain section as discussed above (see Figure 8, lower panel).

Figure 8 Continuum predictions showing in the upper panel the catchments where predicted discharge is expected to exceed the red (and highest) alert threshold, while the lower panel refers to the specific hydrograph of the Reno river at Vergato (red circle in the upper panel)

3.2.2 Lecco, 11-12 June 2019

On 11 and 12 June 2019, Lombardy was hit by heavy rainfall over the provinces of Brescia and Sondrio, then extended to Lecco province, concentrating on the area of Lake Como the most disastrous effects on the ground (see Figure 9). Starting from the late evening of day 11 and until the morning of the 12th, the most intense rains, mostly convective in nature, fell in the area between the Lecco Prealps and Valchiavenna, where the rain gauges recorded very high accumulations, in particular in the areas of Valsassina (Introbio, 125.6 mm in 12 hours) and Valvarrone (Premana, 209.2 mm in 12 hours).

The damage caused by flooding has been very considerable both in the mountain municipalities and in those of the valley. For a few hours, the ENEL dam in Pagnona (Premana) also raised alarm when the water reached the edge of the reservoir dragging a large number of logs and debris. In total, more than 1,100 people have been displaced (about 900 in Dervio and about 200 in Primaluna).

This event has been simulated by WRF at 2.5 km including the assimilation of radar data (reflectivity CAPPI at 2,000, 3,000, and 5,000 m) as well as the temperature at 2 m as provided by IBM Weather Underground stations (at 18, 21, and 00 UTC of the 10 June 2019). The overall degree of agreement between predicted and observed rainfall depth (24 hours, 11 June 2019 12 UTC - 12 June 2019 12 UTC) is good in consideration of the fact that the event is occurring in summer and it is orographic in nature (see Figure 10): the overall extent of the rainfall cluster is rather similar, even if the centroid distance is rather high in the order of about 100 km (see Figure 11 and Table 2).

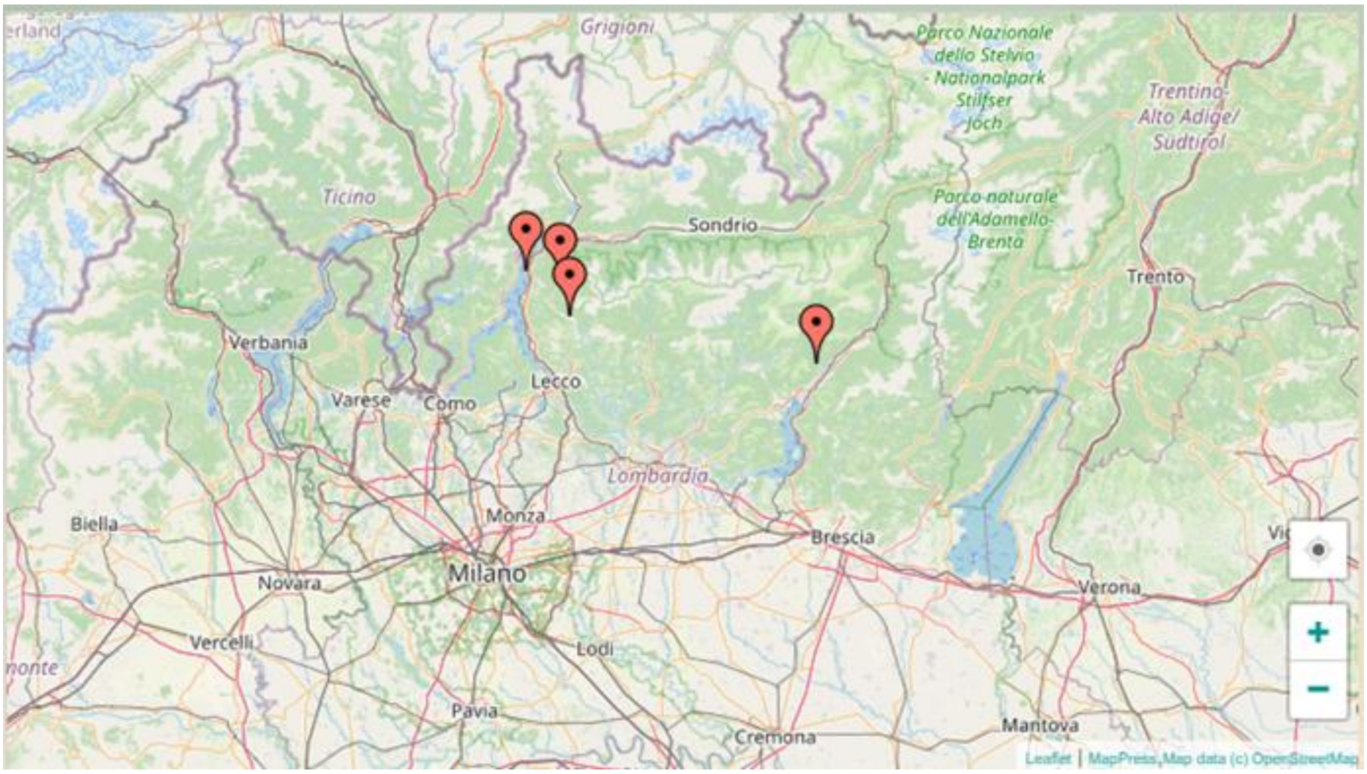

Figure 9 Affected areas during the 11-12 June 2019 event

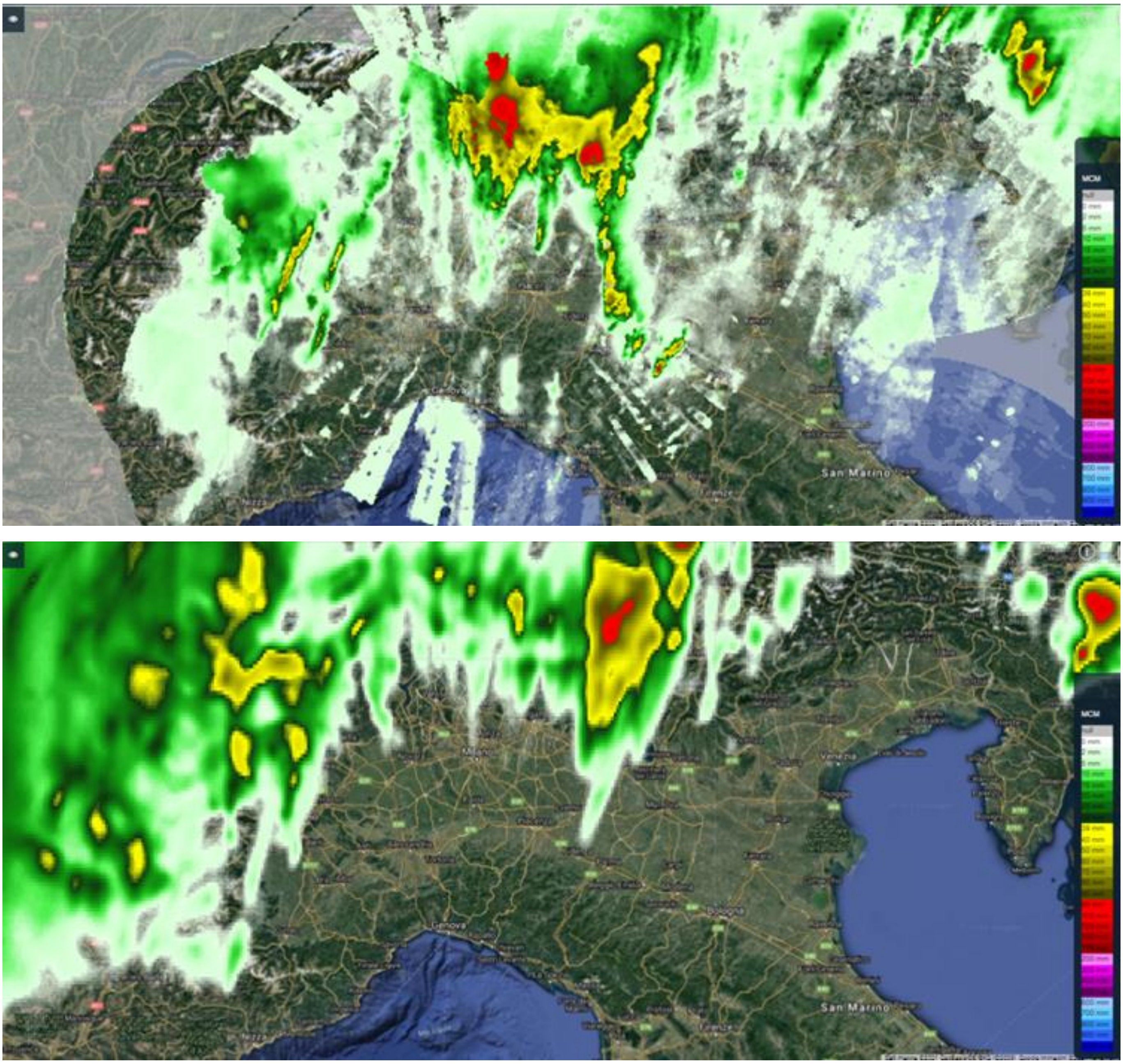

Figure 10 Observed (upper panel) and predicted (lower panel) rainfall depth (24 hours, 11 June 2019 12 UTC - 12 June 2019 12 UTC)

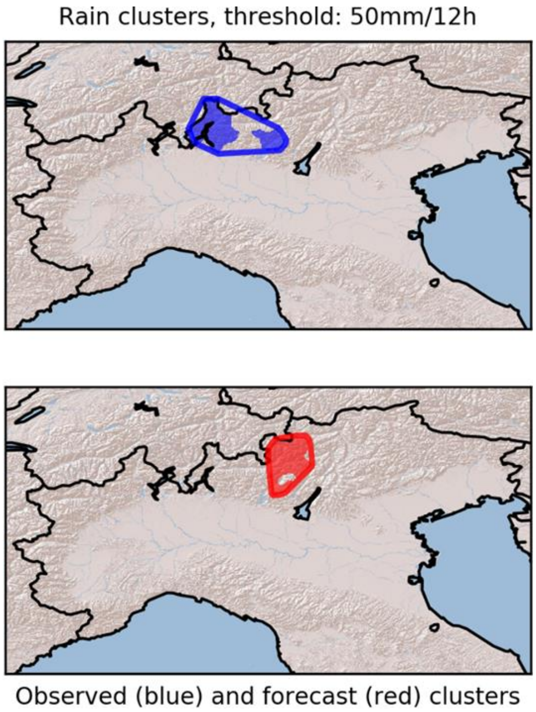

Figure 11 MODE analysis results of the 11-12 June 2019 event

CLUSTER PAIR	CENTROID DISTANCE [km]	OBSERVED AREA [km^2]	FORECAST AREA [km^2]	INTERSECTION AREA [km^2]	FCST INT 90P [mm]	OBS INT 90P [mm]	TOTAL INTEREST
1	93	4,794	3,963	513	94.38	110.86	0.865

Table 2 MODE analysis results of the 11-12 June 2019 event

3.2.3 North of Italy, 22-24 November 2019

Starting from the evening of 22 November 2019, a disturbance crossed Northern Italy, pouring widespread and persistent rains over Liguria and Piedmont (see Figure 12). Between the evening of the 22nd and the morning of the 24th, cumulative values of more than 500 mm/36 h were recorded on the Genova and Savona areas, with peaks of up to 420 mm/24 h in Pianpaludo (SV) and 239 mm/24 h in Corio-Pian Audi (TO) on the 23rd.

The intense rains, falling on soils already saturated by the rains of the previous weeks, have led to hundreds of landslides and the almost immediate response of the rivers and creeks. Considerable inconvenience for the population in various areas of the regions concerned and considerable damage to the main and secondary roads were observed. To these must be added the damage related to storm surges along the Ligurian coasts. One victim and two injured were registered in Piedmont, in the area of Sezzadio (AL). Here three people were overwhelmed by the waters while trying to cross a bridge over the Bormida river whose flood was among the worst in decades, with the flooding of large areas of the plain and the reactivation of the paleoalveo right near Sezzadio. A significant flood event also occurred on the Po River. The flood wave, generated both by precipitation and by the melting of the snows already present in the Alpine arc, reached its mouth on December 3rd. In the various regions crossed by the river, damage and inconvenience were recorded, in particular to residents and activities located in floodplain areas. More than 450 people have been evacuated. The overall toll of the flood event is therefore 1 dead, 2 injured and over 900 displaced.

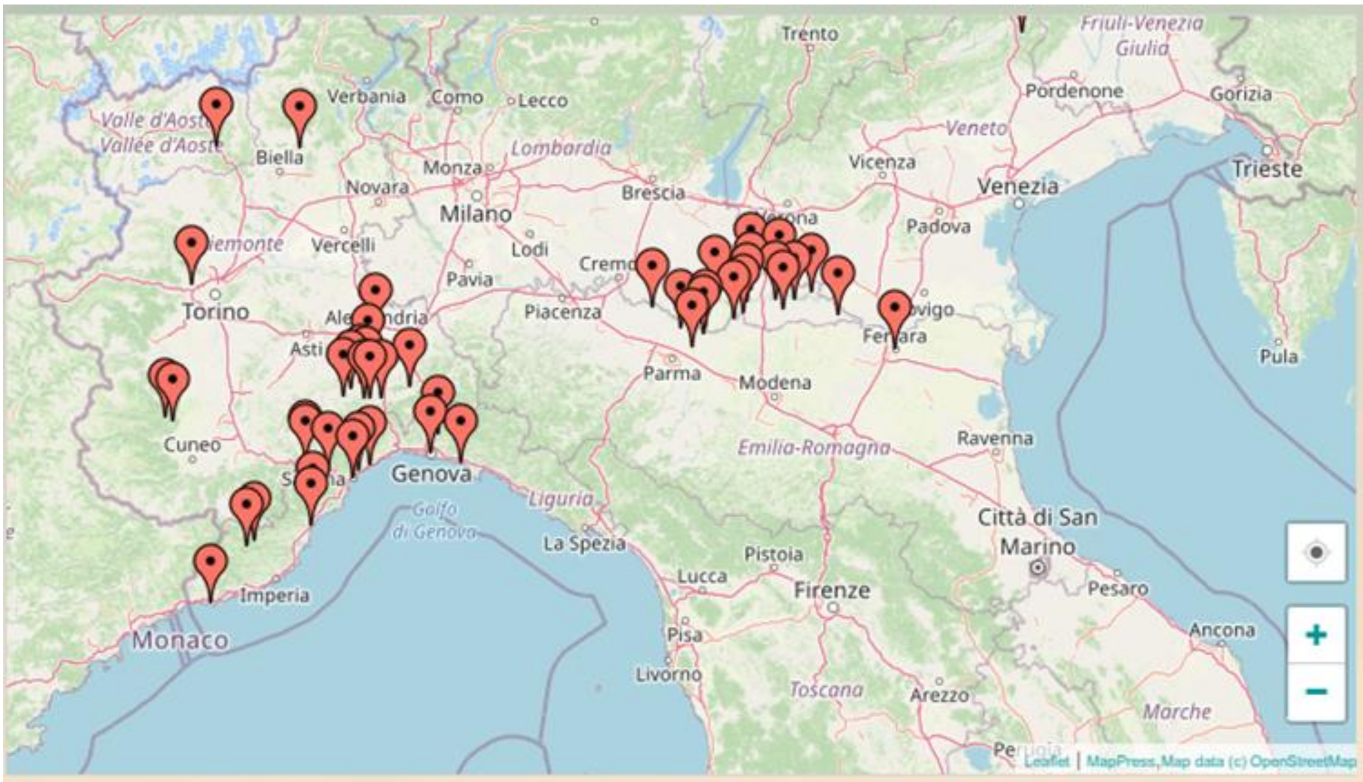

Figure 12 Affected areas during the 22-24 November 2019 event

This event has been simulated by WRF at 2.5 km including the assimilation of radar data (reflectivity CAPPI at 2,000, 3,000 and 5,000 m) as well as the temperature at 2 m as provided by IBM Weather Underground stations (at 18, 21 and, 00 UTC of the 22 November 2019). The overall degree of agreement between the 48 hours rainfall depth predicted and observed (see Figure 13) is good (MODE, 200 mm in 48 hours, see Figure 14 and Table 3). This is particularly true over Western Liguria, while over Norther Piedmont some overestimation in the intensity and spatial extent of the rainfall cluster is apparent. These considerations are well captured by the MODE analysis, where cluster 1 corresponds to Liguria area and cluster 2 to Piedmont one. Cluster 1 in the observed and predicted rainfall depth fields shows the similar spatial extent, a significant overlapping thus resulting in a total interest score equal to 1. Conversely, the predicted cluster 2 is much larger than the observed one and spatial metrics are definitely less positive.

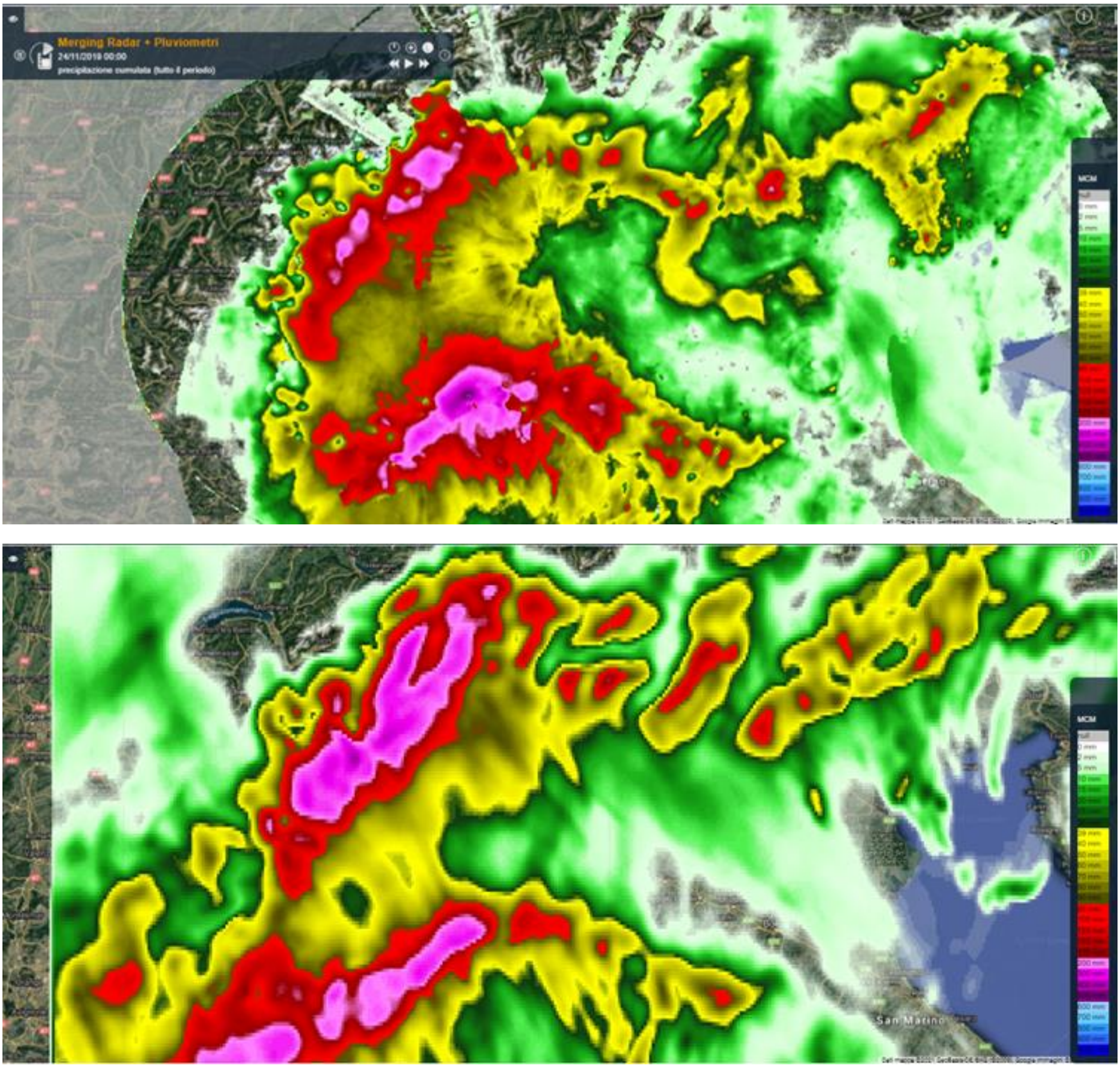

Figure 13 Observed (upper panel) and predicted (lower panel) rainfall depth (48 hours, 22 November 2019 00 UTC - 24 November 2019 00 UTC)

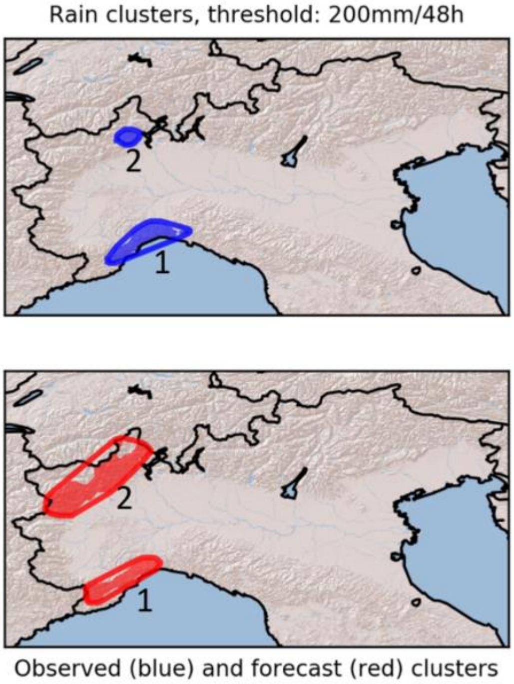

Figure 14 MODE analysis results of the 22-24 November 2019 event

CLUSTER PAIR	CENTROID DISTANCE [km]	OBSERVED AREA [km²]	FORECAST AREA [km²]	INTERSECTION AREA [km²]	FCST INT 90P [mm]	OBS INT 90P [mm]	TOTAL INTEREST
1	43	2,813	2,713	1,431	286.88	374.26	1
2	54	638	6,769	506	319.26	257.92	0.89

Table 3 MODE analysis results of the the 22-24 November 2019 event

The Continuum model hydrological results suggest severe discharge for a large portion of the Pianura Padana catchments which peak discharges above the red alert level (see Figure 15, upper panel), especially in the area of the Tanaro and Bormida catchments which caused indeed many flooding in the Bormida areas, thus in good agreement with the actual observed event (see Figure 15, lower panel).

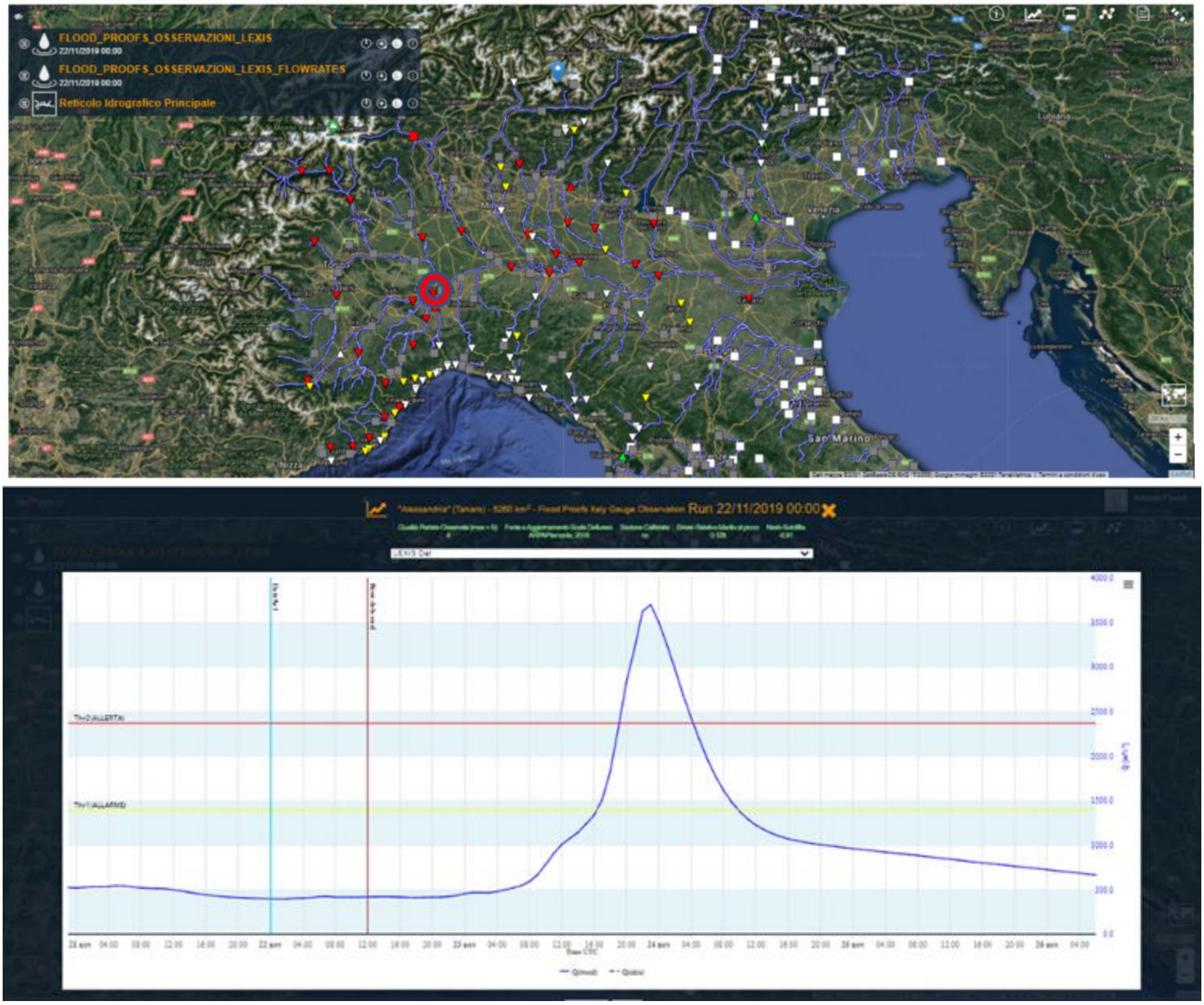

Figure 15 Continuum predictions showing in the upper panel the catchments where predicted discharge is expected to exceed the red (and highest) alert threshold, while the lower panel refers to the specific hydrograph of the Tanaro river in Alessandria (red circle in the upper panel)

3.2.4 North of Italy, 2-3 October 2020

Between the afternoon of the 2nd and the early hours of 3rd October 2020, a rainy event of exceptional intensity affected the regions of the North-West of Italy, in particular the Verbano, the Western Liguria, and the adjacent valleys of Cuneo (see Figure 16).

In these areas, as well as in the French border territories, the particular weather conditions have favoured the occurrence of self-regenerating thunderstorms and huge amounts of rain have fallen in a very few hours. In the Verbano area, the rain gauge of Sambughetto (Valstrona) measured about 504 mm of rain in the 24 hours of October 2. In the Imperia and Cuneo areas daily record values were recorded respectively by the stations of Triora (IM), which at 4:30 am on October 3 measured 426.2 mm, and Limone Pancani (Limone Piemonte, CN) which, for the 24 hours of October 2, recorded about 550 mm.

The high intensity of precipitation has led to widespread phenomena of geohydrological instability with floods and landslides that have damaged both road and rail roads, and compromised the water, electricity (in Liguria alone about 20,000 users were out of service), and telephone networks. In addition to the huge material damage and at least 550 displaced people, the event caused two deaths and one missing. The victims are all connected to a river dynamics: in the territory of Varallo (VC) a man lost his life crashing with his car into the Sesia river, whose waters had eroded the road he was traveling; the same dynamic for the second victim, who fell into the Roja river in the Trucco area (Ventimiglia, IM); the third person is missing in the municipality of Palestro (PV), in the locality of Pizzarrosto, it is a hunter who had found refuge for the night in a farmhouse later invaded by the flooded waters of the Sesia.

Figure 16 Affected areas during the 2-3 October 2020 event

This event has been simulated by WRF at 2.5 km including the assimilation of radar data (reflectivity CAPPI at 2,000, 3,000, and 5,000 m) as well as the temperature at 2 m as provided by IBM Weather Underground stations (at 18, 21 and 00 UTC of 1 October 2020). Figure 17 shows a very good degree of agreement between the observed (upper panel) and predicted (lower panel) 48 hours rainfall depth (02 October 2020 00 UTC - 04 October 2020 00 UTC).

This statement is supported by the results of the MODE analysis (see Figure 18 and Table 4) for the 48 hours rainfall depth and threshold equal to 150 mm. Observed (blue) and forecast (red) clusters look very similar with a significant spatial overlapping and similar extensions. Furthermore, both clusters 1 and 2 have centroid distances between observed and predicted fields below around km which is a rather small value (in the order of 4-5 times the grid spacing).

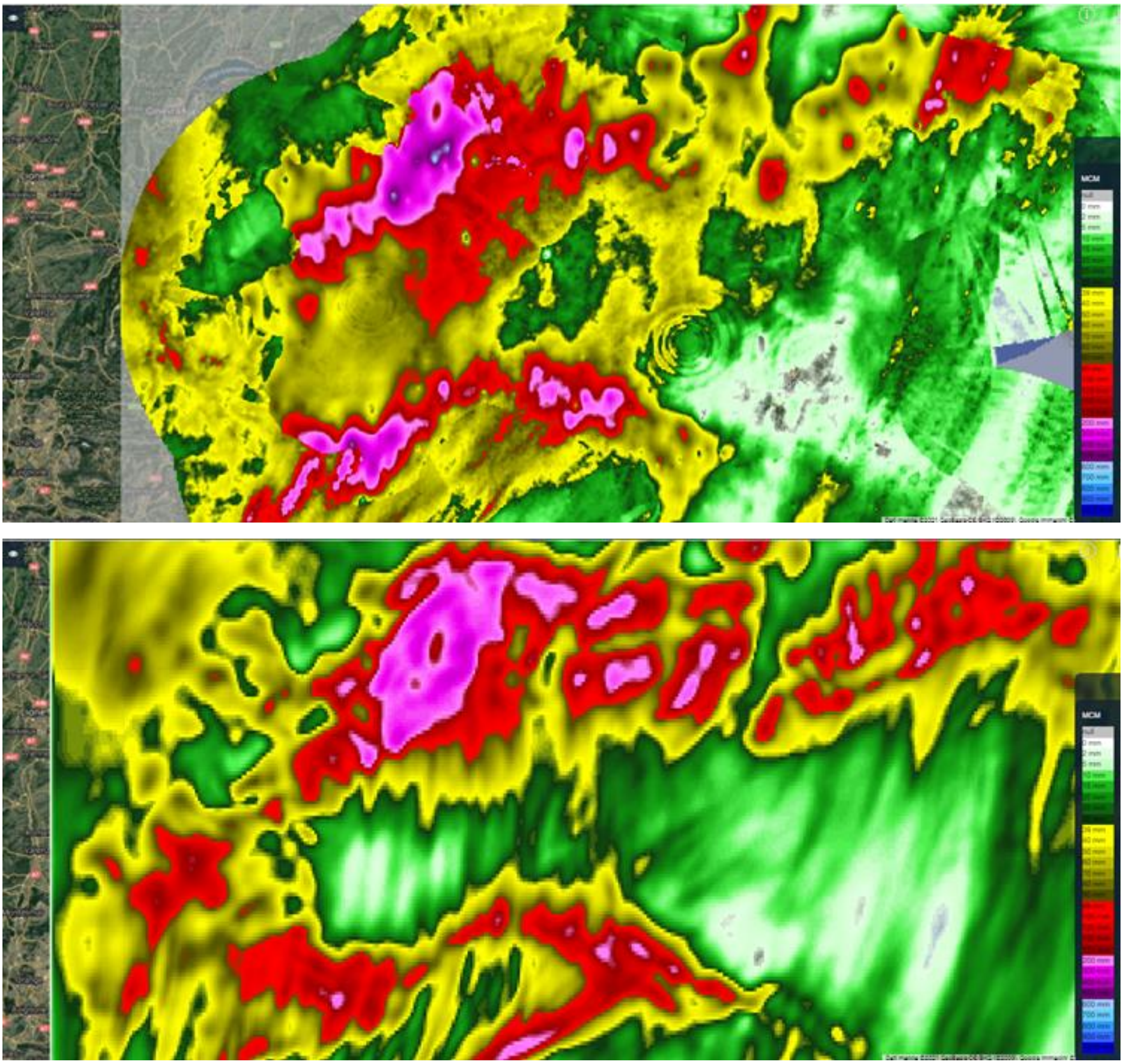

Figure 17 Observed (upper panel) and predicted (lower panel) rainfall depth (48 hours, 02 October 2020 00 UTC - 04 October 2020 00 UTC)

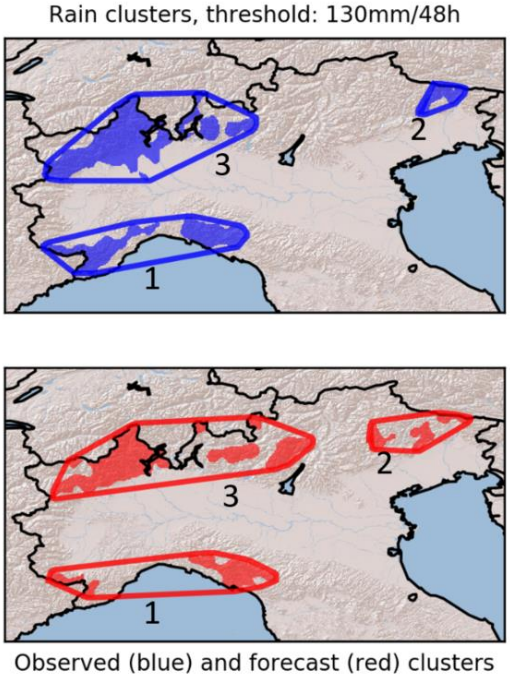

Figure 18 MODE analysis results of the 2-3 October 2020 event

CLUSTER PAIR	CENTROID DISTANCE [km]	OBSERVED AREA [km^2]	FORECAST AREA [km^2]	INTERSECTION AREA [km^2]	FCST INT 90P [mm]	OBS INT 90P [mm]	TOTAL INTEREST
1	66	8,000	5,194	3,125	187.38	298.59	0.98
2	46	1,588	2,663	844	200.37	186.79	0.97
3	127	15,594	13,756	9,506	282.51	365.51	1

Table 4 MODE analysis results of the 2-3 October 2020 event

The Continuum model hydrological results suggest severe discharge for a large portion of North-Western Pianura Padana catchments in Piedmont (Verbano area) with peak discharges above the red alert level (see Figure 19).

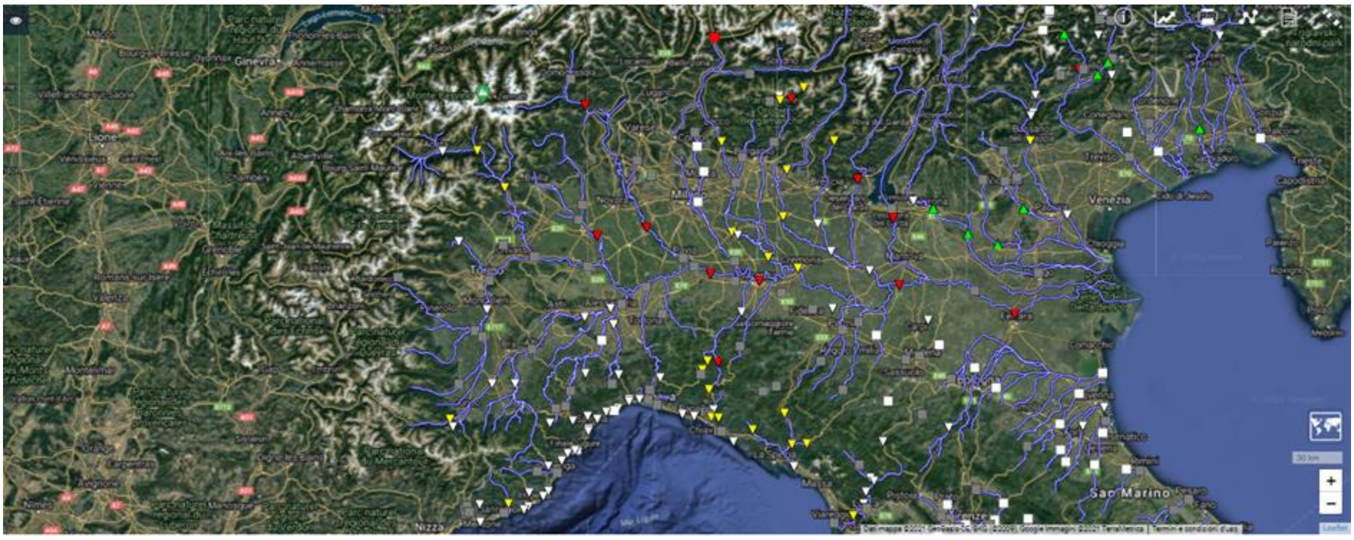

Figure 19 Continuum predictions showing in the upper panel the catchments where predicted discharge is expected to exceed the red (and highest) alert threshold

3.2.5 Sardinia, 28 November 2020

In the period 27-29 November 2020 Sardinia was affected by a disturbance that produced intense convective rainfall affecting in particular Nuoro, Oristano, and Campidano. The torrential rains were mainly located in the inland areas of the province of Nuoro. The highest rainfall accumulations were recorded on 28 November at the rain gauges of Oliena (500 mm), Dorgali Filitta (446 mm), and Bitti (329 mm). On the same day the village of Bitti was hit by the flood wave of the Cuccureddu stream. In addition to the people who lost their lives, there were also 68 displaced people in Bitti. Throughout the island there has been extensive damage to infrastructure: many roads flooded and erased by the fury of water, collapsed bridges, and destroyed irrigation pipelines. Farms and livestock farms, many of which remained completely isolated for hours, also experienced damage. Communications were also difficult due to an electrical and telephone blackout.

This event has been simulated by WRF at 2.5 km including the assimilation of radar data (reflectivity CAPPI at 2,000, 3,000, and 5,000 m) as well as the temperature at 2 m as provided by IBM Weather Underground stations (at 18, 21 and 00 UTC 28 October 2020). The degree of agreement between the 24 hours observed rainfall and predicted one (28 November 2020 00 UTC - 29 November 2020 00 UTC) is overall good even if the predicted rain depth underestimates the observed peak rainfall (above 200 mm in 24 hours) over Northern Sardinia (see Figure 20 upper panel): this statement is also supported by MODE analysis findings (see Figure 21 and Table 5 MODE analysis results), where it is apparent that the observed convective structures above 100 mm in 24 hours occupy overall a larger area than predicted ones and the overall pattern is different as reflected also by the centroid distance value around 40-50 km.

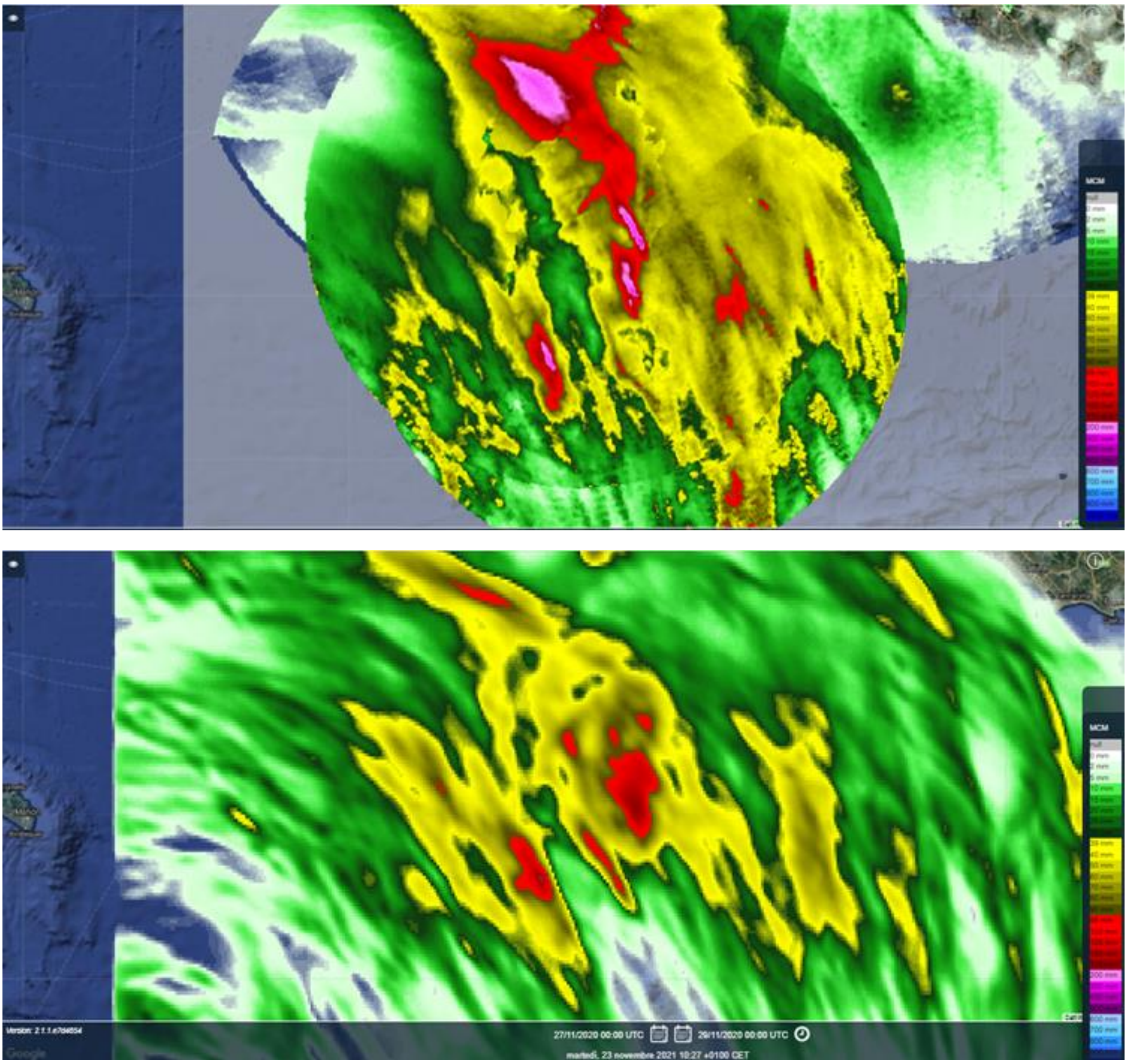

Figure 20 Observed (upper panel) and predicted (lower panel) rainfall depth (24 hours, 28 November 2020 00 UTC - 29 November 2020 00 UTC)

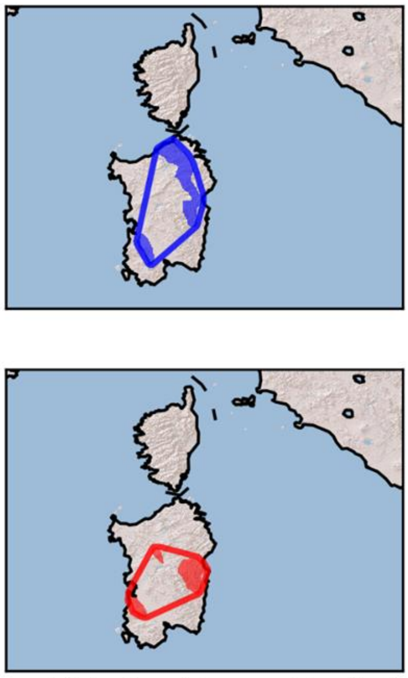

Figure 21 MODE analysis results of the 28-29 November 2020 event

CLUSTER PAIR	CENTROID DISTANCE [km]	OBSERVED AREA [km²]	FORECAST AREA [km²]	INTERSECTION AREA [km²]	FCST INT 90P [mm]	OBS INT 90P [mm]	TOTAL INTEREST
1	43	5,175	3,294	1,525	168.83	185.98	0.96

Table 5 MODE analysis results of the 28-29 November 2020 even

This event is also investigated with the WRF-ERDS workflow (see next sections).

3.2.6 Northern Italy, 13 July 2021

On 13 July 2021 the deep North Atlantic trough, which caused widespread flooding and heavy damage in Germany, Holland, and Belgium, was also responsible for widespread instability over Piedmont, which during the day affected several times almost all the North-Western Italy territory. During the day, the region was affected by heavy rainfall, with values accumulated in 24 hours significant in the Verbano-Cusio-Ossola in Piedmont. In particular, the stations of Cicogna (VB) and Larecchio (VB) recorded about 185 mm and 182 mm respectively in 24 hours. In the afternoon, a strong hailstorm affected the Turin area with grains larger than 5 cm. In the evening, intense rainfall of short duration affected the Roero area: the Castellinaldo d'Alba (CN) rain gauge recorded about 52 mm in an hour, corresponding to a return time of 50 years. Heavy rainfall on the Verbano-Cusio-Ossola, with cumulative values in 24 hours above 180 mm in some stations, has led to sudden flash-flood phenomena in various catchments of the area. The largest increases were recorded during the morning on the River Toce which, in Pontemaglio (VB), has approached the danger threshold (10:30 UTC) and on the Anza stream that, in San Carlo (VB), has exceeded the threshold of attention (8:30 UTC). As a consequence of the higher contributions, it was recorded, starting from the early afternoon of July 13, an increase in the level of Lake Maggiore, which reached its maximum value in the late morning of the 14th July (12:30 UTC), below the guard threshold. Severe rainfall phenomena were also observed over Veneto with peak values around 200 mm.

This event has been simulated by WRF at 2.5 km including the assimilation of radar data (reflectivity CAPPI at 2,000, 3,000 and 5,000 m) as well as temperature at 2 m as provided by IBM Weather Underground stations (at 18, 21 and

00 UTC of 13 July 2021). Figure 22 shows a quite satisfactory agreement between the observed (upper panel) and predicted (lower panel) 24 hours rainfall depth scenarios (13 July 2021).

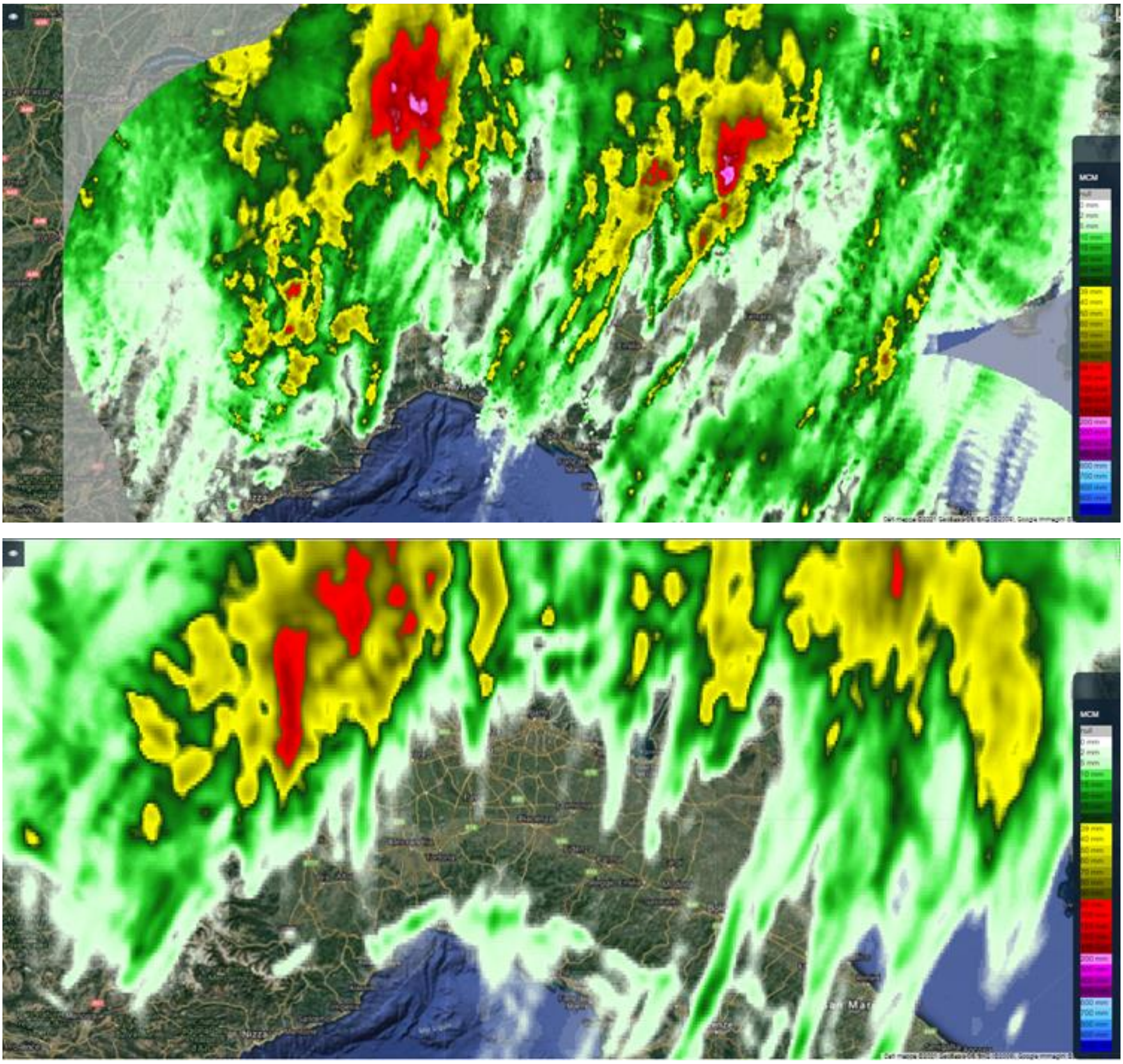

Figure 22 Observed (upper panel) and predicted (lower panel) rainfall depth (24 hours, 13 July 2021 00 UTC - 14 July 2021 00 UTC)

This statement is supported by the results of the MODE analysis (see Figure 23 and Table 6) for the 24 hours rainfall depth and threshold equal to 50 mm. Observed (blue) and forecast (red) clusters over northern Piedmont and Veneto respectively look rather similar. Indeed, observed and predicted clusters 1 show a smaller centroid distance in comparison to their cluster 2 counterparts even if severe rainfall structures above 50 mm have overall a larger extent inside the forecast cluster than the observed one. Conversely, while the observed and predicted clusters 2 exhibit a rather large centroid distance (about 120 km), the respective severe rainfall structure included in both clusters 2 sums up to similar values around 4,600-4,900 km^2.

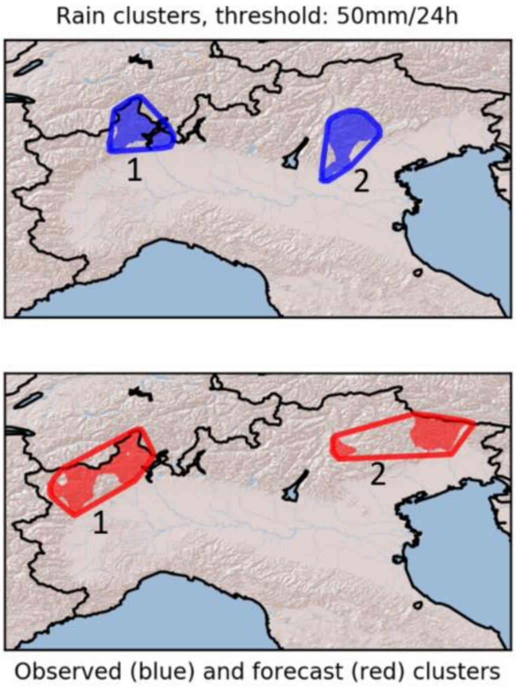

Figure 23 MODE analysis results of the 13 July 2021 event

CLUSTER PAIR	CENTROID DISTANCE [km]	OBSERVED AREA [km²]	FORECAST AREA [km²]	INTERSECTION AREA [km²]	FCST INT 90P [mm]	OBS INT 90P [mm]	TOTAL INTEREST
1	60	4,713	7,513	3,044	129.53	144.03	0.96
2	126	4,894	4,494	494	82.25	140.41	0.86

Table 6 MODE analysis results of the 13 July 2021 event

Figure 24 shows the Continuum results (lower panel refers to the specific hydrograph of the Toce river in Candoglia, circled in red in the upper panel).

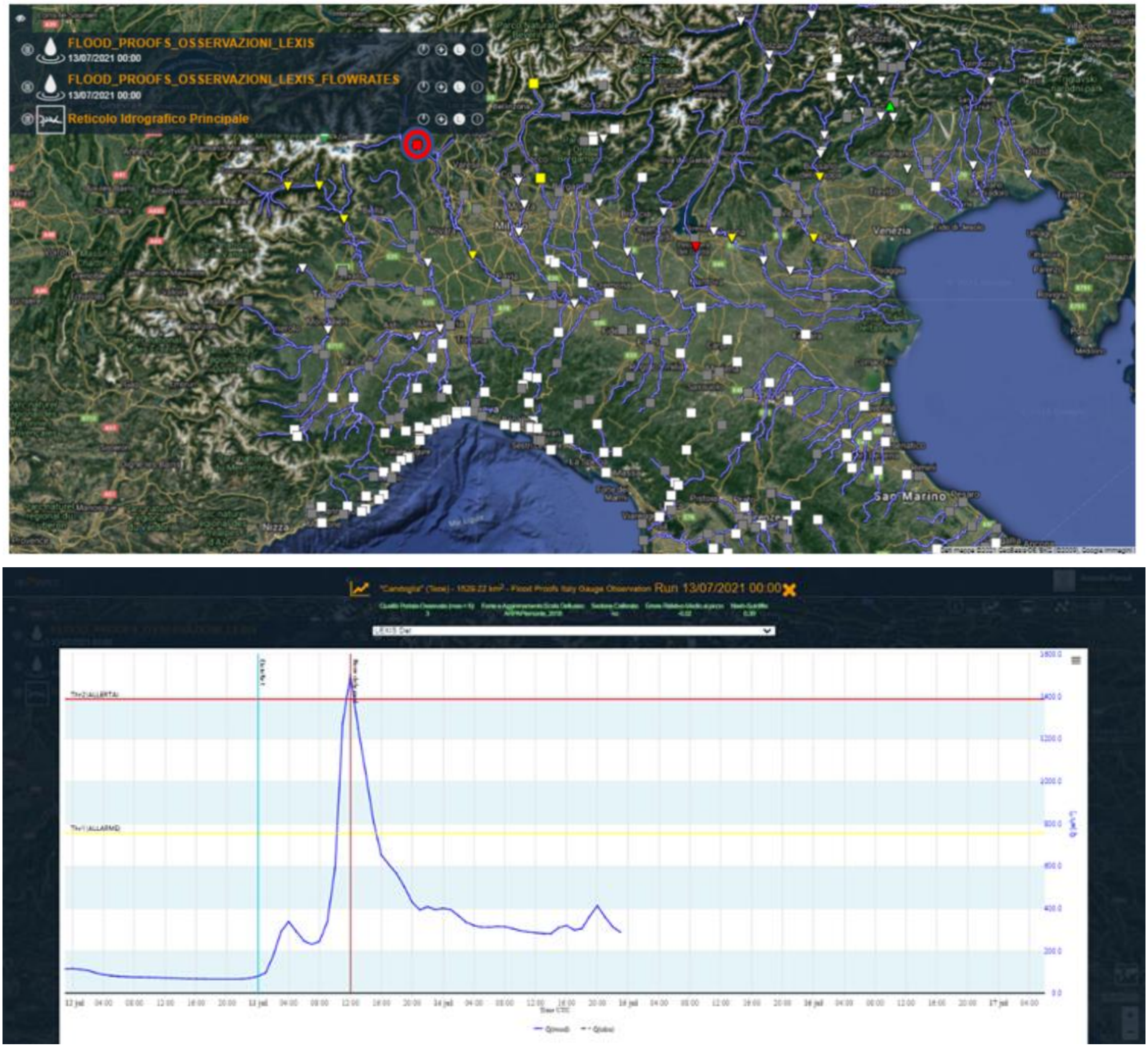

Figure 24 Continuum predictions showing in the upper panel the catchments where predicted discharge is expected to exceed the red (and highest) alert threshold, while the lower panel refers to the specific hydrograph of the Toce river at Candoglia (red circle in the upper panel)

3.2.7 Northern Italy, 7 July 2021

On 7 July 2021, fresh air infiltration at high altitude triggered a series of lines of thunderstorms that, driven by the winds of libeccio, have affected the mountain and foothill areas of the Western and Northern Alpine region. On 8 July, however, the promontory of high pressure has definitively yielded under the pressure of the Atlantic trough that has passed quickly over our region, increasing in a way marked atmospheric instability everywhere, with very strong thunderstorms accompanied by hailstorms widespread and gusts of wind that occasionally also resulted in tornadoes. Short-term heavy rainfall affected the lowland areas, while remarkable accumulated rainfall values have been recorded in the Verbano province. On 7 July 2021 the Verolengo (TO) rain gauge recorded 50 mm in an hour corresponding to a return time included between 10 and 20 years, while the next day Brandizzo Malone (TO) rain gauge measured 60.2 mm in one-hour corresponding to a return time of between 50 and 100 years.

This event has been simulated by WRF at 2.5 km including the assimilation of radar data (reflectivity CAPPI at 2,000, 3,000, and 5,000 m) as well as the temperature at 2 m as provided by IBM Weather Underground stations (at 18, 21 and 00 UTC of 7 July 2021). The overall large-scale pattern looks similar with elongated rainfall structures both in the observed (see Figure 25, upper panel) and in the predicted 24 hours rainfall fields. However, the WRF model produces more widespread precipitation patterns, with thicker and wider rainfall patterns. This statement is reflected in the forecast area around 9,500 km^2, about 1.75 the observed, but still with an overall good localization of the predicted scenario (centroid distance about 80 km), thus supportive of Civil Protection applications (see Figure 26 and Table 7).

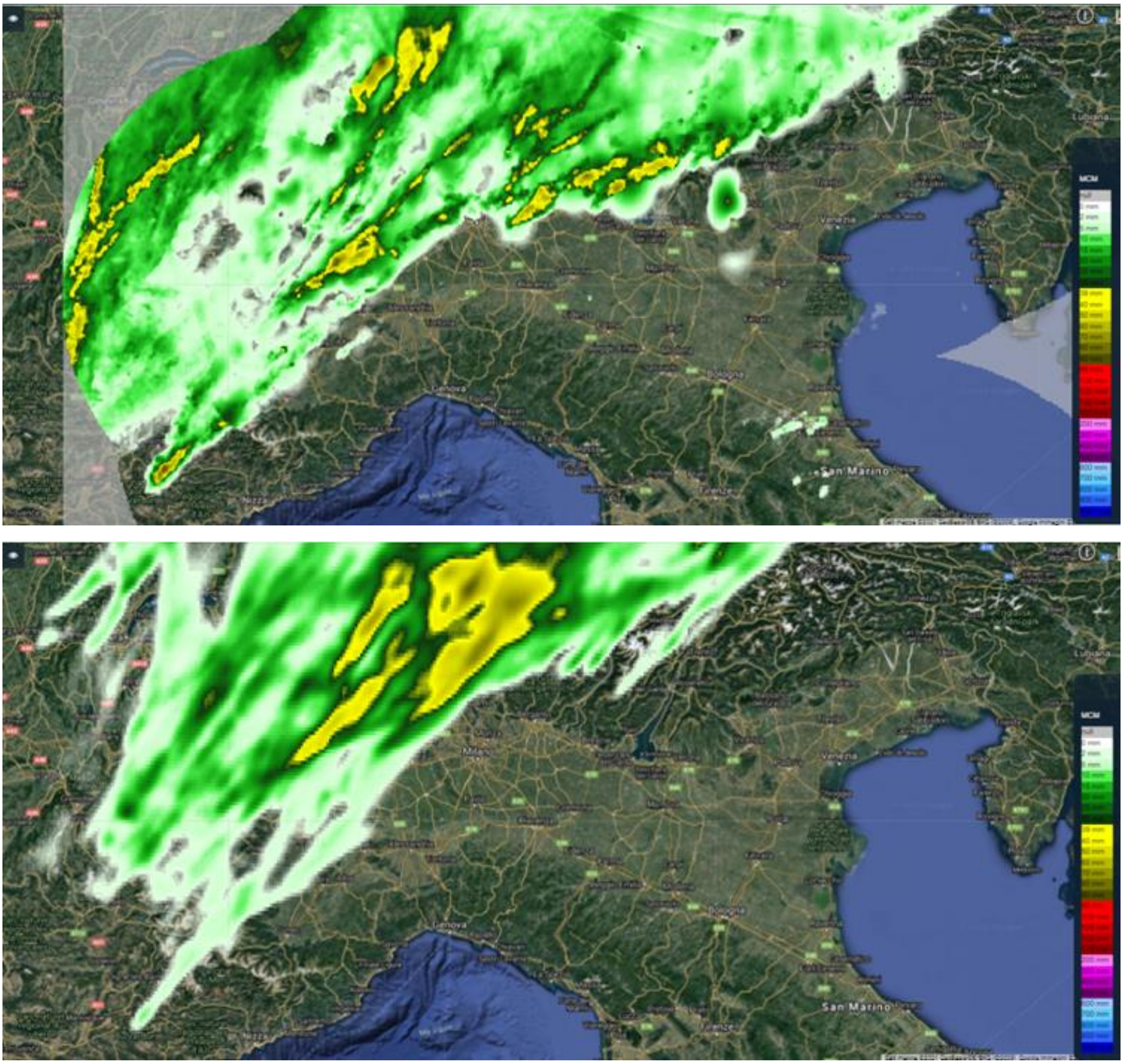

Figure 25 Observed (upper panel) and predicted (lower panel) rainfall depth (24 hours, 7 July 2021 00 UTC - 8 July 2021 00 UTC)

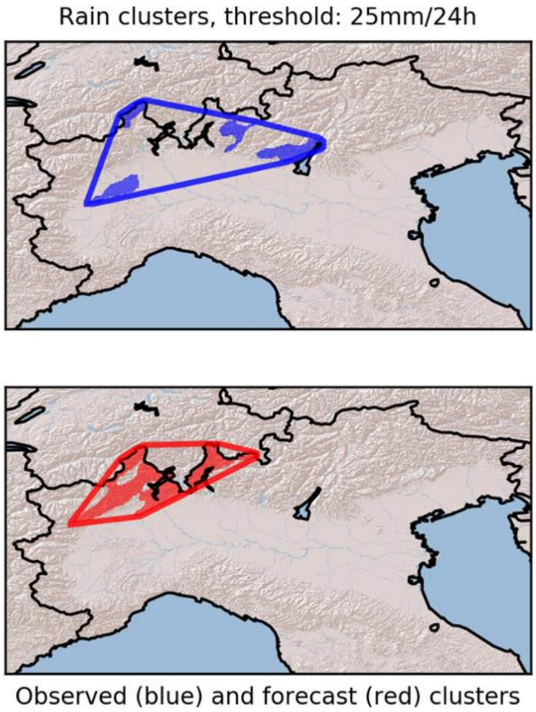

Figure 26 MODE analysis results of the 7 July 2021

CLUSTER PAIR	CENTROID DISTANCE [km]	OBSERVED AREA [km²]	FORECAST AREA [km²]	INTERSECTION AREA [km²]	FCST INT 90P [mm]	OBS INT 90P [mm]	TOTAL INTEREST
1	84	5,381	9,450	788	64.59	55.36	0.88

Table 7 MODE analysis results of the 7 July 2021

3.2.8 Sicily and Calabria, Apollo Medicane, October 2021

During the last week of October 2021 an intense Mediterranean hurricane (Medicane), named Apollo by the Eumetnet Storm Naming project, affected many countries on the Mediterranean coasts.

While tropical storms like hurricanes require a minimum sea surface temperature of 26°C for their development, Medicanes can form over sea surfaces with temperatures below this threshold. Medicanes are most likely to form during the autumn and winter months, when strong temperature gradients exist and atmospheric instability is driven by cold air flowing across relatively milder seas. Similar to tropical storms, the fuel for a Medicane is provided by enormous quantities of moisture evaporating from the warm sea surface. The temperature difference between the air and the water creates unstable conditions that result in the formation of a low-pressure system. The rising moist air produces deep convective clouds (cumulonimbus clouds) that generate thunderstorms and heavy rainfall. Surrounding air rushes in to replace the air "lost" near the surface which continuously feeds the weather system. If the wind direction with height remains uniform the system can grow and develop into a large storm.

The Apollo Medicane deaths toll peaked up to 7 people, due to flooding from the cyclone in the countries of Tunisia, Algeria, Malta, and Italy. It persisted over such areas for about one week (24 October – 1 November 2021) and produced very intense rainfall phenomena and widespread flash-flood and flood episodes especially over Eastern Sicily and Southern Calabria on 24 - 26 October 2021. Emergency authorities issued a red alert warning for parts of Sicily and Calabria, Southern Italy, as heavy rainfall from Medicane Apollo produced flash floods that inundated populated regions. Eastern Sicily experienced the highest levels of rainfall, with a total of 520 mm reported at Linguaglossa, Catania, from 24 to 26 October. On 24 October, heavy downpours produced more than 300 mm of rain near Catania, which is nearly half the average annual rainfall for the island. Over 300 mm of rainfall was reported in Syracuse, with 279.8 mm recorded at Lentini on 25 October.

LEXIS project modelled in real-time every day from 23 October 2021 to 29 October 2021 this weather scenario by WRF at 2.5 km including the assimilation of radar data (reflectivity CAPPI at 2,000, 3,000, and 5,000 m) as well as the temperature at 2 m as provided by IBM Weather Underground stations.

Figure 27 shows a good degree of agreement between 48 hours observed rainfall depth and predicted one for the most intense phase of the event, still with a certain degree of overestimation of the spatial extent over Eastern Sicily. This statement is supported by the results of the MODE analysis (see Figure 28 and Table 8) for the 48 hours rainfall depth and threshold equal to 150 mm. Observed (blue) and forecast (red) clusters look quite similar with a significant spatial overlapping while rainfall areas with a peak above 150 mm sum up to about 9,200 km^2 significantly larger than the observed ones which sum up to 4,500 km^2. Positively enough, the centroid distance between observed and predicted fields is below 13 km, which is a rather small value (in the order of 4-5 times the grid spacing).

The Continuum model hydrological results suggest severe discharge for eastern Sicily and Calabria, which peak discharges above the red alert level (see Figure 29 upper panel). As a proof of the good performance skills of the WRF-Continuum workflow for this event, it is shown the predicted discharge evolution at the Lentini catchment location (see Figure 29 lower panel), indeed affected by severe observed flooding phenomena on 25 October 2021.

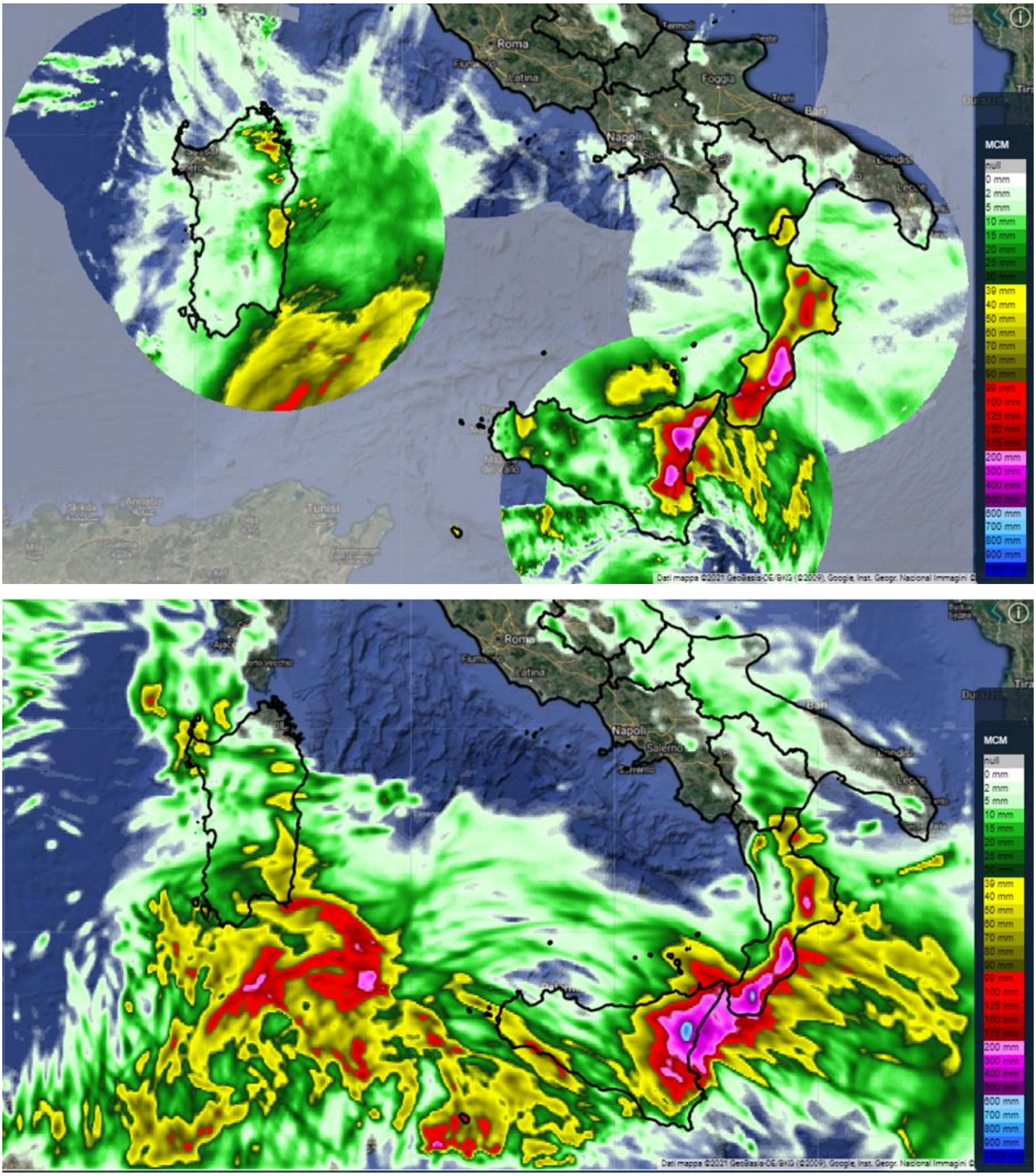

Figure 27 Observed (upper panel) and predicted (lower panel) rainfall depth (48 hours, 24 October 2021 00 UTC - 26 October 2021 00 UTC)

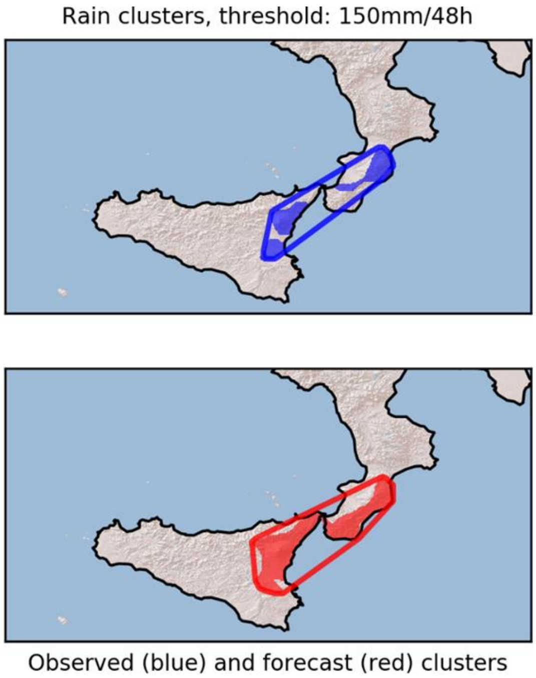

Figure 28 MODE analysis results of the Apollo Medicane

CLUSTER PAIR	CENTROID DISTANCE [km]	OBSERVED AREA [km²]	FORECAST AREA [km²]	INTERSECTION AREA [km²]	FCST INT 90P [mm]	OBS INT 90P [mm]	TOTAL INTEREST
1	13	4,469	9,150	3,994	417.29	275.26	0.96

Table 8 MODE analysis results of the Apollo Medicane

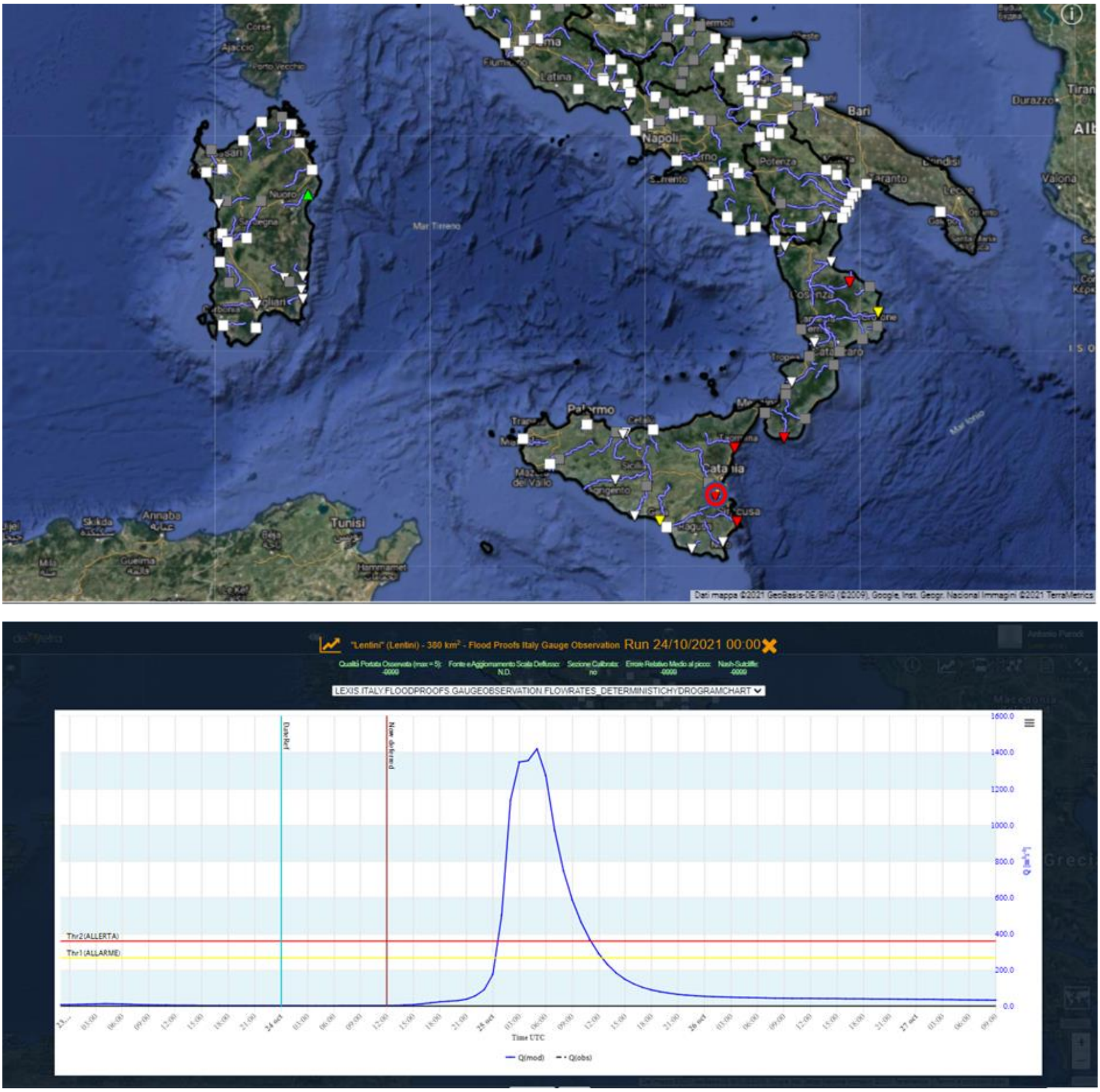

Figure 29 Continuum predictions showing in the upper panel the catchments where predicted discharge is expected to exceed the red (and highest) alert threshold, while the lower panel refers to the specific hydrograph of the Lentini river (red circle in the upper panel)

4 DESCRIPTION OF THE CASE STUDIES AND RESULTS FOR WRF-RISICO WORKFLOW

4.1 FOREST FIRE EVENTS DURING JULY-AUGUST 2019

During the period between 7 and 11 July 2019 Southern Italy was affected by widespread wildland fires. These events affected mostly Sicily and in particular the Siracusa and Catania provinces (Table 9) with burnt areas peaking up to about 500 ha.

FIRE DATE	AREA [ha]	PROVINCE
7 July 2019	157	Siracusa (Sicily)
8 July 2019	76	Siracusa (Sicily)
8 July 2019	75	Catania (Sicily)
8 July 2019	55	Catania (Sicily)
9 July 2019	21	Catania (Sicily)
9 July 2019	47	Catania (Sicily)
10 July 2019	507	Catania (Sicily)
10 July 2019	194	Siracusa (Italy)

Table 9 Burnt areas in the Catania and Siracusa provinces during the period from 7 to 10 July 2019 (source EFFIS)

The WRF-RISICO workflow has been executed for the aforementioned period 7-10 July 2019: WRF model has assimilated at 18, 21, and 00 UTC the day before each forecast date the radar reflectivity CAPPI (at 2,000, 3,000, and 5,000 m) as well as in-situ 2 m temperature data provided by IBM Weather Underground stations.

The RISICO model forecast is daily at 1-hour temporal resolution and the predictive variable under consideration is the fireline intensity defined as the rate of energy or heat release per unit time per unit length of fire front (kW/m).

The selected observed forest fire variable is the forest fire reports sent to the Unified Air Operations Centre (COAU) at the Italian Civil Protection Department (airplane symbol in the maps). The COAU is active continuously throughout the 24 hours throughout the year and it represents the Command and Control Center of all air vehicles, namely Canadair airplanes, made available for the activity of forest fire extinguishing planning and coordinating flight activities both nationally and internationally.

The comparison between the fireline intensity value at 12 UTC for each forecasting day and a corresponding number of Canadair airplanes involved in fire extinction activities is reported in the following Table 10 and Table 11and it suggests, in a qualitative manner, that RISICO has been capable to detect areas potentially prone to the occurrence of wildland forest fires in different portions of Italy.

DATE	REGIONS	CANADAIR FLIGHTS NUMBER	PEAK FIRELINE INTENSITY [kW/m]
07/07/2019	Sardinia, Sicily	8	≈2,000 kW/m (see Figure 30)
08/07/2019	Puglia, Sicily	12	2,000-3,500 kW/m (see Figure 31)
09/07/2019	Calabria, Sicily	9	1,700-2,000 kW/m (see Figure 32)
10/07/2019	Calabria, Sicily	19	≈3,500 kW/m (see Figure 33)

Table 10 Forest fire risk summary for the period 7 July – 10 July 2019

DATE	REGIONS	CANADAIR FLIGHTS NUMBER	PEAK FIRELINE INTENSITY [kW/m]
11/08/2021	Lazio, Sardinia, Sicily	23	2,000-3,500 kW/m (see Figure 34)
12/08/2021	Lazio, Campania, Sardinia, Calabria, Sicily	36	2,000-3,500 kW/m (see Figure 35)
13/08/2021	Umbria, Lazio, Campania, Puglia, Calabria, Sicily	30	1,700-2,000 kW/m (see Figure 36)
14/08/2021	Lazio, Campania, Calabria, Sardinia, Sicily	34	2,000-3,500 kW/m (Figure 37)
15/08/2021	Tuscany, Lazio, Campania, Basilicata, Calabria, Sicily	45	2,000-3,500 kW/m (Figure 38)

Table 11 Forest fire risk summary for the period 11 August – 15 August 2021

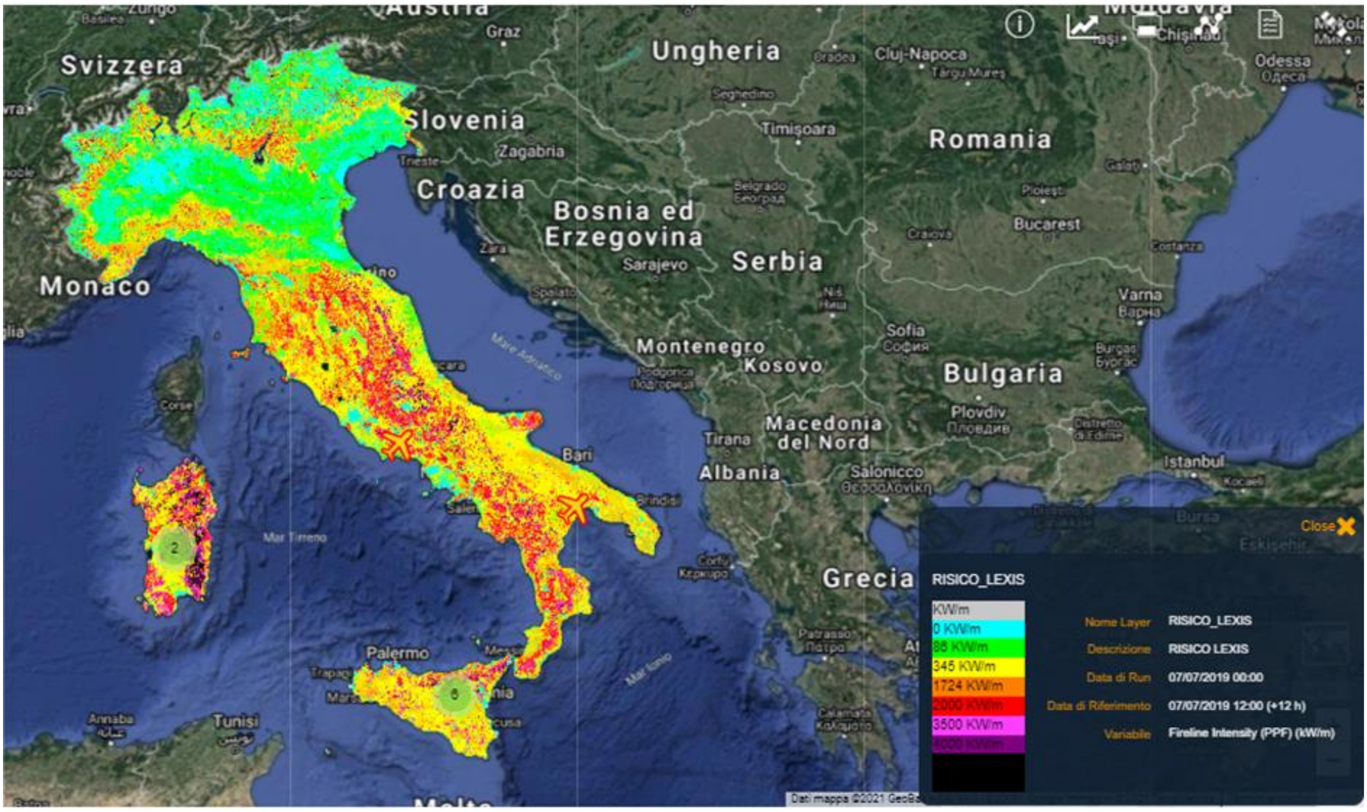

Figure 30 Predicted fireline intensity on 07/07/2019 at 12 UTC and number of Canadair airplanes flights during the day

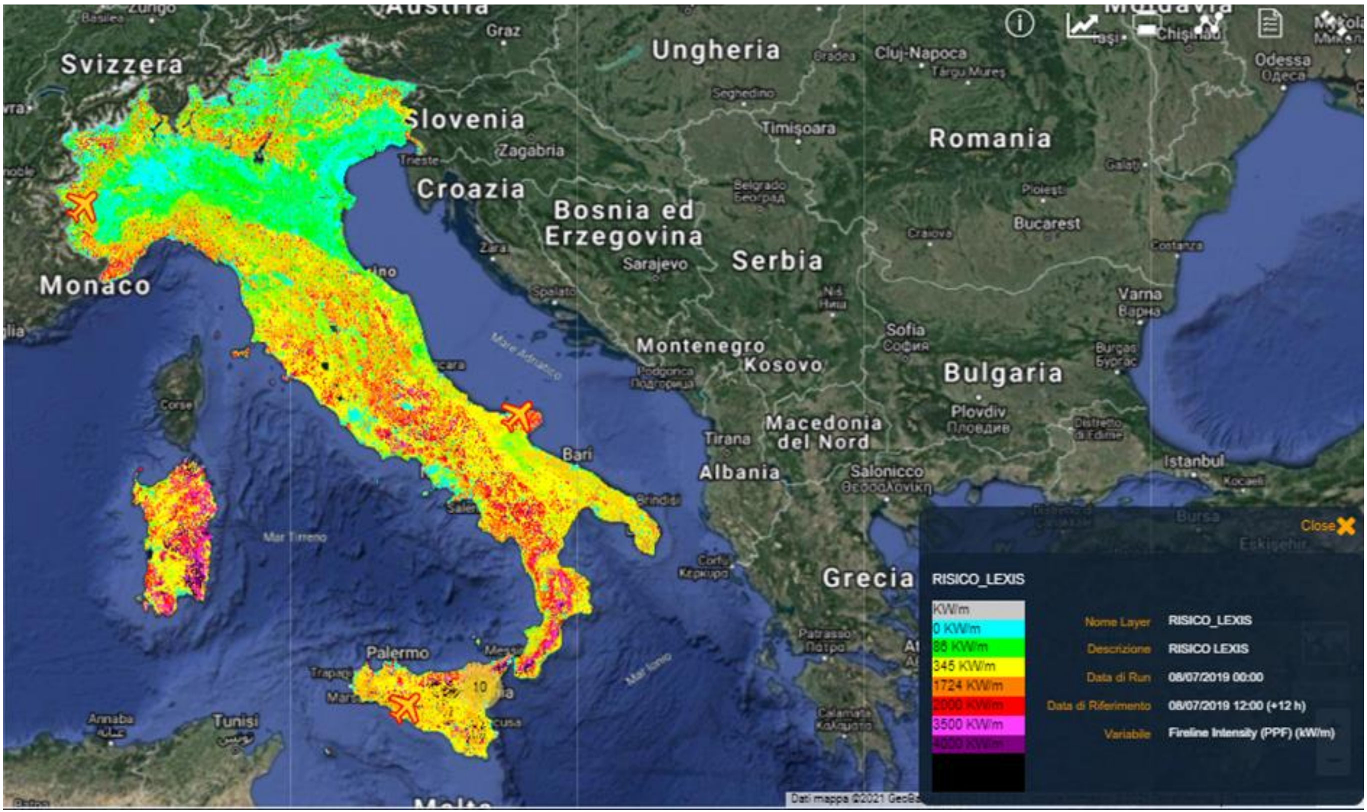

Figure 31 Predicted fireline intensity on 08/07/2019 at 12 UTC and number of Canadair airplanes flights during the day

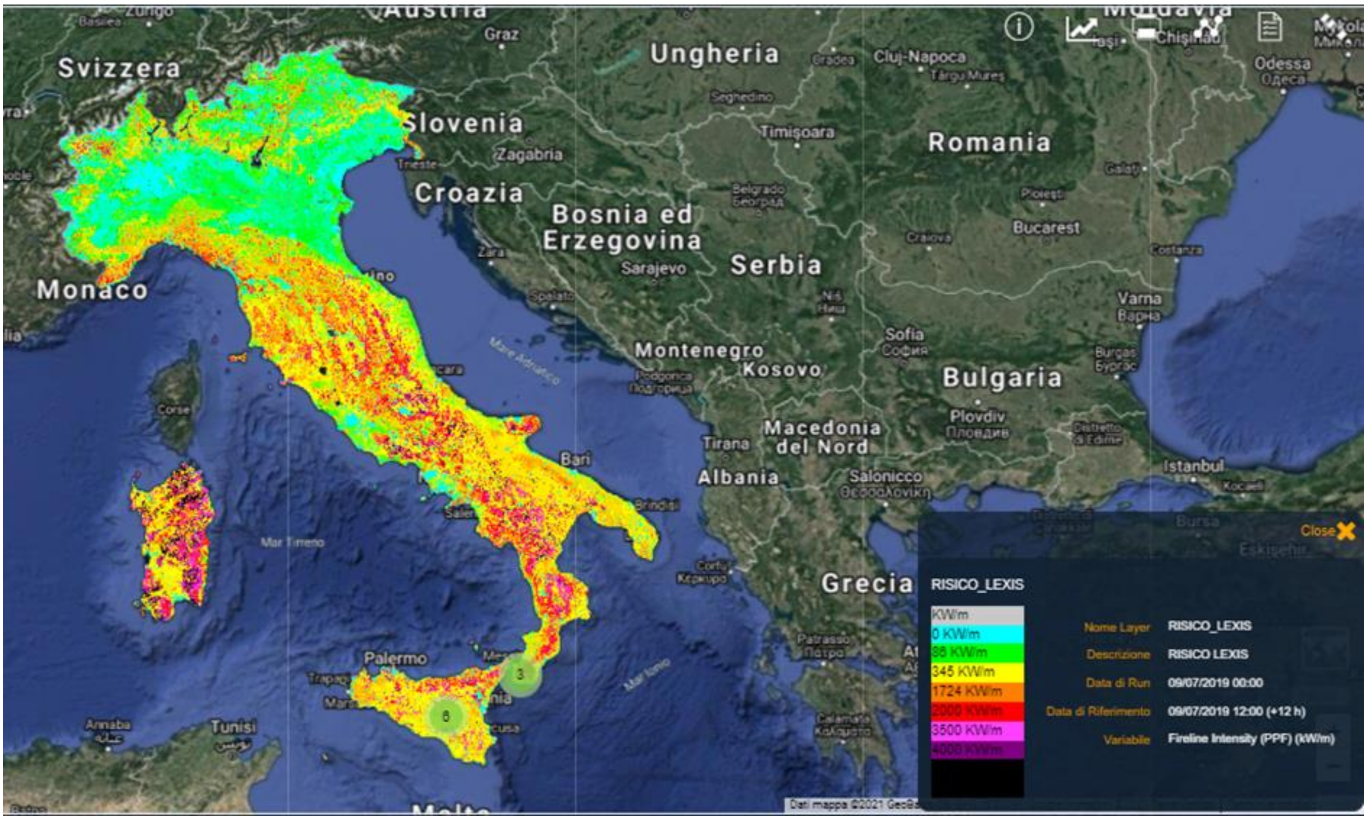

Figure 32 Predicted fireline intensity on 09/07/2019 at 12 UTC and number of Canadair airplanes flights during the day

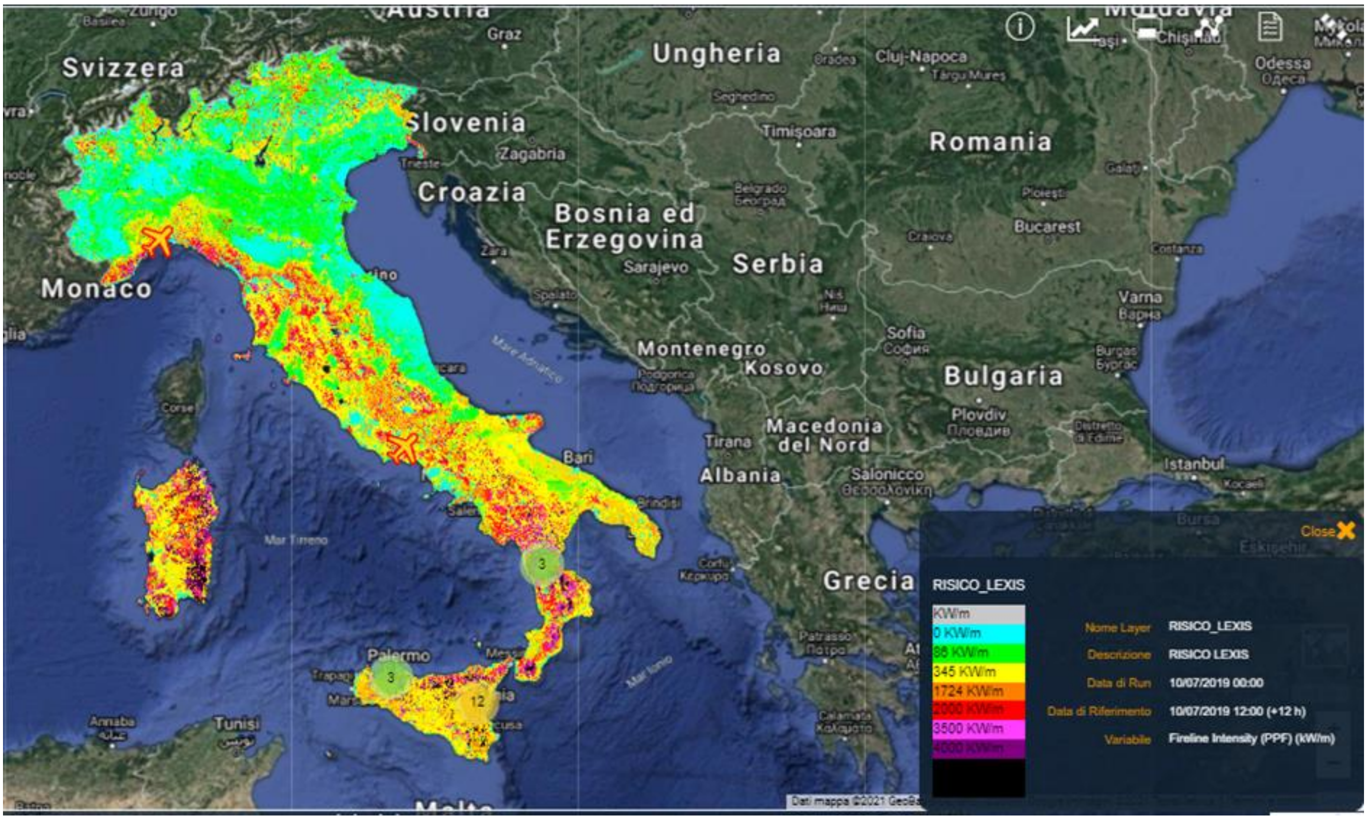

Figure 33 Predicted fireline intensity on 10/07/2019 at 12 UTC and number of Canadair airplanes flights during the day

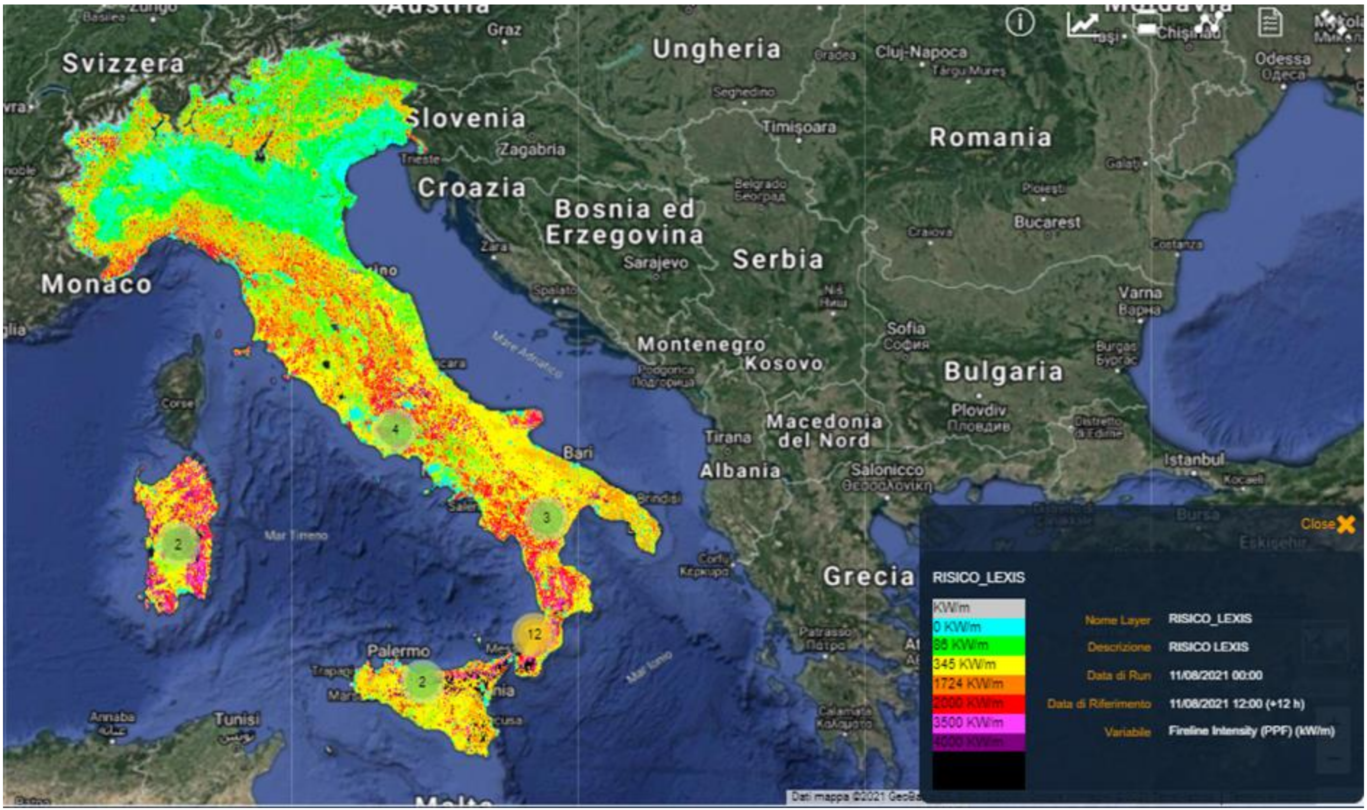

Figure 34 Predicted fireline intensity on 11/08/2021 at 12 UTC and number of Canadair airplanes flights during the day

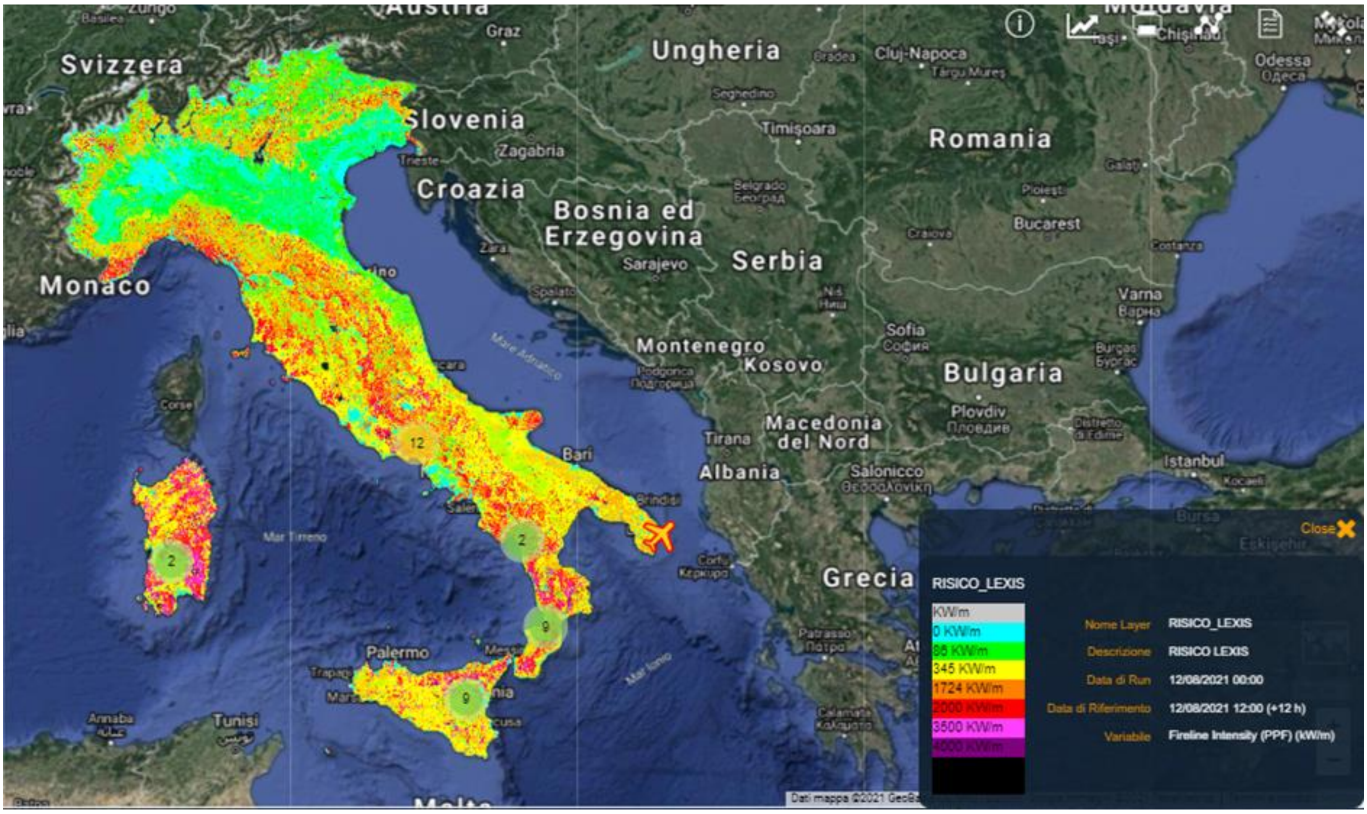

Figure 35 Predicted fireline intensity on 12/08/2021 at 12 UTC and number of Canadair airplanes flights during the day

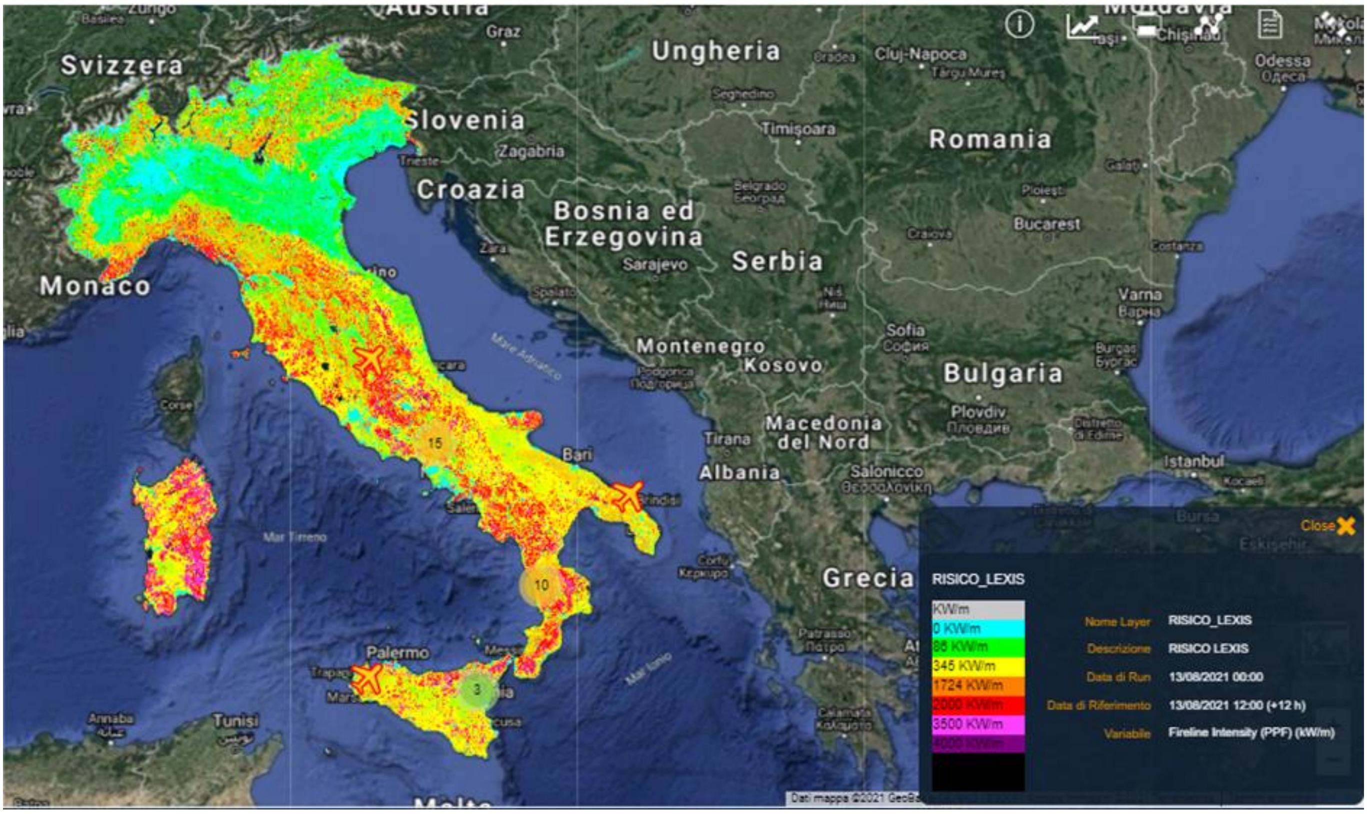

Figure 36 Predicted fireline intensity on 13/08/2021 at 12 UTC and number of Canadair airplanes flights during the day

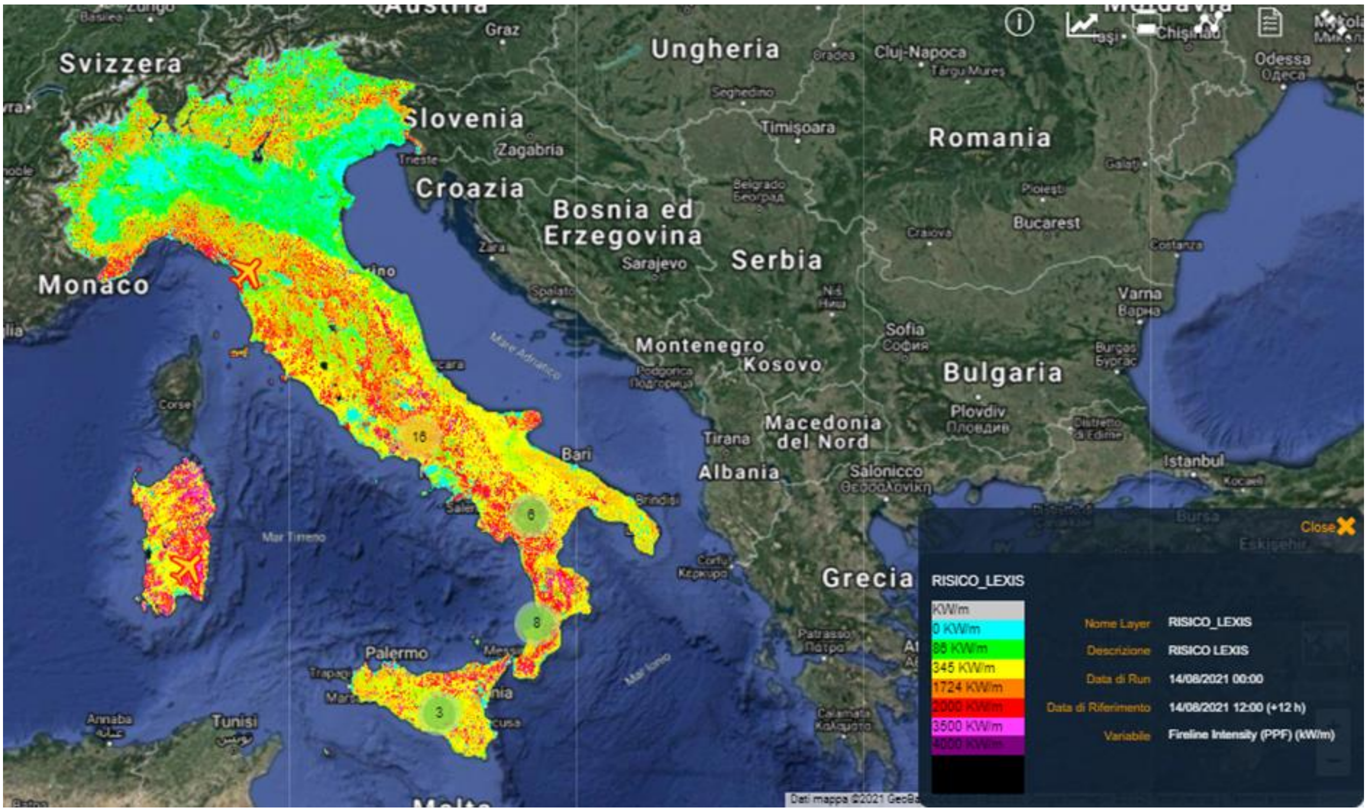

Figure 37 Predicted fireline intensity on 14/08/2021 at 12 UTC and number of Canadair airplanes flights during the day

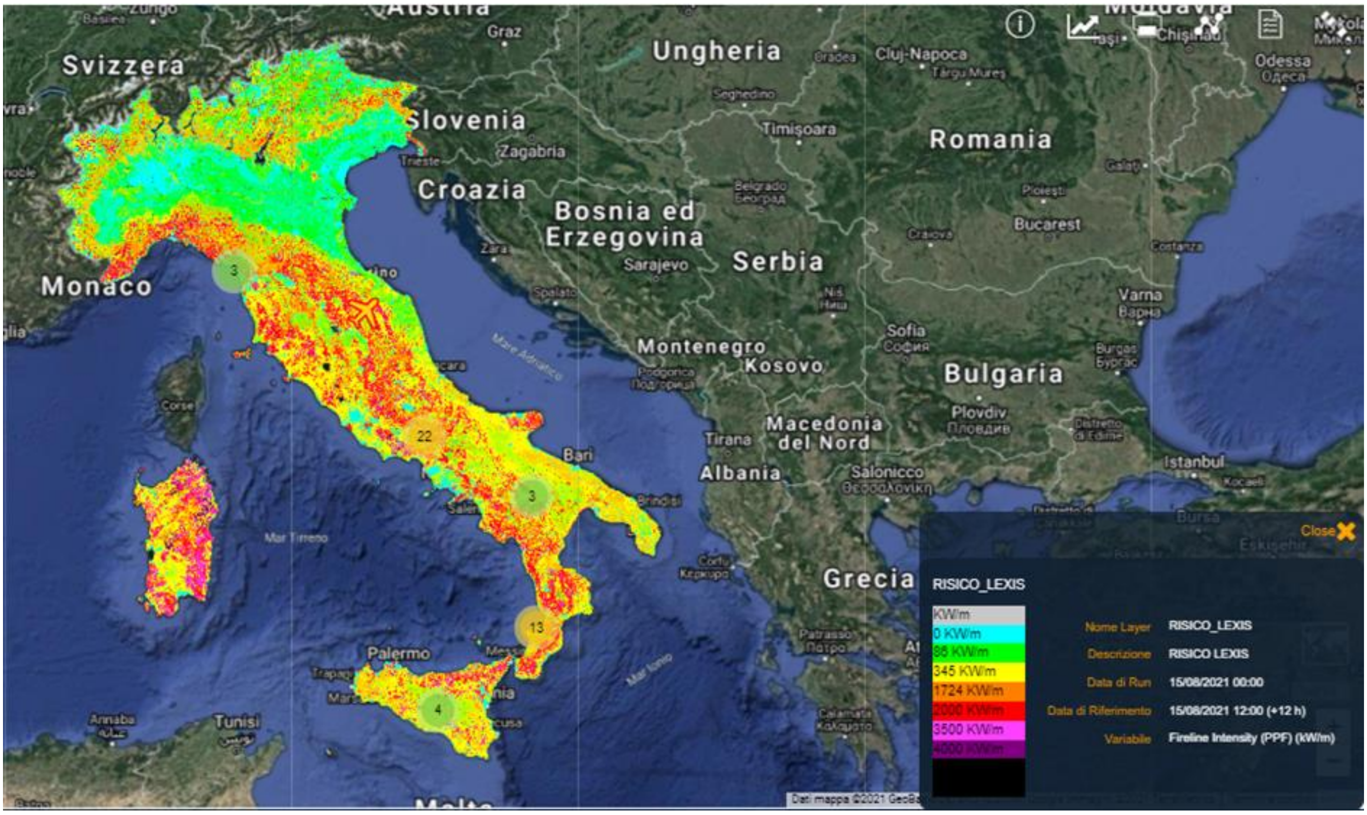

Figure 38 Predicted fireline intensity on 15/08/2021 at 12 UTC and number of Canadair airplanes flights during the day

Burnt areas in the Catania and Siracusa provinces during the period 11-15 August 2021 are reported in Table 18 (Appendix A).

5 DESCRIPTION OF THE CASE STUDIES AND RESULTS FOR WRF-ERDS WORKFLOW

5.1 THE WRF-ERDS WORKFLOW

The Extreme Rainfall Detection System (ERDS) is a tool for the monitoring and forecasting of rainfall events with a global spatial coverage developed by ITHACA. ERDS is also an early warning system: it compares rainfall depths with specific pre-calculated rainfall thresholds to issue heavy rainfall alerts in places where the rainfall depth is higher than the threshold [9].

Before the inclusion of ERDS in the WP7 of the LEXIS project, two different datasets were used. NASA/JAXA Global Precipitation Measurement (GPM) Integrated Multi-SatellitE Retrievals for GPM (IMERG) Early run data (0.1° spatial resolution, 30 minutes temporal resolution, ~4 hours latency) was used to perform a near real-time rainfall monitoring [9]. Global Forecast System (GFS) model data (0.25° spatial resolution) was instead used as a source of rainfall forecasts. Thanks to these datasets, ERDS was able to provide information over the past 12, 24, 48, 72, and 96 hours and for the upcoming 12, 24, 48, 72, and 96 hours.

WRF model data executed by CIMA was then included to provide more accurate information over Europe, with the aim of increasing the extreme rainfall detection accuracy over this area.

The threshold values used by ERDS are data-dependent (each dataset has its own set of thresholds), time-dependent (threshold values increase as the time interval increase) and space-dependent (each pixel has a different threshold value). The methodology used for the evaluation of the rainfall threshold is described in [9].

5.2 THE CASE STUDIES

The entire WRF-ERDS workflow has been applied to several heavy rainfall events that affected Italy: Table 12 summarizes the case studies reported in this deliverable, listed in ascendant order. Each case study has been selected for a particular characteristic, to evaluate the extreme rainfall detection accuracy in different conditions that usually put a strain on early warning systems based on large-scale rainfall datasets (e.g., rainfall events with peculiar patterns, short-duration events, very intense convective events, etc).

LOCATION	DATE
Tuscany (Central Italy)	4 June 2020
Palermo (Sicily Island, South of Italy)	15 July 2020
Liguria (North of Italy)	7 September 2020
Calabria (Italy)	20/23 November 2020
Sardinia (Italy)	28/29 November 2020

Table 12 List of the case studies analysed with the WRF-ERDS workflow

5.2.1 Tuscany, 4 June 2020

An accumulated rainfall of about 100 mm / 6 hours (with values up to 70-80 mm in 1 hour and up to 200 mm in 24 hours) was recorded near Lucca, while the Arezzo province was affected by a maximum peak of 70-80 mm in 6 hours [10]. In the northern part of the region, more than 100 mm of rain fell in 3 hours, corresponding to an estimated return period of about 200 years in some small areas [10]. On the contrary, about 10 mm of rainfall was recorded in the territories from Livorno to Firenze [10]. This case study has been selected for the complex shape of the accumulated rainfall depth map (see Figure 39a) with the aim to assess both the timing and the spatial distribution of the alerts issued by ERDS.

Despite the slight underestimation, the WRF model was able to properly forecast the spatial distribution of the rainfall pattern (see Figure 39c). The provision of forecasts and related heavy rainfall alerts with such a level of detail was not possible in the previous version of ERDS due to the low spatial resolution of GFS data (more than 20 km). Moreover, thanks to WRF data, information about the locations that would be affected by the event were available in the early morning, several hours before the event affected these areas.

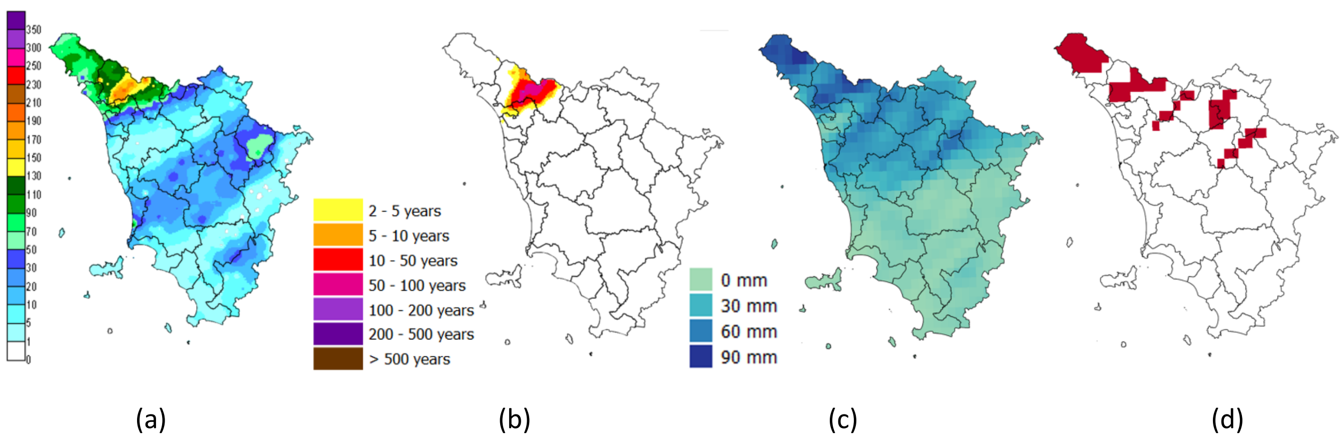

Figure 39 Spatial interpolation of the 24-hour rainfall depths recorded by rain gauges during the 4th June (a) and corresponding return period (b). 24-hour rainfall forecast provided by WRF model during the 4th June(c) and heavy rainfall alerts provided by ERDS using WRF data as input (d).

GPM IMERG Early run data was able to measure correctly the rainfall depths in the eastern part of the region (Figure 40a). An alert was also issued by ERDS over this area after having download the GPM data acquired on the 4th of June at 21:30 UTC (made available with a ~4 hours latency). A severe underestimation is instead present in the North-West part of the Tuscany region, as emerged by comparing Figure 39a with Figure 40a. More specifically, rain gauge data measured around 200 mm of rainfall in some locations (see orange zones of Figure 39a) while GPM data provided 40 to 80 mm in the same areas, not allowing ERDS to issue an alert.

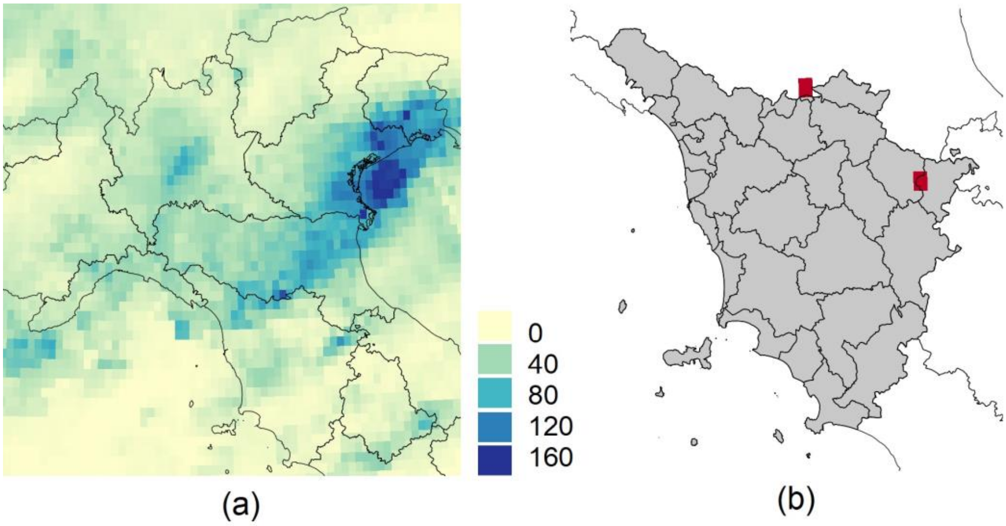

Figure 40 Accumulated rainfall over North of Italy evaluated using GPM IMERG Early run data acquired from 04/06/2021 00:00 UTC and 04/06/2021 23:59 UTC (a) and heavy rainfall alerts issued by ERDS using GPM data as input (b)

Summarizing, WRF data allowed us to reproduce the rainfall pattern with higher accuracy, supporting thus a more timely and precise heavy rainfall identification. Moreover, WRF data allowed to compensate the severe underestimation in the North-West areas of Tuscany region. Measuring very localized events with similar rainfall rates is usually a challenging task for radar or IR-based instruments that are on-board satellites, as those that are involved in the GPM Mission.

5.2.2 Palermo, 15 July 2020

An extreme rainfall event affected Palermo (Sicily Island, Italy) during the afternoon of 15th July 2020: more than 130 mm of rain fell in about 2.5 hours, producing widespread damages due to urban flooding phenomena. The event was not properly forecasted by meteorological models operational at the time of the event, and the Italian Civil Protection did not issue an alert on that area (including Palermo). During that day, only a yellow alert for thunderstorms was issued on northern-central and western Sicily, on a scale from yellow (low) to orange (medium) to red (high). Furthermore, in the afternoon the radar was not measured due to technical problems.

The entire event was initially analysed with ERDS and with the WRF-ERDS workflow. Then, a more complex data assimilation test was also performed.

For this specific case study, GPM data cannot be used due to the ~4 hours latency in data availability. In this case the data latency in longer than the event duration.

No alert was issued using GFS data due to the severe underestimation of the rainfall forecast. Both the 00 UTC and the 12 UTC model runs of the 14th July forecasted about 5 mm of rainfall depth in 48 hours. Similar amounts were provided by the 24- and 48-hour forecasts of the 00 UTC model run of the 15th July.

A WRF modelling experiment (three nested domains with 22.5, 7.5, and 2.5 km grid spacing, innermost over Italy) was executed, by assimilating the National weather radar reflectivity mosaic. Also, in this case, the WRF model produced forecasts affected by an underestimation of the rainfall depths, despite lower entities if compared to GFS data.

The 22.5 km resolution data are not presented here considering the spatial resolution similar to GFS one.

The 7.5 km resolution data, instead, allowed an improvement. More specifically, the 00 UTC model run of the 14th July forecasted in the eastern areas near Palermo about 48 mm of rainfall in the following 48 hours (see Figure 41a), not enough to allow ERDS to issue an alert (see Figure 41b) considering that the 48-hour rainfall threshold of that area is 60 mm. Lower amounts of rainfall were forecasted by the 00 UTC (see Figure 41c) and the 12 UTC model run of the 15th July, not allowing thus to issue an alert (see Figure 41d).

More precise forecasts are those at 2.5 km resolution. The 00 UTC model run of the 14th July forecasted 56 mm of rainfall in the upcoming 48 hours near Palermo, about 10 km far from the city (see Figure 41e). Even if this forecast did not allow an alert to be issued over the city, an alert was issued 30 km far from Palermo, in the South-East direction (see Figure 41f). The 00 UTC model run of the 15th July forecasted a different rainfall pattern, as happened in the 7.5 km resolution case, with 24-hour rainfall depths that reach lower values than those obtained the previous day (see Figure 41g). In this case, an alert was issued about 20 km far from Palermo, while no alerts were issued over the city (see Figure 41h).

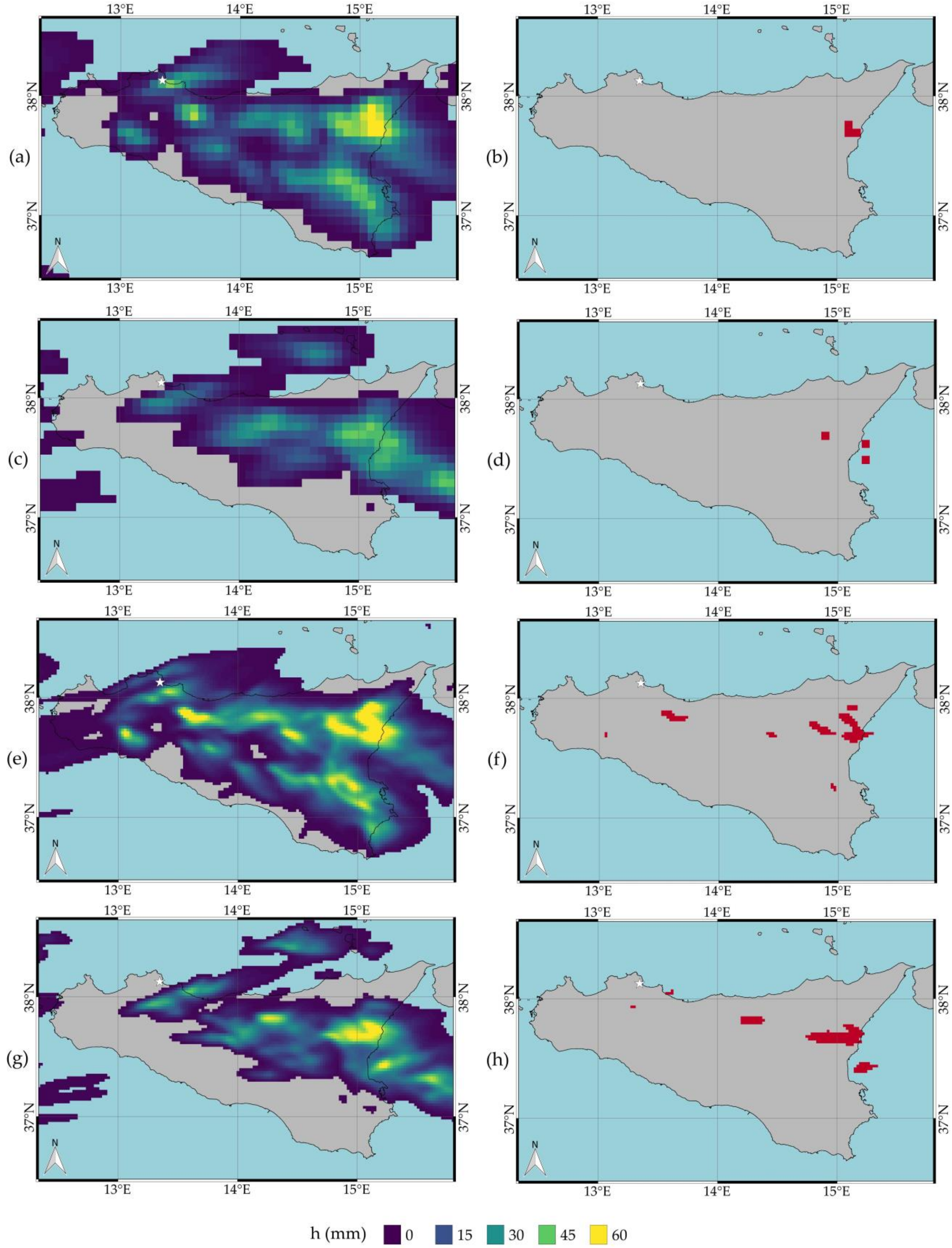

Figure 41 The figure shows: 48h rainfall forecasts (a) and heavy rainfall alerts (b) provided by the 00 UTC model run of the 14th July at 7.5 km resolution; 24h rainfall forecasts (c) and heavy rainfall alerts (d) provided by the 00 UTC model run of the 15th July at 7.5 km resolution; 48h rainfall forecasts (e) and heavy rainfall alerts (f) provided by the 00 UTC model run of the 14th July at 2.5 km resolution; 24h rainfall forecasts (g) and heavy rainfall alerts (h) provided by the 00 UTC model run of the 15th July at 2.5 km resolution. The white star represents the position of the city of Palermo.

Despite the alerts were given about 20/30 km far from the city of Palermo, the result represents a significant step forward. However, as mentioned before, ad additional data assimilation experiment with three nested domains (22.5, 7.5, and 2.5 km resolution) was performed by assimilating into the 15th July 2020 12 UTC model run both weather radar data and a combination of in-situ weather measurement collected over Italy by hygrometers, anemometers, and thermometers managed by the regional hydrometeorological agencies and then collected by the Italian Civil Protection Department.

A first experiment was performed assimilating only weather radar data and hygrometers, a second one involved only weather radar data and anemometers while the last one involved weather radar data, hygrometers, anemometers, and thermometers. The latter option allowed to provide more reliable forecasts: it resulted in the prediction of about 50 mm of accumulated rainfall in 3 hours less than 30 km far from the most affected area. In this case, ERDS issued an alert by thresholding the 24-hour rainfall depth values (see Figure 42a): a cluster of pixels with rainfall depths higher than the pluviometric threshold is visible about 15 to 30 km far from Palermo (see Figure 42b).

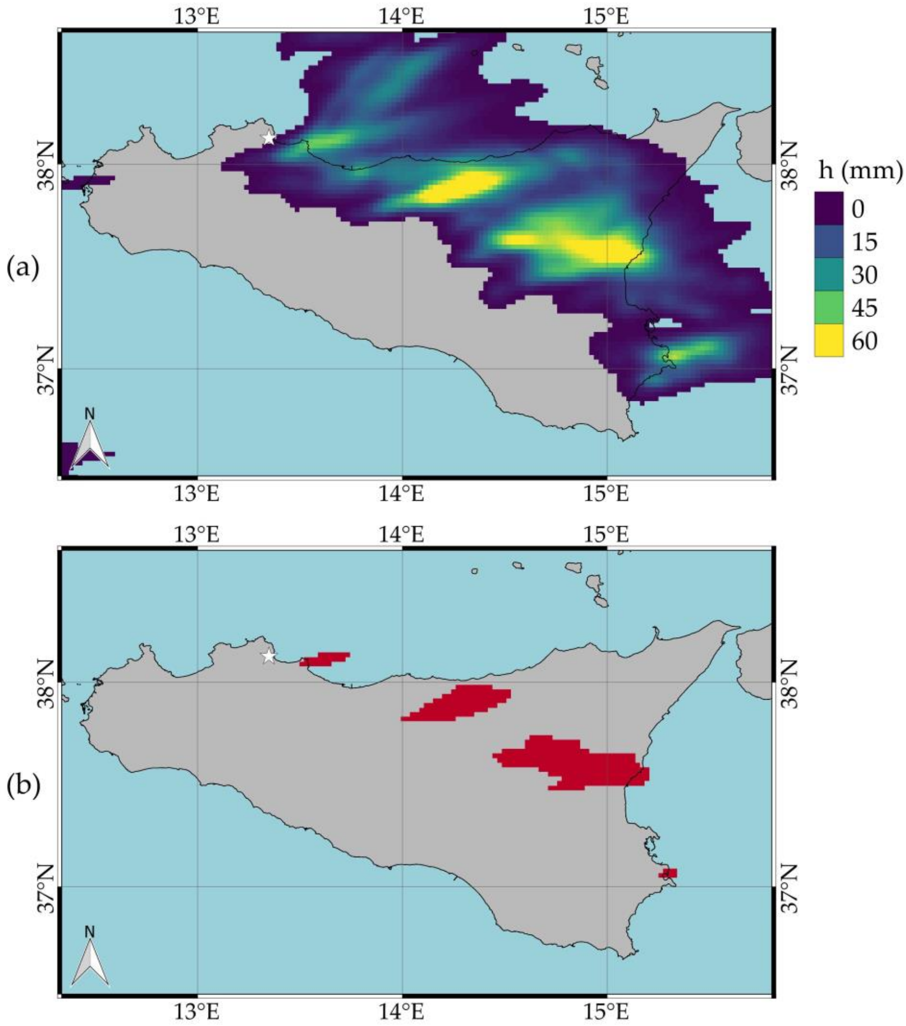

Figure 42 24-hour rainfall depth evaluated using the 2.5 km resolution model run of the 15th July 2020 12 UTC (a) and heavy rainfall alerts issued by ERDS using this data. The white star represents the position of Palermo.

5.2.3 Liguria, 7 September 2020

The meteorological event that affected the region between 6 and 7 September resulted in rainfall with a prevalent convective character, concentrated in particular in the central and eastern part of the region. An intense convective event affected the coastal areas of the Liguria region, between Genova and Portofino, on 7th September 2020. The following rainfall amounts were recorded: 60.8 mm at Genova Pontedecimo, 83 mm at Genova Bolzaneto, 64.4 mm at Genova Quezzi, 60 mm at Genova Fiumara, 83.4 mm at Rapallo, 80.2 mm at Camogli. More information is available in the disaster report drawn up by the local agency for environmental protection[1].

Due to the severe underestimation of GFS data, no alert was issued by ERDS. The 48-hour forecast of the 6 September 2020 00 UTC model run forecasted about 25 mm near Genova, the 48-hour forecast of the 6 September 2020 12 UTC model run forecasted about 15 mm while the 24-hour forecast of the 7 September 2020 00 UTC model run forecasted about 10 mm.

More promising results were obtained with WRF data. Figure 43 shows the 48-hour forecast of the 00 UTC model run of the 6 September 2020. A peak rainfall depth of 72 mm was estimated near the coastline. The 48-hour rainfall threshold for this area is 84 mm thus a heavy rainfall was not provided only due to a slight underestimation.

The analysis of the forecasts produced by this workflow suggests also a possible new modification of the thresholding methodology. The 00:00 UTC model run of the 6th September forecasted 72 mm of rainfall in 48 hours (see Figure 43), not allowing to issue an alert (as mentioned before, the 48-hour threshold for that area is 84 mm). However, the model forecasted very low rainfall amounts (11 mm) in the first 24 hours, from 6th September 00 UTC until 7th September 00 UTC. Thus, most of the rainfall is related to the 7th of September. If analysed in this context, the application of the 24-hour rainfall threshold to a rainfall depth of 61 mm in 24 hours would allow an alert (see Figure 43) to be issued (the 24-hours threshold for that area is 60 mm).

This case study allowed us to detect a possible new improvement in the WRF-ERDS workflow.

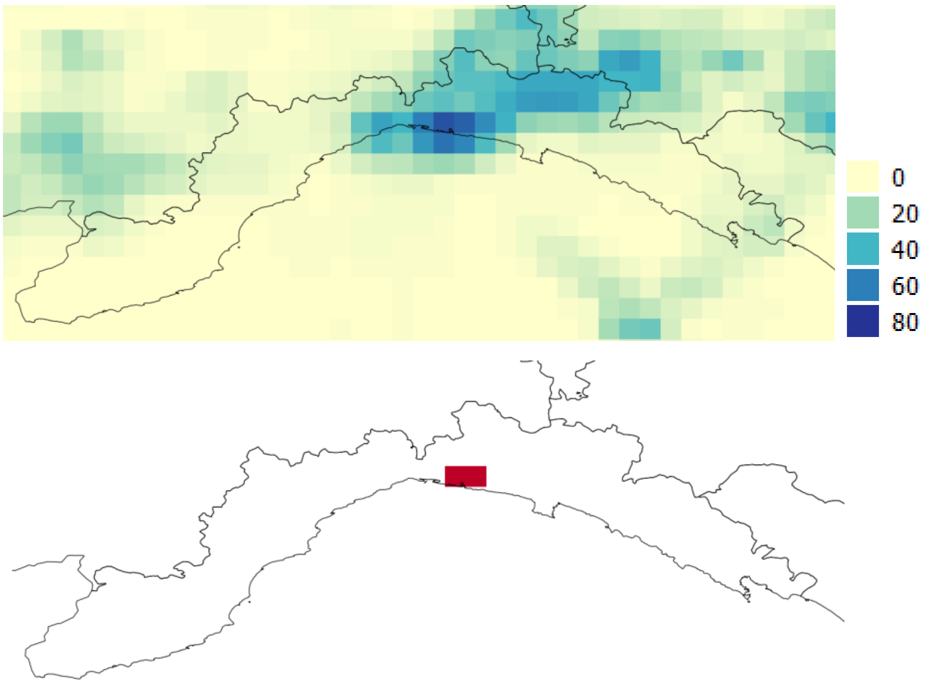

Figure 43 The 48-hour rainfall forecast produced by the 6th September 2020 WRF model (up) and heavy rainfall alerts issued by ERDS (down)

5.2.4 Calabria, 20/23 November 2020

A heavy rainfall event affected Southern Italy, and in particular Calabria region, between 20 and 23 November 2020. Significant rainfall depths (> 200 mm) [11] were recorded by most of the rain gauges located in Crotone and Cosenza provinces (see Figure 44).

[1] Disaster report drawn up by the local agency for environmental protection: https://old.arpal.liguria.it/contenuti_statici//pubblicazioni/rapporti_eventi/2020/REM_20200906-07_Arancione_vers20210527.pdf

Figure 44 Position of the rain gauges that recorded more than 200 mm in Crotone and Cosenza provinces

The outputs of the standard ERDS model were analysed in a first step, and then compared with those of WRF-ERDS workflow.

In Table 13, the time reported in the second column is the acquisition time: in this analysis it should be considered that the GPM data is available with a ~ 4 hours latency, thus the alert publication is shifted in time of about 4/5 hours.

INTERVAL	DATE OF THE FIRST ALERT	LOCATION OF THE FIRST ALERT
12 hours	21/11/2020 04:00 UTC	Over the coastline near Crotone
24 hours	21/11/2020 05:00 UTC	Over the coastline near Crotone
48 hours	21/11/2020 06:00 UTC	Over the sea, between Crotone and Cirò Marina
72 hours	21/11/2020 07:00 UTC	Over the sea, between Crotone and Cirò Marina
96 hours	21/11/2020 07:00 UTC	Over the sea, between Crotone and Cirò Marina

Table 13 Date of the first alerts provided by ERDS using GPM data as input

ERDS was able to provide timely alerts by using GPM data as input in the coastal areas of the Crotone province (between Cariati and Capo Rizzuto) while in the eastern areas of Cosenza province it was not able to provide an alert due to an underestimation of the rainfall rates in the GPM data. During the entire event (20/11/2020 23:00 UTC to 23/11/2020 23:00 UTC) GPM data estimated between 20 and 60 mm of rainfall in that area, while rain gauges measured more than 200 mm in several locations.

The same analysis was carried out using also GFS data. Table 14 contains the dates of the first alerts provided by ERDS using GFS data as input. Also, in this case it should be noted that the output is made available with a ~ 6 hours latency.

INTERVAL	DATE OF THE FIRST ALERT	LOCATION OF THE FIRST ALERT
12 hours	21/11/2020 00:00 UTC	In the northern part of Cosenza province
24 hours	20/11/2020 12:00 UTC	In the northern part of Cosenza province
48 hours	20/11/2020 00:00 UTC	In the northern part of Cosenza province
72 hours	20/11/2020 12:00 UTC	Over the coastline of Cosenza province, between Rossano and Cirò Marina
96 hours	No alert	No alert

Table 14 Date of the first alerts provided by ERDS using GFS data as input

WRF data allowed ERDS to provide more accurate alerts. The first one was provided over the eastern part of Cosenza province in the morning of the 19th of November by thresholding the 48-hour forecast produced by the 19th November 00 UTC model run (see Figure 45a). No alerts were provided over Crotone. Proper alerts were issued the following day, the 20/11/2020 (see Figure 45b-d).

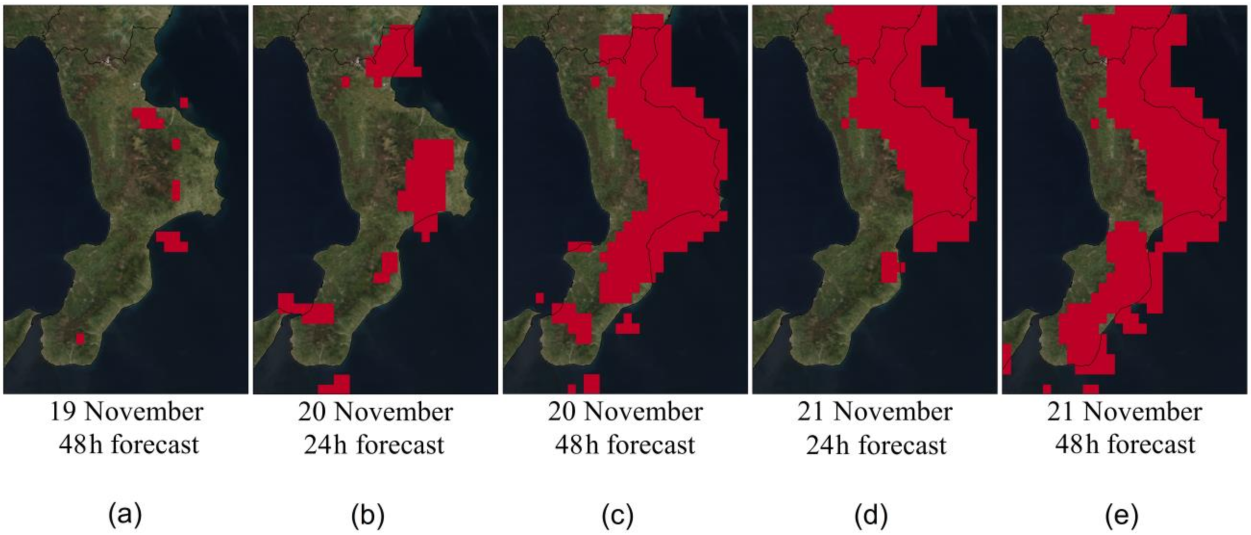

Figure 45 Location of the alerts issued by ERDS using WRF data

5.2.5 Sardinia, 28/29 November 2020

A convective event significantly impacted the southern and eastern areas of Sardinia Island between the 28th and the 29th of November 2020, with a daily rainfall depth of 500.6 mm recorded at Oliena and 328.6 mm recorded at Bitti. During the 28th, the town of Bitti (Nuoro province) was hit by a severe flood event. A description of the damages caused by this event is available on Polaris web page[2] (it also includes some videos registered during the flooding).

Near real-time information provided by GPM data allowed us to issue alerts starting from the late morning of the 28th November (see Figure 46a) [12]. The first alert over Sardinia based on GFS data was provided in the late afternoon of the 27th November, about 40 km far from Bitti (see Figure 46b), while in the early morning of the

[2] Polaris web page: https://polaris.irpi.cnr.it/event/alluvione-di-bitti-nu/

28th November, a new and more precise alert was issued over Bitti (see Figure 46c). The first alert based on WRF data was instead provided in the morning of the 27th November (see Figure 46d-e) and the system continued to issue alerts until the evening of the 29th November, confirming that, for this type of event, precise forecasts are needed to provide timely alerts. By using WRF data, ERDS was able to provide heavy rainfall alerts one day before than with the other data.

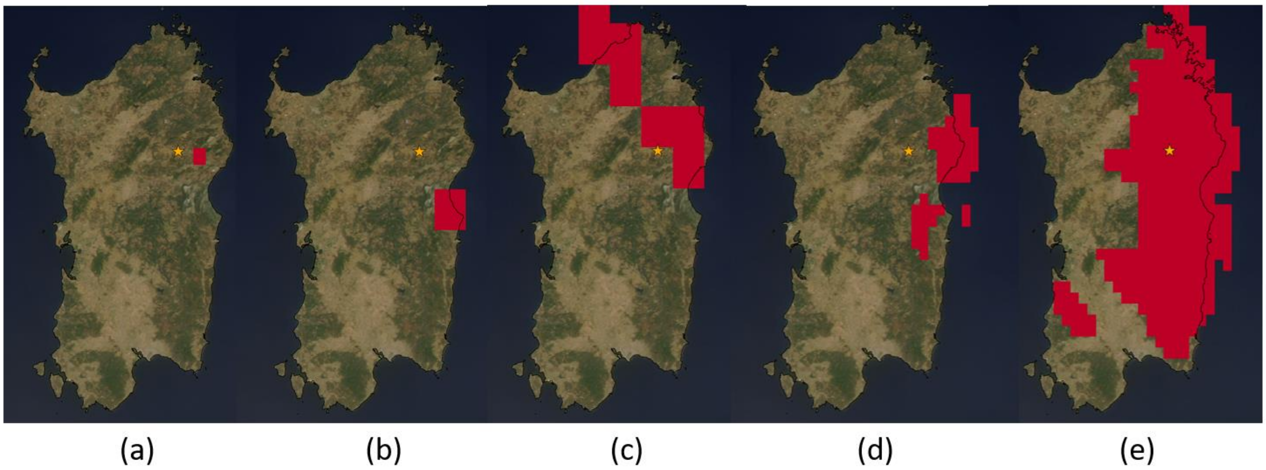

Figure 46 Heavy rainfall alerts issued by ERDS using the 24-hour rainfall depth evaluated using GPM data on 28/11/2020 at 05:00 UTC (a). Heavy rainfall alerts issued using the 24-hour forecast of GFS model data of 27/11/2020 12:00 UTC (b) and using the 12-hour forecast of GFS data of 28/11/2020 00:00 UTC (c). Heavy rainfall data evaluated using the 24-hour (d) and 48-hour (e) forecasts of WRF model data of 27/11/2020 00:00 UTC.

6 DESCRIPTION OF THE CASE STUDIES AND RESULTS FOR WRF-ADMS WORKFLOW

6.1 GENERAL RESULTS FOR THE INDUSTRIAL AND URBAN USE CASES

The industrial and urban air quality uses cases are based together on a specific WRF configuration for France performed by CIMA. The general workflow for these two use cases is presented in Figure 47.

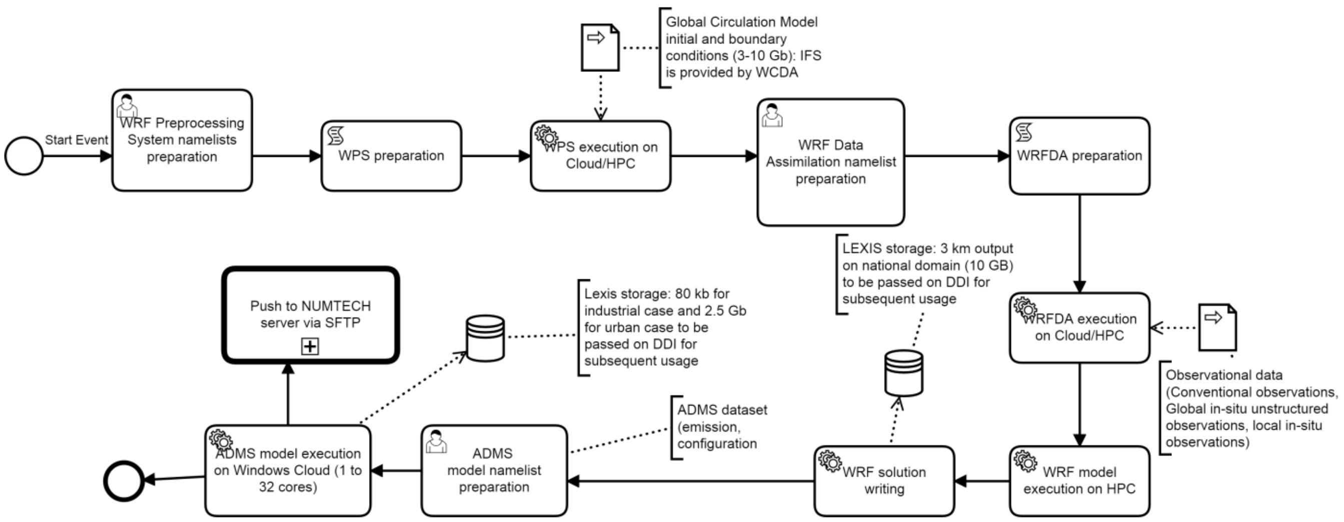

Figure 47 Workflow for ADMS use cases

The interest of this configuration is:

- The use of IFS global forecast from ECMWF,
- The use of the Meteo France precipitation radar observation during the assimilation phase at the start of the forecast,
- The use of the Weather Underground temperature observation during the assimilation phase at the start of the forecast.

The improvement from this configuration will be detailed below in each specific use case, but we can already identify as major results that:

- The LEXIS platform was able to execute "complex" workflow mixing steps which request various infrastructure: simple Linux server for WRF pre-treatment (WPS step) or WRF post-treatment (extraction and conversion of WRF files to ADMS met files), HPC Linux servers for WRF simulation (such as for example using 512 cores) to cloud server using Windows virtual machine image for ADMS execution (from one server with one cloud for an industrial use case to 32 cores cloud server to launch in parallel 32 urban executions to achieve 160 sub-runs for one forecast). This execution is not only transparent for the user, but the LEXIS Dynamic Allocation Module [13] allows to identify at the start of the execution the available resources at the different centres (LRZ and IT4I in this case) to run the workflow according to different specified rules.
- Without the capacity to manage easily so many independent windows cloud runs, NUM will neither test the urban use case as it is done (see specific section).
- The LEXIS platform was able to connect to an external server to exchange data during the execution of a workflow. In our case this concerns Weather Underground data provided via a specific CIMA server and the transfer of the outputs to NUM server.
- The LEXIS platform was able to integrate the WCDA API developed by ECWF to download from a transparent and easy way the IFS forecast for a user. This point is very important to promote the use in the future of the ECMWF data. It is the first time that NUM experiments operational and automatic download from ECMWF.
- The management of the dataset (location, replication or duplication, transfer, uploading, and downloading) among the different data storage associated to LEXIS (LRZ and IT4I in this case) with a common and transparent way for the user. It is also demonstrating the capacity to divide the workflow. In our case, it was demonstrating the capacity to separate the WRF part and the ADMS part to run first the WRF simulation and then execute the ADMS workflow from the dataset generated by the WRF workflow.
- Last weeks allowed testing operational scheduled execution of workflow (compared to manual execution) in order to test the capacity of the LEXIS environment to be used for daily operational forecast.

To these positive results, we must mention that some points need to be further evaluated in the next months before a full commercial exploitation plan for NUM:

- The full execution time is slightly longer than the execution time NUM can observe with its operational chain (same spatial resolution) with its in-house server. But at this stage, with the performed test, it is not so easy to compare since the LEXIS simulation integrates an assimilation part, which is not inside the NUM simulation, different downloading input data (see below), a different WRF version, and the LEXIS execution is based on a capacity to securely switch from different servers / data storage located in Europe which logically adds some treatment time, security process, etc.
- Sometimes download of IFS data via WCDA API is long and is slightly longer than the download of GFS global forecast (US NCEP production) which can limit the exploitation in some operational context. This is due to the fact that WCDA is still a pre-operational service at ECMWF and IFS data are twice the resolution of GFS data. ECMWF is actively working on optimizing WCDA to release it as a fully operational service. Nonetheless, LEXIS demonstrates with the Italian use cases the capacity to download the US GFS forecast.

6.2 URBAN USE CASE

This use case corresponds to the simulation of air quality over the Paris area performed by NUM, especially in 2018 for different applications.

In comparison to official AIRPARIF measurement network, there were shown various kinds of differences with forecasts and the objective with LEXIS was to demonstrate that improving the weather forecast can lead to correct some errors (other factors concern emission forecast which is not so simple to capture at urban scale).

We identify a list of dates in 2018 for which the previous modelling leads either to over- or under-prediction of NO_2 peaks (main pollutant at a local scale and not impacted by long-range transport of pollution).

The first result of LEXIS is a “technical” improvement of Paris’s modelling. Indeed, urban local modelling requires to simulate all emission sources at a local scale with a precise geometry as much as possible. Generally, it is impossible, and the modeller makes a choice between high resolution and reasonable computation time. One of the LEXIS demonstrations for this use case is not only to show if we obtain improvement on outputs but also to demonstrate it is easy (and affordable for exploitation plan) to not limit the urban modelling.

Considering the capacity of the LEXIS cloud server and the LEXIS management service, we have decided to update the modelling of Paris without considering limitations. The result is a great extension of the modelling as shown in Figure 48 (blue compared to red) in terms of:

- Simulated area with a domain which covers now the full metropolitan region of Paris (772 km^2 with 950,000 outputs points at the surface) and not only the “inner centre” of Paris (106 km^2 with 80,000 outputs points at the surface).
- Emission sources since no limitations were introduced on the simulated roads which are now 76,000 compared to 3,500 previously, and the other emission sources (also considering the increase of domain) are 4,000 compared to 800.

The practical consequence is that the urban case requires now to manage 160 sub-runs in regard to 13 previously.

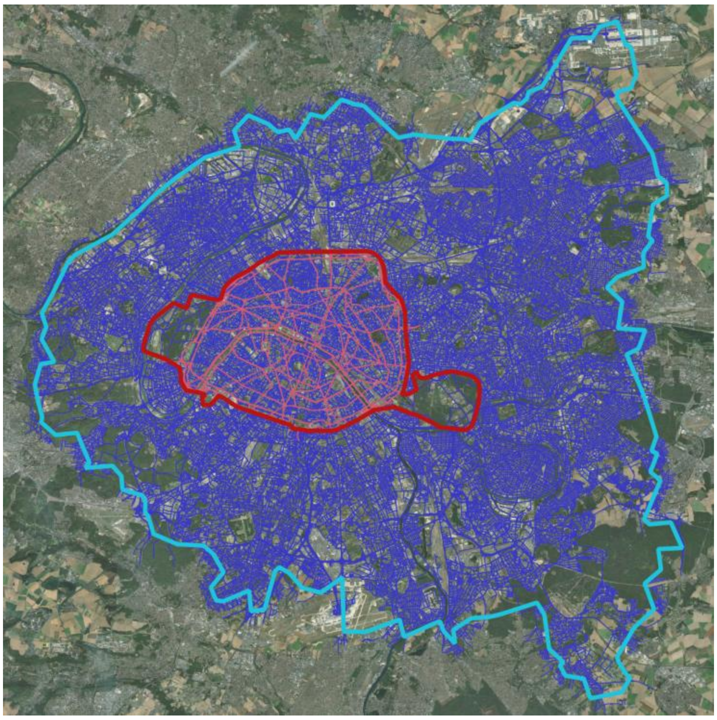

Figure 48 Comparison of previous modelling of Paris (in red) and new modelling with LEXIS (in blue)

Even if the execution time for the ADMS urban part is around 3 hours at this time for 24 hours of the forecast, which can be longer for operational applications, we have demonstrated the capacity to launch such heavy urban simulations from a transparent way for the user. Note that these 3 hours are obtained with a virtual machine of 32 cores, meaning that 5 series of 32 sub-runs are launched sequentially. Using 5 virtual machines of 32 cores in parallel will conduct to an execution time of around 30 minutes which is then very acceptable (for identical cost since the total core-hours used is the same).

We can also note that for the following discussion, the impact of this improvement on comparison must be limited since we are regarding local air pollution at the air-quality station for which the local modelling around was already "good" in the previous modelling. The interest of such new modelling is to better capture the local pollution everywhere in the domain, and one next step is to compare the results obtained with this new modelling to the AIRPARIF station outside the inner part of Paris.

Figure 49 shows one example of NO_2 surface pollution map obtained from the two modelling configurations (for 9 June 2018 at 12 HTU). We clearly see the difference in terms of spatial resolution with much more visible impacts from roads, as well as more pollution spots.

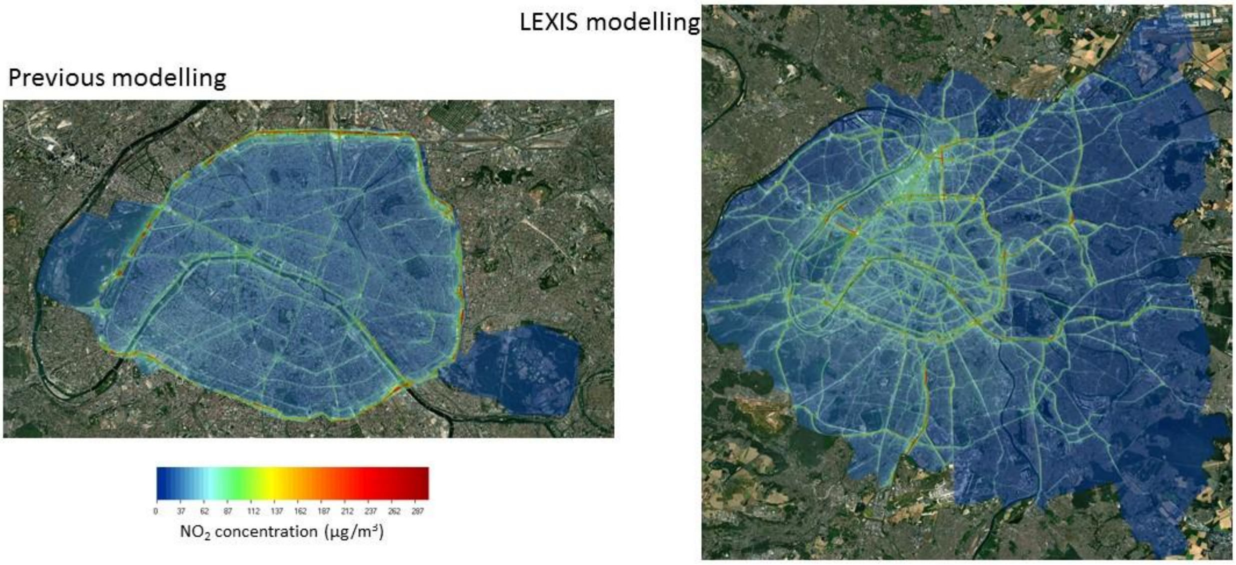

Figure 49 NO_2 concentration simulated for the 09/06/2018 12HTU from NUM modelling (left) and LEXIS modelling (right)

The detailed results of the different simulated dates are given in Appendix B.

Initial analysis shows that it seems that during the first part of summer (June and July), simulations always over-predict concentrations during the day (especially the afternoon), and the LEXIS configuration does not improve this situation. It must remind that this result can be also the consequence of over-predicted forecast emission from sources, so with few impacts from the weather forecast. From the end of July, we observe the opposite with simulations, which generally under-predict observed peaks. In this situation, LEXIS performs generally better than the initial NUM simulation.

We must also mention that one characteristic of the LEXIS modelling is at the start of the day (around 6 to 8 HTU) a tendency to favour higher concentration than observed. These false peaks in the morning impact negatively the daily score which could be better than the NUM modelling is the output will be like NUM for this period. Further analyses are required to understand this effect, especially to investigate the difference in the boundary layer height which can easily impact the concentration at the surface for these hours.

Table 15 resumes the positive or negative impact obtained with the LEXIS simulation compared to the previous NUM simulation.

DATE	LEXIS IMPACT
09/06/2018	-
23/06/2018	-
27/06/2018	--
15/07/2018	+
18/07/2018	similar
19/07/2018	-
26/07/2018	similar
27/07/2018	+
03/08/2018	++
27/09/2018	+
16/09/2018	similar
05/10/2018	+

Table 15 Impact of LEXIS modelling on forecast simulation over Paris (++ means excellent better result for LEXIS simulation, + means better result for LEXIS, - means lower result for LEXIS simulation compared to previous NUM simulation)

The KPI at the start of the project was to achieve **10%** improvement in some air quality statistics (probably more on daily basis than on annual basis). From the table, concerning NO_2 simulation and for the simulated period, we can observe that LEXIS is slightly better than the previous modelling with on more positive date than negative date (so **8%** improvement). Of course, this must be confirmed on a larger period (ideally over one year).

This result is encouraging, especially because no adaptation or strong analysis of the LEXIS WRF simulation to ADMS urban simulations was done probably we can expect better results in the future than in this first demonstration phase.

6.3 INDUSTRIAL USE CASE

For this use case, we choose one industrial site (a TOTAL refinery in France) for which NUM provides operational weather and air-quality forecast from 2005. These forecasts are one element of TOTAL decision tools to manage the production of the refinery according to various constraints, including the environmental ones. Especially, it is requesting to avoid SO_2 peaks around the refinery.

According to the forecasted activities of the refinery (and thus forecasted atmospheric emission), the system estimates for the next days the air-quality impacts of the site in link to weather forecast provided by NUM. If we take away cases of non-controlled emission sources, false peaks and miss SO_2 peaks (by comparison to the air-quality measurement network around the site) are thus mainly related to the bad weather forecast. When a SO_2 peak is simulated, TOTAL activates various actions to reduce its emission (and thus reduce its production or activate some emission treatment), this implies financial cost, which could be several k Euros per day.

Figure 50 shows example of forecast maps of SO_2 for three days/period:

- Morning of 6 August 2018: the simulated peaks (orange colour) at stations "Pasteur" or "Parscau du Plessis" were false peaks are compared to observed values (below to 30 µg/m^3).

- Morning of 24 July 2018: it was observed a peak of 229 µg/m^3 at station "Megretais" (North of the site).
- Morning of 1 September 2018: the simulated peaks were under-estimated with observed values around 170 µg/m^3.

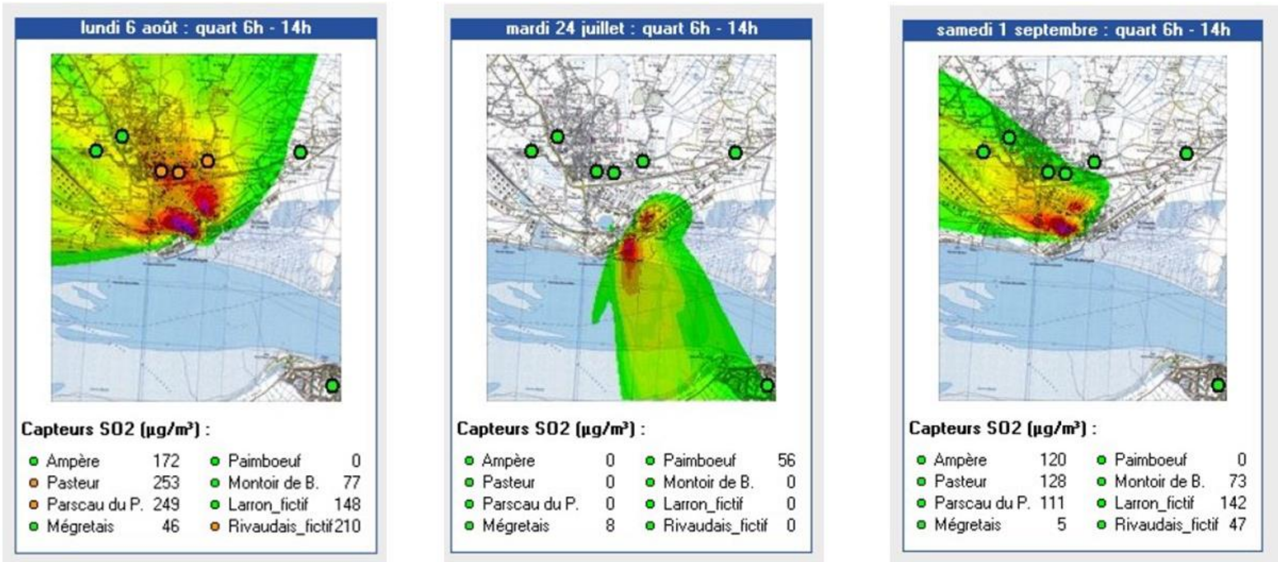

Figure 50 Examples of simulated SO_2 surface maps (circles correspond to location of some measurement stations)

The objective is then to avoid false simulated peaks, to avoid miss simulated peak and to better simulate true peaks.

The result obtained for the selected period (similar period than for the urban case to limit simulation) is given in Appendix C.

We can note that the Megretais station is a very complex situation to simulate. Indeed, the station is far away from the main emission sources of the site, and generally, it is a complex atmospheric dispersion process, which allows emissions from the source to impact the station. It was ambitious to try to see if LEXIS modelling can improve such a situation, whereas it is more than 15 years that such specific conditions are not easily reproduced by WRF at a resolution of 2 km.

We also mention a note that each morning between 8 HTU and 10 HTU, there are strong impacts at a surface simulated by LEXIS modelling, which are not observed. This behaviour is quite like those observed for the urban case, but more important here. Either this is due to the specific WRF configuration, or further analysis of the extraction and conversion of WRF outputs into meteorological parameters for ADMS simulation must be done to understand this specific behaviour. Especially, the industrial site is located on the Atlantic Ocean coast and the difference between coast and earth can be very important at a period where no strong weather phenomena is developed (most of the simulated cases here with low wind conditions, etc.), especially in the morning when the sun begins to warm the earth surface.

Table 16 resumes the results detailed above, excluding the behaviour observed for the period 8 to 10 hours.

DATE	LEXIS IMPACT	DATE	LEXIS IMPACT
24/07/2018	Similar	11/09/2018	Similar
03/08/2018	-	17/09/2018	+
06/08/2018	+	22/09/2018	- / Similar
11/08/2018	+	27/09/2018	+
19/08/2018	+	05/10/2018	+
01/09/2018	Similar	12/10/2018	Similar
08/09/2018	+		

Table 16 Impact of LEXIS modelling on forecast simulation over Industrial site

The expected KPI was a **25% reduction** in the number of forecasted false alerts and missing air pollution peaks over a year for an industrial site. We are not able to simulate a full-year period, but for the simulated dates, we can calculate a global improvement of **5 cases on 13, so 38%** which is quite encouraging, especially if we concentrate on previous over-prediction forecasts which are quite reduced in this demonstration.

7 DESCRIPTION OF THE CASE STUDIES AND RESULTS FOR WRF-LIMAGRAIN WORKFLOW

7.1 MAIN RESULTS

Since it was not possible to simulate a long period due to the limited time at the end of the project, NUM and LIMAGRAIN decided to focus on a use case, which can be evaluated with one month or less of WRF simulations. This use case concerns the forecast of the ideal date to harvest maize used as cattle feed for milk production. This forecast is then evaluated by comparison to the use of real observation data (knowing that in reality such local observation is far to be available at each agricultural parcel, and farmers use a lot of numerical data in consequence).

Such use case relies mainly on the capacity of the weather forecast to correctly simulate the temperature. If the temperature forecast from the middle to the end of the production period is too cold, this can lead decision to start the harvest too much soon compared to reality. The consequence is that the quality of the feed (via the plant dry matter rate) can be reduced and in consequence the milk production from the cattle.

The agricultural workflow (see Figure 51) consists of the execution of WRF forecast over France (using IFS forecast over Europe, Meteo France precipitation radar, and Weather Underground temperature as inputs). WRF outputs are pushed to NUM server. The WRF forecast at different locations in France has been extracted and ingested in a LIMAGRAIN decision tool outside the LEXIS infrastructure.

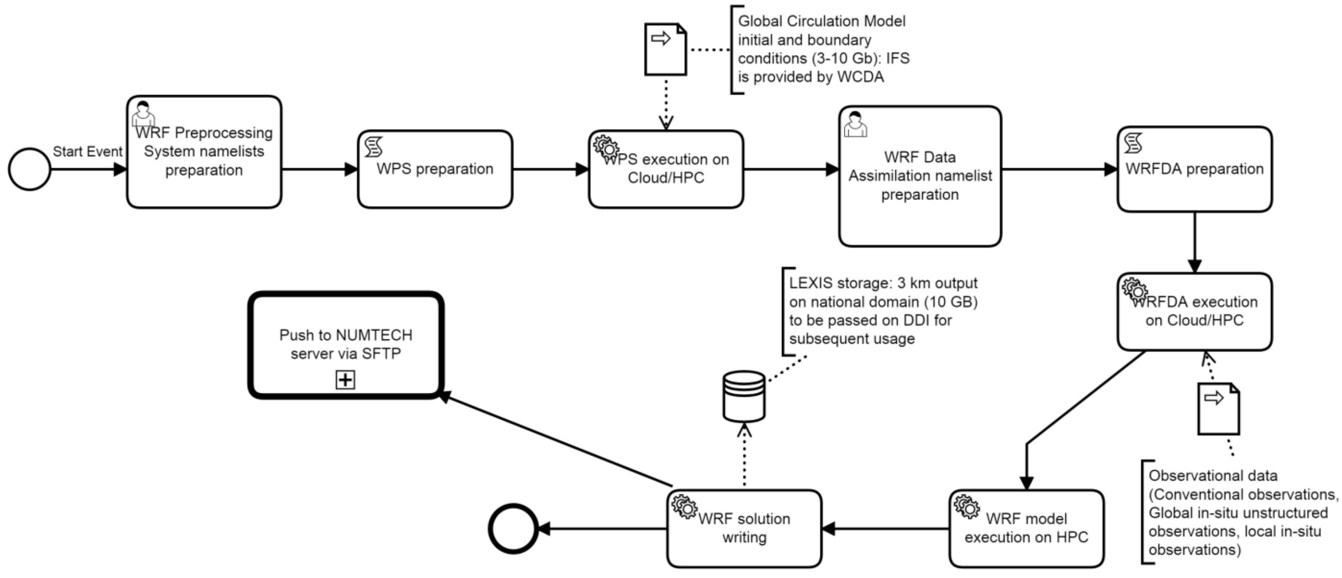

Figure 51 Workflow for Agricultural use case

We focus on 6 French departments (at Northwest and Northeast of France) used for the maize production for animals feeding:

- Ain,
- Creuse,
- Ile et Villaine,
- Maine et Loire,
- Mayenne,
- Meurthe et Moselle.

Ideally, we will need to simulate the full period of the maize production, that is to say 150 days, but this was not possible due to the late availability of the LEXIS environment for WP7 execution. With LIMAGRAIN, we decided to focus from the 1st to 15th August 2018 because: (i) August is a central period for maize production, and (ii) high temperatures were observed in some of France's regions during this period, with a strong underestimation of the NUM forecast used by LIMAGRAIN in 2018.

For each department, Table 17 compares results obtained from LEXIS and NUM simulations. It is presented the mean difference of the cumulative bias of forecast for daily temperature over the period compared to observation, the result in terms of plant dry matter rate, and the delta on days for recommendation to start the harvest.

DEPARTMENT	LEXIS CUMULATIVE TEMP DIFFERENCE WITH OBS (°C)	NUM CUMULATIVE TEMPS DIFFERENCE WITH OBS (°C)	LEXIS BIAS ON PLANT DRY MATTER RATE INDEX	NUM BIAS ON PLANT DRY MATTER RATE INDEX	LEXIS DELTA ON HARVEST (DAYS)	NUM DELTA ON HARVEST (DAYS)
Ain	-4.99	-35.43	-0.22	-1.54	-0.43	-3.08
Maine et Loire	1.10	-24.26	0.05	-1.05	0.10	-2.11
Ile et Villaine	4.69	-7.44	0.20	-0.32	0.40	-0.64
Creuse	11.09	-19.65	0.48	-0.85	0.96	-1.71
Mayenne	-3.97	-18.59	-0.17	-0.81	-0.35	-1.62
Meurthe et Moselle	0.09	0.00	0.01	-35.58	-1.55	-3.09

Table 17 Comparison between LEXIS and NUM forecast for agricultural use case

For the simulated period, we observed that NUM forecast under-estimated the cumulative temperature between 20 to 35°C (except Ile et Villaine with 7°C) whereas LEXIS forecast is between 0 to 5°C (except Creuse with overestimation of 11 °C). The consequence in terms of plan dry matter rate and thus in the recommendation to start harvest is for NUM forecast a delta of 1 to 3 days, compared to nearly zero for LEXIS (except Creuse with 1 day).

These results are obtained for a simulated period of 15 days, if we extrapolate them to a complete agricultural period of 150 days considering that the results are similar on this period, the recommendation could be of several weeks for NUM forecast (this was confirmed in 2018) compared to few days for LEXIS.

We can note that the initial KPI was an improvement of 10% for yield production for corn. But this KPI cannot be evaluated at this stage because it is required to simulate a much longer period, and probably the improvement can be less since it is based on additional weather parameters (precipitation rate, humidity of the soil, soil temperature, etc.) and not only temperature. At this stage, it is also difficult to determine what is the main factor for this improvement: the spatial resolution? the use of IFS? the assimilation of Meteo France radar? the assimilation of Wunderground station? the configuration of WRF from CIMA? the version of WRF used?

Nevertheless, the observed improvement for the LEXIS forecast (around 80%) is far beyond what we could expect at the start, even focusing only on air temperature.

To go further and plan exploitation, we need (i) to determine which elements are essential in this improvement since some are not free to use from commercial activities (IFS, Meteo France radar, or Wunderground) and (ii) simulate a longer period to analyse the impact on another agricultural decision tools.

8 SUMMARY

Objective "*Increase the timeliness and quality of emergency management services*" has been mainly investigated using the WRF-ERDS workflow. Obtained results show how taking advantage of HPC resources to perform finer weather forecast experiments, it is possible to significantly improve the capabilities of early warning systems as ERDS. The results obtained with the WRF-ERDS workflow highlight that the inclusion of WRF data increased the heavy rainfall detection capabilities in all the case studies, suggesting also possible future improvements. The inclusion of WRF data allowed to have in all the case studies that we analysed:

- More reliable information on the spatial distribution of the rainfall depth, allowing thus to provide more reliable alerts also in the case of complex weather systems,
- More accurate forecasts in terms of accumulated rainfall, allowing to reduce the number of missed alarms,
- More timely alerts (usually 12-48 hours in advance with respect to the other data) thanks to the higher accuracy and to the bi-daily updates.

We then suggest using WRF data over Europe, while GPM and GFS data still remain of fundamental importance in areas not covered by the WRF model.

The main results were presented at several conferences (101st American Meteorological Society Conference, ASITA 2021 Conference, European Meteorological Society Conference) and published in conference proceedings. An article was also written and submitted (review ongoing at the time of the writing of this deliverable).

Summarizing, the KPI n°1 (improve the forecast of the number and location of actual impacted areas) has been successfully achieved. Consequently, being increased identification of the impacted areas, KPI n°2 (decrease the proportion of unusable imagery) and KPI n°3 (decrease time-to-availability of post-event imagery) are automatically satisfied.

Objective "*Quantitative assessment in terms of affected people and economic losses for forest fire and flood natural hazards*" is linked to two different KPIs: (I) reduction of 25% in the false alert rate for forest fire and flood; (II) reduction of 25% in the missed alert rate for forest fire and flood.

For all the WRF-Continuum and WRF-RISICO workflows, the results were satisfactory from a Civil Protection standpoint, both in terms of the capability of detecting flood risk scenarios as well as forest fire risk scenarios. Very interesting and not expected at the beginning of the project, was the possibility of using the LEXIS platform to simulate in near-real time the Apollo Medicane, which caused heavy rainfall and flooding in Tunisia, Algeria, Southern Italy, and Malta, resulting in a death toll of seven people and economical damages peaking up to about €220 million. Still, more experiments would have been necessary to prove more quantitatively this KPI.

Objective "*Sustainable food production and protection of the environment*" is instead related to a KPI of a 10% improvement in the yield production estimation by agronomic model for one crop campaign. The observed KPI for the use of the upgraded weather forecast is far beyond those expected. For the use case which has been tested, the improvement is near 80%. This result must be confirmed on more complex agronomic decision tools, but it is quite encouraging for commercial exploitation.

Objective "*Sustainable activity of industrial sites by limiting emission reduction action and thus economic losses*" has a KPI of a 25% reduction in the number of forecasted false alerts and missing air pollution peaks over a year for an industrial site while Objective "*Enhanced urban air quality of life building on the integration of improved weather data*" has a KPI of a 10% improvement in some air quality statistics (probably more on daily basis than on annual basis) produced by the urban model. Concerning the atmospheric dispersion urban case, the impact of the upgraded weather forecast is less visible as expected compared to the industrial case. One reason is that urban air-quality simulation is more sensible to the quality of the emission forecast, whereas forecast of industrial emission could be much more estimated. But LEXIS service allows using more easily a large number of cloud cores for urban simulation than thus to improve the modelling (extend the simulated domain, extend the sources which are explicitly modelled, etc.). For the two cases (urban and industrial), the expected KPI was reached.

Summarizing, the case studies investigated within WP7 proved that LEXIS Project significantly improved the model's results through the exploitation of geographically distributed HPC infrastructures. For these applications, faster and more accurate forecasts are now available.

REFERENCES

[1] LEXIS Deliverable, *D7.4 Deployment of the First Test-bed Infrastucture Components in HPC/Cloud.*

[2] LEXIS Deliverable, *D7.6 Deployment of Test-bed Infrastructure Components and Adoption of Weather and Climate Data Interchange for Model Layer Interoperability.*

[3] LEXIS Deliverable, *D7.8 Final Deployment of Test-bed Infrastructure Components with Full Interoperable Model Layers.*

[4] N. Roberts and H. Lean, "Scale-selective verification of rainfall accumulations from high-resolution forecasts of convective events," *Monthly Weather Review,* vol. 136, pp. 78-97, 2008.

[5] E. Ebert, "Fuzzy verification of high-resolution gridded forecasts: a review and proposed framework," *Meteorological Applications,* vol. 1, pp. 51-64, 2008.

[6] P. Eckert, "COSMO Priority Project "INTERP"," 2009.

[7] A. Rossa, P. Nurmi and E. Ebert, "Overview of methods for the verification of quantitative precipitation forecasts," *Precipitation: Advances in Measurement,* pp. 419-452, 2008.

[8] A. Davis, B. Brown and R. Bullock, "Object-based verification of precipitation forecasts. Part I: Methodology and application to mesoscale rain areas," *Mon. Wea. Rev.,* vol. 134, pp. 1772-1784, 2006.

[9] P. Mazzoglio, F. Laio, S. Balbo, P. Boccardo and F. Disabato, "Improving an extreme rainfall detection system with GPM IMERG data," *Remote Sensing,* vol. 11, no. 6, p. 677, 2019.

[10] CFR Toscana, "Disaster report 4-5 June 2020.," 2020. [Online]. Available: https://www.cfr.toscana.it/supports/download/eventi/report_evento_04-05_giugno_2020.pdf.

[11] S. Arcuri, F. Fusto, L. Marsico and R. Rotundo, "Evento pluviometrico del 21 – 23 novembre 2020. Rapporto di evento.," 2020. [Online]. Available: https://www.cfd.calabria.it//DatiVari/Pubblicazioni/rapporto%20evento%2021-23%20novembre_2020_finale.pdf.

[12] P. Mazzoglio, P. Pasquali, A. Parodi and A. Parodi, "Improving weather forecasts by means of HPC solutions: the LEXIS approach in the 2020 Bitti flood event," in *EMS Annual Meeting 2021*, online, 2021.

[13] LEXIS Deliverable, *D2.4 Report of LEXIS Technology Deployment - Updated Test-Beds Infrastructure.*

A APPENDIX - BURNT AREAS IN THE CATANIA AND SIRACUSA PROVINCES

FIRE DATE	AREA (ha)	PROVINCE
11 August 2021	29	Agrigento (Sicily)
11 August 2021	45	Caserta (Campania)
11 August 2021	64	Caserta (Campania)
11 August 2021	25	Catania (Sicily)
11 August 2021	486	Catanzaro (Calabria)
11 August 2021	581	Catanzaro (Calabria)
11 August 2021	749	Catanzaro (Calabria)
11 August 2021	83	Enna (Sicily)
11 August 2021	7	Messina (Italy)
11 August 2021	30	Messina (Italy)
11 August 2021	87	Messina (Italy)
11 August 2021	15	Palermo (Sicily)
11 August 2021	165	Palermo (Sicily)
11 August 2021	191	Palermo (Sicily)
11 August 2021	9778	Palermo (Sicily)
12 August 2021	13	Agrigento (Sicily)
12 August 2021	74	Agrigento (Sicily)
12 August 2021	87	Caltanissetta (Sicily)
12 August 2021	432	Caltanissetta (Sicily)
12 August 2021	5	Caserta (Campania)
12 August 2021	49	Caserta (Campania)
12 August 2021	51	Caserta (Campania)
12 August 2021	38	Catania (Sicily)
12 August 2021	6	Catanzaro (Calabria)
12 August 2021	9	Catanzaro (Calabria)
12 August 2021	20	Catanzaro (Calabria)
12 August 2021	89	Catanzaro (Calabria)
12 August 2021	549	Catanzaro (Calabria)
12 August 2021	138	Catanzaro (Calabria)
12 August 2021	750	Enna (Sicily)

12 August 2021	7	Messina (Italy)
12 August 2021	32	Messina (Italy)
12 August 2021	78	Messina (Italy)
12 August 2021	85	Messina (Italy)
12 August 2021	111	Messina (Italy)
12 August 2021	345	Messina (Italy)
12 August 2021	1950	Palermo (Sicily)
13 August 2021	41	Agrigento (Sicily)
13 August 2021	3	Caserta (Campania)
13 August 2021	348	Catania (Sicily)
13 August 2021	3	Catanzaro (Calabria)
13 August 2021	5	Catanzaro (Calabria)
13 August 2021	6	Catanzaro (Calabria)
13 August 2021	10	Catanzaro (Calabria)
13 August 2021	11	Catanzaro (Calabria)
13 August 2021	3	Cosenza (Calabria)
13 August 2021	18	Cosenza (Calabria)
13 August 2021	74	Cosenza (Calabria)
13 August 2021	129	Cosenza (Calabria)
13 August 2021	227	Cosenza (Calabria)
13 August 2021	256	Enna (Sicily)
13 August 2021	12	Palermo (Sicily)
13 August 2021	14	Palermo (Sicily)
14 August 2021	143	Agrigento (Sicily)
14 August 2021	5	Caserta (Campania)
14 August 2021	142	Caserta (Campania)
14 August 2021	3	Catanzaro (Calabria)
14 August 2021	9	Cosenza (Calabria)
14 August 2021	10	Cosenza (Calabria)
14 August 2021	30	Cosenza (Calabria)
14 August 2021	33	Cosenza (Calabria)
14 August 2021	54	Cosenza (Calabria)

14 August 2021	54	Cosenza (Calabria)
14 August 2021	59	Cosenza (Calabria)
14 August 2021	143	Cosenza (Calabria)
14 August 2021	296	Cosenza (Calabria)
14 August 2021	49	Enna (Sicily)
14 August 2021	3	Messina (Sicily)
14 August 2021	7	Messina (Sicily)
14 August 2021	37	Messina (Sicily)
14 August 2021	38	Messina (Sicily)
14 August 2021	39	Messina (Sicily)
14 August 2021	661	Messina (Sicily)
14 August 2021	76	Palermo (Sicily)
15 August 2021	14	Caserta (Campania)
15 August 2021	15	Caserta (Campania)
15 August 2021	36	Caserta (Campania)
15 August 2021	134	Caserta (Campania)
15 August 2021	607	Caserta (Campania)
15 August 2021	2	Catanzaro (Calabria)
15 August 2021	20	Catanzaro (Calabria)
15 August 2021	29	Catanzaro (Calabria)
15 August 2021	29	Catanzaro (Calabria)
15 August 2021	45	Catanzaro (Calabria)
15 August 2021	5	Cosenza (Calabria)
15 August 2021	20	Cosenza (Calabria)
15 August 2021	22	Cosenza (Calabria)
15 August 2021	33	Cosenza (Calabria)
15 August 2021	24	Enna (Sicily)
15 August 2021	113	Enna (Sicily)
15 August 2021	247	Enna (Sicily)
15 August 2021	13	Messina (Sicily)
15 August 2021	187	Messina (Sicily)
15 August 2021	41	Palermo (Italy)

15 August 2021	4	Reggio Calabria (Calabria)
15 August 2021	59	Reggio Calabria (Calabria)
15 August 2021	4	Vibo Valentia (Calabria)
15 August 2021	5	Vibo Valentia (Calabria)
15 August 2021	9	Vibo Valentia (Calabria)
15 August 2021	12	Vibo Valentia (Calabria)
15 August 2021	14	Vibo Valentia (Calabria)
15 August 2021	41	Vibo Valentia (Calabria)

Table 18 Burnt areas in the Catania and Siracusa provinces during the period 11-15 August 2021 (source EFFIS)

B APPENDIX – DETAILED RESULTS FOR ADMS URBAN CASE

Some detailed results for ADMS urban case:

- 09/06/2018 - False forecast NO_2 pollution peaks initially:
  - NUM forecast: mean daily over-estimation of 24 µg/m^3, with similar behaviour over all the stations.
  - LEXIS forecast: mean daily over-estimation of 33 µg/m^3, with similar behaviour over all the stations.
- 23/06/2018 - False forecast NO_2 pollution peaks initially:
  - NUM forecast: mean daily over-estimation of 22 µg/m^3, with similar behaviour over all the stations.
  - LEXIS forecast: mean daily over-estimation of 36 µg/m^3, with similar behaviour over all the stations.
- 27/06/2018 False forecast NO_2 pollution peaks initially:
  - NUM forecast: mean daily over-estimation of 13 µg/m^3, with similar behaviour over all the stations.
  - LEXIS forecast: mean daily over-estimation of 36 µg/m^3, with similar behaviour over all the stations.
- 15/07/2018 - False forecast NO_2 pollution peaks initially:
  - NUM forecast: mean daily over-estimation of 40 µg/m^3, with similar behaviour over all the stations.
  - LEXIS forecast: mean daily over-estimation of 35 µg/m^3, with similar behaviour over all the stations.
- 18/07/2018 - False forecast NO_2 pollution peaks initially:
  - NUM forecast: mean daily over-estimation of 31 µg/m^3, with similar behaviour over all the stations.
  - LEXIS forecast: mean daily over-estimation of 32 µg/m^3, with similar behaviour over all the stations.
- 19/07/2018 - False forecast NO_2 pollution peaks initially:
  - NUM forecast: mean daily over-estimation of 6 µg/m^3, with similar behaviour over all the stations.
  - LEXIS forecast: mean daily over-estimation of 12 µg/m^3, with similar behaviour over all the stations.
- 26/07/2018 - Miss NO_2 pollution peaks initially:
  - NUM forecast: mean daily over-estimation of 32 µg/m^3.
  - LEXIS forecast: mean daily over-estimation of 45 µg/m^3. But the result depends to the stations, with 1 station on 6 for which LEXIS is worse, 4 stations with similar results than NUM, and one station with a strong improvement (under-estimation of 12 µg/m^3 compared to zero).
- 27/07/2018 - Miss NO_2 pollution peaks initially and false forecast NO_2 pollution peaks:
  - NUM forecast: mean daily over-estimation of 4 µg/m^3, with similar behaviour over all the stations.
  - LEXIS forecast: mean daily over-estimation of 1 µg/m^3, with similar behaviour over all the stations. If we focus on the real observed peaks in the morning, the results are similar. But if we focus on the false peaks period in the afternoon, the improvement is an over-estimation of only 36 µg/m^3 compared to 50 µg/m^3.
- 03/08/2018 - False forecast NO_2 pollution peaks initially:
  - NUM forecast: mean daily over-estimation of 22 µg/m^3, and over-estimation of 57 µg/m^3 during peak period.
  - LEXIS forecast: mean daily over-estimation of 26 µg/m^3, and over-estimation of 36 µg/m3 during peak period. Specially for the station “Paris 15eme”, NUM peak of 166 µg/m^3 drops to 59 µg/m^3 with LEXIS compared to a measured value of 21 µg/m^3.
- 16/09/2018 – over and underestimation of NO_2 concentrations depending to the hours:
  - NUM forecast: mean daily over-estimation of 8 µg/m^3, with similar behaviour over all the stations.
  - LEXIS forecast: mean daily over-estimation of 8 µg/m^3, with similar behaviour over all the stations.
- 27/09/2018 - Miss NO_2 pollution peaks initially:
  - NUM forecast: mean daily under-estimation of 25 µg/m^3, with similar behaviour over all the stations.
  - LEXIS forecast: mean daily under-estimation of 11 µg/m^3, with similar behaviour over all the stations.
- 05/10/2018 - Miss NO_2 pollution peaks initially:
  - NUM forecast: mean daily under-estimation of 12 µg/m^3, with similar behaviour over all the stations.
  - LEXIS forecast: mean daily under-estimation of 6 µg/m^3, with similar behaviour over all the stations.

C APPENDIX – DETAILED RESULTS FOR ADMS INDUSTRIAL USE CASE

Some detailed results for ADMS industrial use case:

- 24/07/2018: Observation shows peak at Megretais, not simulated by NUM but also not simulated by LEXIS. Results are then similar between the two forecasts.
- 03/08/2018: Peak is observed at Pasteur station (118 µg/m^3). NUM simulated only 40 µg/m^3 at maximum, but LEXIS less.
- 06/08/2018: Measurement shows value near zero µg/m^3 at Ampere, Pasteur and Parscau du Plessis, whereas NUM forecasts are respectively 172, 253 and 249. LEXIS forecasts are close to observation, so correspond to a great improvement.
- 11/08/2018: Measurement shows value near zero µg/m^3 at Ampere, Pasteur and Parscau du Plessis, whereas NUM forecasts are respectively 117, 179 and 215. LEXIS forecasts are close to observation, so correspond to a great improvement.
- 19/08/2018: LEXIS forecast at Megretais is around 49 µg/m^3 compared to 20 µg/m^3 for NUM forecast, which is better but under-estimates the 159 µg/m^3 which is measured.
- 01/09/2018: Measurement corresponds to two peaks at Pasteur, one around 13HTU with 170 µg/m^3 and one around 18HTU with 180 µg/m^3. NUM forecast simulates the first peak with a value of 109 µg/m^3, and not the second peak, whereas LEXIS forecast misses the two peaks.
- 08/09/2018: Measurement shows value near zero µg/m^3 at Ampere, Pasteur and Parscau du Plessis, whereas NUM forecasts are respectively 127, 189 and 193. LEXIS forecasts are close to observation, so correspond to a great improvement, if we exclude the period near 8 HTU.
- 11/09/2018: No high values are measured, except 35 µg/m^3 at Megretais where NUM forecast simulates 105 µg/m^3 and LEXIS 90 µg/m^3. So, these are quite similar results.
- 17/09/2018: Measurement shows value near zero µg/m^3 at Ampere, Pasteur and Parscau du Plessis, whereas NUM forecasts are respectively 173, 206 and 227. LEXIS forecasts are close to observation, so correspond to a great improvement, if we exclude the period near 8 HTU.
- 22/09/2018: Measurement shows value around 70 µg/m^3 at Parscau du Plessis and 165 µg/m^3 at Megretais (different time). NUM forecast over-predicts the peak at Parscau du Plessis but LEXIS totally misses the peak. NUM forecast over-predict the value at Ampere and Pasteur, whereas LEXIS forecast is good. At Megretais, LEXIS and NUM forecasts are similar and under-predict the measurement by twice.
- 27/09/2018: It is yet a day with overestimation of NUM forecast for Ampere, Pasteur and Parscau du Plessis; and a better simulation of LEXIS.
- 05/10/2018: Same situation, with the problem of over-estimation of LEXIS around 8 HTU.
- 12/10/2018: Situation is complex with two observed peaks at Parscau du Plessis with one more predicted by NUM modelling and one by LEXIS. For Pasteur and Ampere, simulations are similar.