# Verification of weather forecasts by comparing limited area models with observations and recorded data: some case studies

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## Abstract

Two case studies have been analysed in order to verify mesoscale weather forecasts. Limited area models' operation has been compared to observations, as recorded by weather stations and shown by radars and satellites. Two events have been selected, both of them happened in the Italian territory during the 2020 autumn season. First, a warm conveyor belt approaching the central Mediterranean Sea, with very intense precipitation affecting especially northwestern Italy; this event, which occurred on 2nd and 3rd October 2020, is also known as the 2020 Piedmont flood. Then, severe and very localized quasi-stationary thunderstorms, developed in mid Tyrrhenian Sea and affecting the coasts of southern Latium on 14th November 2020. Forecast charts of expected precipitation and atmospheric parameters have been compared to recorded and observed data, showing some inaccuracy in models' outputs. Above all, underestimates of rainfall have locally emerged. For the second case study, a failure in forecasting thunderstorms has been observed.

Reference: g.iannuzzi90@gmail.com
Keywords: Weather forecasts; Limited Area Models; Mesoscale; MOLOCH; BOLAM; Warm conveyor belt; Quasi-stationary thunderstorms; 2020 Piedmont flood.

### 1. Introduction

The Mediterranean climate is characterized by a precipitation distribution in which the dry period coincides with the warm season, while the highest amount of yearly rainfall occurs in the cold autumn and winter seasons (Köppen 1936). This is related to changes of the atmospheric circulation and to strong temperature contrasts between cold air masses coming from higher latitudes and the warm sea surface, heated during the hot and sunny summer. Although the Mediterranean region is among those more strongly affected by a reduction of precipitation in climate projections, the interpretation of observed precipitation trends is still uncertain (Cherif et al. 2020, Giorgi and Lionello 2008, Kelley et al. 2012, Lionello et al. 2012, Norrant and Douguédroit 2005). Trends are not uniform in space and depend critically on the selected period and the intensity of the events. Consequently, there is no consensus on their attribution to anthropogenic climate change. In such context, autumn rainfalls affecting the Mediterranean continue to manifest themselves as relatively frequent, intense and potentially dangerous phenomena.

This paper focuses on two severe precipitation events that happened in Italy during the 2020 autumn season and were characterized by different synoptic contexts: event 1, which occurred in Piedmont from 1st to 4th October 2020, and event 2, which occurred on 14th November 2020 in southern Latium. These two case studies have been selected because they are characterized by different spatial scales and dynamics, therefore posing different challenges to forecasters. The first event, known as the 2020 Piedmont flood, has been focused between β and α-mesoscales (ranging from about 20 km to 2000 km), since it was strongly influenced by the synoptic context with some mesoscale contribution, such as the orographic obstacle set by the Alps. Huge amounts of rainfall were recorded by many weather stations and several floods and landslides affected wide areas, especially in the valleys of the Maritime Alps. The second event, which occurred in southern Latium, has been related to the development of quasi-stationary thunderstorms affecting the coast and the inland. Such events are not always easy to forecast and their prediction requires forecasters with good experience in analysing weather charts and with a thorough knowledge of the local geography. Although the amount of precipitation was not comparable to the previous case and no significant damage affected the territory, this event represents an interesting case study with a focus on the γ-mesoscale (ranging from 2 to 20 km).

The two events are presented in separate sections, each one divided into three sub-sections: synoptic context; forecasts and recorded data; discussion. Precipitation forecasts have been compared to observations from weather stations, satellites and radars. A few atmospheric parameters have been analysed, especially at the mesoscale, in order to focus on the meteorological forcing of the precipitation. The discussion section addresses any errors or failed forecasts in the model simulations. Considerations about the performance of the models are proposed in the conclusions.

## 2. Methods

Since this paper is mainly focused on the mesoscale, limited area models (LAMs) have been analysed. In particular, two main models, MOLOCH and BOLAM, both elaborated by CNR-ISAC (National Research Council-Climate and Atmospheric Science Institute), have been taken into consideration. MOLOCH is a non-hydrostatic model, with a grid size of 1.25 km, that produces high spatial detailed forecasts, allowing an explicit representation of convective phenomena (convection can generally be resolved with a resolution of about 1 km or less). The initial and boundary conditions for MOLOCH are provided by BOLAM, a limited-area hydrostatic model with a grid size of 8.3 km, also developed by CNR-ISAC, which integrates the primitive equations, with a parameterization of the atmospheric convection. The initial and boundary conditions for BOLAM are derived from the analyses (at 00:00 UTC) and forecasts of the GFS global model. MOLOCH runs start at 03:00 UTC of each day.
For the case study about the Piedmont flood, some of the images and data shown (ECMWF analysis products and rain gauges from the official measurement network) have been taken from the event report published by the regional environmental protection agency of Piedmont (ARPA Piemonte). For the second event, in addition to data recorded by weather stations of the regional agrometeorological service of Latium (SIARL), some rain gauges from meteorological amateur associations, such as Meteonetwork, have been used. Meteonetwork is a non-profit organization in the field of meteorology and climatology, with a Scientific Council which guarantees a highly scientific content of the products offered.
Radar images were taken from the Civil Protection Department (DPC), that has developed and manages the national radar network, which at present consists of 24 operational radars. This network has been realized through fusing weather radar data in real time (the so-called mosaic process), in order to realize a large-scale meteorological monitoring and to improve the quality of the measurements made by the single radar.
Finally, satellite products were taken from NASA's EOSDIS Worldview (Terra/MODIS satellite) and EUMETSAT's ePort (Meteosat Second Generation satellite), two web portals that allow to select among several satellite products from a big daily archive of images and recorded data.

## 3. Event 1: the 2020 Piedmont flood. Synoptic context

Between 1st and 3rd October 2020, Europe was affected by a deep trough, extending from the English Channel to the Iberian Peninsula. Surface pressure reached its lowest level on 2nd October at 00 UTC over Brittany (Fig. 1a), with a decrease of about 24 hPa in 24 hours, typical values of the so-called explosive cyclogenesis (Sanders and Gyakum 1980, Kouroutzoglou et al. 2011). This synoptic configuration has favored, during 2nd October and the following day, a considerable advection of tropical maritime air masses over southern France and northwestern Italy. This flow was primarily due to three atmospheric modifications that occurred over the European continent: first, a shift of the surface low and of the upper trough towards south; then, the strong jet stream approaching the Alps (fig. 1b); finally, the hot, humid air, initially located over the Iberian Peninsula (fig. 1c), directing towards northeast. As reported by ARPA Piemonte, Limone Piemonte and some other stations were affected by an event with a return period higher than 200 years.

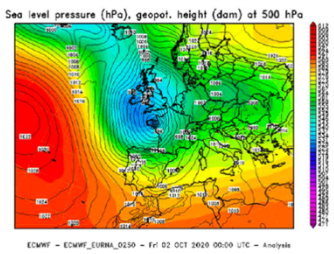


**Fig. 1a** ECMWF analysis: mean sea level pressure and geopotential at 500 hPa, 00 UTC, 02/10/2020 (from ARPA Piemonte)

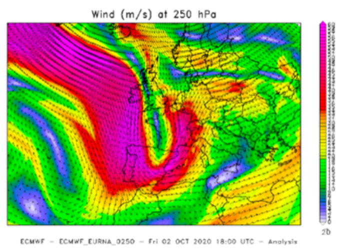


**Fig. 1b** ECMWF analysis: wind (jet stream) at 250 hPa, 18 UTC, 02/10/2020 (from ARPA Piemonte)

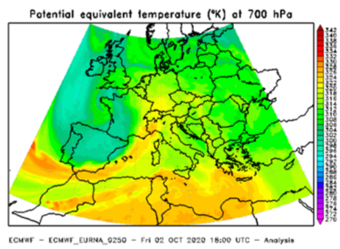


**Fig. 1c** ECMWF analysis: equivalent potential temperature at 700 hPa, 18 UTC, 02/10/2020 (from ARPA Piemonte)

Satellite images suggest the probable development of an atmospheric river, extended from northern Africa to central Europe, which carried huge amount of moist air towards northeast, in contrast with the air mass coming from the high latitudes and directed towards the Iberian Peninsula. Figure 2a shows the differences between the two distinct air masses over Europe. The reddish areas represent the descent of cold and dry air, associated with a strong advection of Potential Vorticity (PV). In particular, the product shows the pressure level, expressed in hPa, at which potential vorticity values equal to 1.5 PVU (Potential Vorticity Units) were reached. Higher pressure values mean a stronger descent of cold, stratospheric air into the troposphere that can enhance cyclogenesis under some circumstances (i.e. with the coexistence of a baroclinic region on lower levels). Greenish areas represent ozone-poor, warm tropical air masses with high upper-level tropospheric humidity (source: Eumetrain).

In figure 2b the MSG Water Vapour channel image clearly shows the moist stream (appearing in white) originated over northern Africa and extended to northwestern Italy, in contrast with the dry air mass (appearing in grey) over the Iberian Peninsula and part of France. High relative humidity at 300 hPa is represented with blue lines and confirms the huge content of water vapour, even at high altitudes, of the warm air mass approaching the Mediterranean. These characteristics, standing for a strong, anomalous ascent into the upper troposphere of tropical air directed poleward, are typical of the atmospheric phenomenon known as Warm Conveyor Belt, generally responsible for dangerous heavy rainfall amounts over Mediterranean (Eckhart et al. 2003; Oertel et al. 2019), especially when associated with deep embedded convection (Flaounas et al. 2018). The small box inside figure 4b shows a zoom image over northwestern Italy, where values of relative humidity at 300 hPa up to 100% and more were reached.

In figure 2c, Mediterranean Sea surface temperature anomalies, as reported by CEAM (Centre d'Estudis Ambientals del Mediterrani) are shown. Values of + 2-3°C were reached in northern Mediterranean Sea and may have contributed in providing further energy and moisture to the storm, as usual in early autumn.

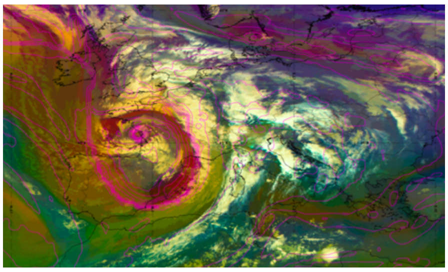

**Fig. 2a** MSG Airmass RGB and Height PV=1.5 (pink lines) at 00 UTC, 03/10/2020 (from Eumetrain ePort).

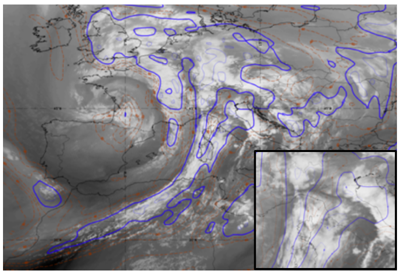

**Fig. 2b** MSG Water Vapour channel (7.3 μm) and relative humidity at 300 hPa at 00 UTC, 03/10/2020. The narrow blue lines stand for 100% relative humidity, the thick blue lines for 80%, the dashed orange for 60% (from Eumetrain ePort)

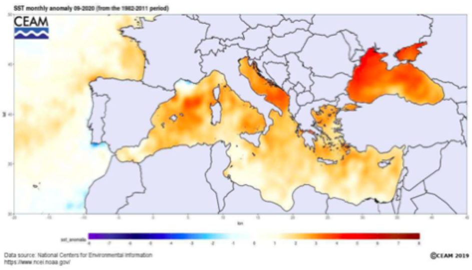

**Fig. 2c** Sea surface temperature monthly anomaly (September 2020) (from CEAM)

### 3.1 Forecasts and recorded data

For the first half of 2nd October (00-12 UTC) MOLOCH forecasted cumulated precipitation (fig. 3a) with high values especially on the Ossola Valley and at the southeastern regional border with Liguria (on the northwesternmost part of the Apennines). In these two areas the model predicted cumulated rainfall exceeding 25 mm in the previous 12 hours, up to 100 mm and more, locally. For other areas of Piedmont, the forecasted values were very small and never exceeding 25 mm.

For the second part of the day (from 12 UTC of 02/10/2020 to 00 UTC of 03/10/2020) the rainfall amount predicted by the model dramatically increased, with cumulated precipitation widely exceeding 150 mm, up to 300 mm locally, particularly on the Maritime Alps and the Ossola Valley, while in the plains the expected values were mainly between 10 and 25 mm approximately (fig. 3b). As for the previous 12 hours, the central area of Piedmont showed the lowest values of expected rainfall. For other lowland areas, such as the Bormida Valley, the low Scrivia Valley and the plain near Alessandria, the values predicted were generally between 25 and 75 mm, with the highest ones that were forecasted close to the border with Liguria, where the average elevation on the ground is higher. Precipitation amounts up to 100 mm were also forecasted on the western border between Piedmont and France, following the Alpine chain (Cottian Alps).

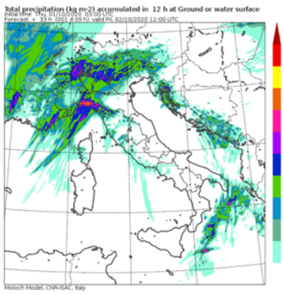

**Fig. 3a** MOLOCH Forecast +33 h: 12 hours cumulated precipitation at 12 UTC, 02/10/2020 (from CNR-ISAC)

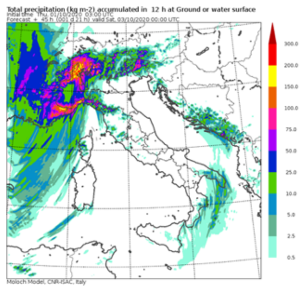

**Fig. 3b** MOLOCH Forecast +45 h: 12 hours cumulated precipitation at 00 UTC, 03/10/2020 (from CNR-ISAC)

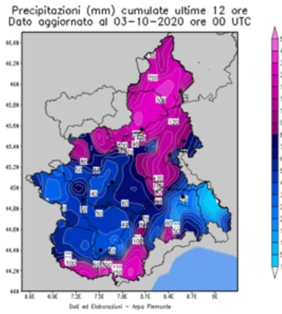


**Fig. 3c** 12 hours cumulated precipitation at 00 UTC, 03/10/2020 (from ARPA Piemonte)

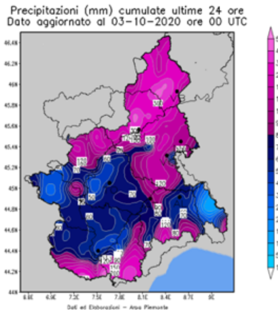


**Fig. 3d** 24 hours cumulated precipitation at 00 UTC, 03/10/2020 (from ARPA Piemonte)

Focusing on convective precipitation only, the BOLAM model (fig. 4a-b) predicted a cumulative convective contribution to the rainfall of about 75-100 mm in 24 hours, mostly starting from the second half of 2nd October (fig. 4b).

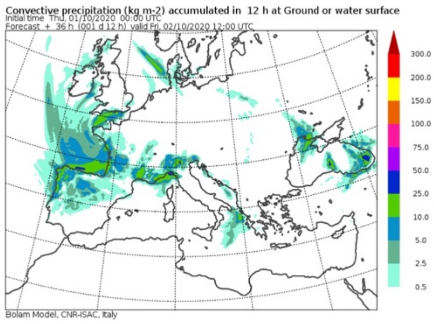


**Fig. 4a** BOLAM Forecast +36 h: convective precipitation cumulated in 12 hours at 12 UTC, 02/10/2020 (from CNR-ISAC)

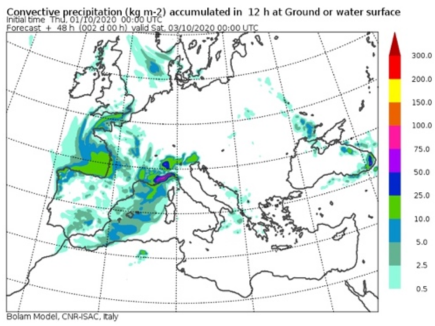


**Fig. 4b** BOLAM Forecast +48 h: convective precipitation cumulated in 12 hours at 12 UTC, 02/10/2020 (from CNR-ISAC)

The following are some daily rainfall data, as of the day of 2nd October, recorded by ARPA Piemonte network and representing the maximum registered values in the provinces affected by the highest amount of precipitation: Limone Piemonte-Pancani (CN, 1875 m a.s.l.), 549.4 mm; Valstrona-Sambughetto (VB, 742 m a.s.l.), 504.4 mm (fig. 5b); Piedicavallo (BI, 1040 m a.s.l.), 470.2 mm; Fobello (VC, 873 m a.s.l.), 349.2 mm. Regarding the wind speed, at 18 UTC of 2rd October MOLOCH forecasted very intense winds at 700 hPa (fig. 5a), with speed widely exceeding 24 m/s, up to 40 m/s (hurricane force in the Beaufort scale). The model saw the westernmost part of Piedmont (Cottian Alps and their foothills) as the least affected by severe upper winds. The analysis map at 700 hPa (fig. 5b) shows that over a large part of Piedmont wind speed was higher than 50 knots (1 knot is approximately equal to 0.5 m/s), tending to confirm what the model had predicted. In the map of forecasted wind at 10 m (fig. 5c), some convergence on central-eastern Piedmont is recognizable, where the easterly winds over the central Po Valley meet the southerly ones coming from the Ligurian Gulf, both with speed ranging from 8 to 14 m/s (highest values mostly predicted on western Lombardy). The registered values (fig. 5d) tend to confirm the ones that were forecasted. Higher wind gusts values were locally observed in the Ossola Valley, where low-level convergence probably reached its peak.

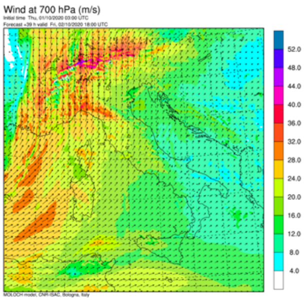


**Fig. 5a** MOLOCH Forecast +39 h: wind (m/s) at 700 hPa, 18 UTC, 02/10/2020 (from CNR-ISAC)

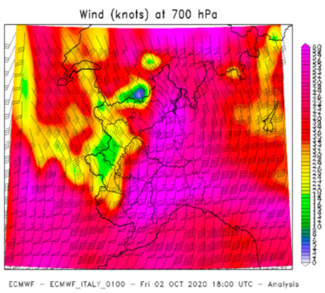


**Fig. 5b** ECMWF analysis: wind (knots) at 700 hPa, 18 UTC, 02/10/2020 (from ARPA Piemonte)

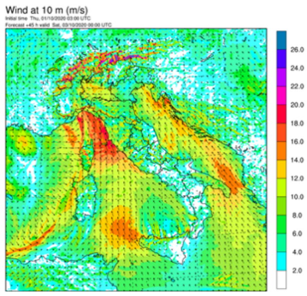


**Fig. 5c** MOLOCH Forecast +45 h: wind (m/s) at 10 m, 00 UTC, 03/10/2020 (from CNR-ISAC)

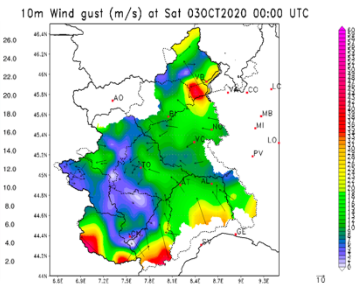


**Fig. 5d** 10 m wind gust (m/s), registered by the Piedmont monitoring network at 00 UTC, 03/10/2020 (from ARPA Piemonte)

### 3.2 Discussion

Rainfall data recorded by the weather stations network, as represented by the spatial distribution of precipitation in figures 3c-d, tend to confirm the quantities forecasted by the model for northern Piedmont. In these area MOLOCH had overall predicted rainfall ranging between a minimum of about 80 mm, in the lowlands of Novara, to a maximum of about 400 mm, in the Ossola Valley. However, here some weather stations recorded rainfall much more intense than expected, exceeding an accumulation of 400 mm in the 24 hours of 2nd October and, in at least one case, even over 500 mm in 24 hours (Sambugheto rain gauge). MOLOCH has been fairly accurate also in simulating the daily precipitation expected on Alessandria plain (from 30 to 100 mm, approximately), where the recorded amounts were quite close to the forecasted ones, with the only exception represented by lower precipitation (less than 20 mm in 24 hours) recorded at the far eastern regional border.
The model proved to be not particularly accurate in forecasting rainfall in central Piedmont, especially between the provinces of Cuneo, Turin, Asti and Vercelli, where the daily recorded values were widely around 70-80 mm. The underestimate in the forecast is quite evident particularly for the plains between Cuneo and Turin, where the model forecasted only about 30 mm in 24 hours, while the estimate for the Susa Valley proved to be quite accurate (about 40-50 mm expected and recorded, too). On the Maritime Alps, instead, MOLOCH had predicted precipitation only up to a maximum of about 200 mm in 24 hours, mainly on the French side of the mountain range (in fig. 3b, the yellow area located just south of the border between Cuneo province and France). Here, several rain gauges recorded cumulated precipitation exceeding 250 mm in 24 hours, up to the record value reached by Limone Piemonte station (549.4 mm). Figures 6 and 7 show some rainfall data regarding the Maritime Alps.

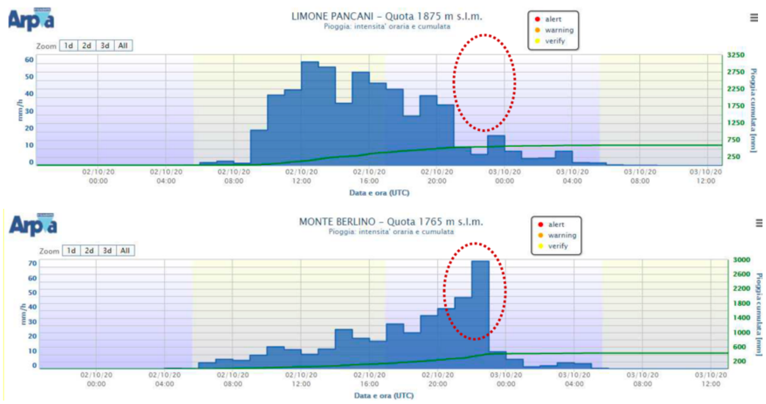


**Fig. 6** Hourly (blue) and total (green) rainfall on 2nd and 3rd October recorded by weather stations of Limone Pancani (above) and Monte Berlino (below) (from ARPA Piemonte). The red dashed circle highlights how the storm shifted eastward during the afternoon of 2nd October (Monte Berlino station is located about 30 km east of Limone Piemonte)

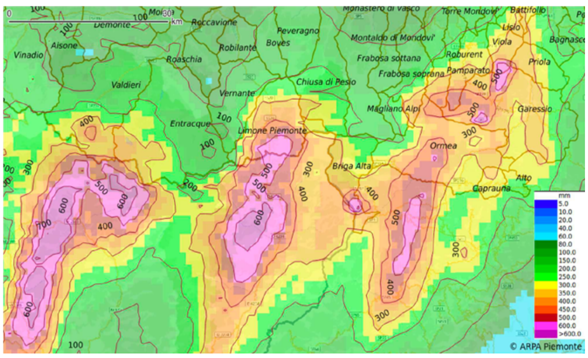


**Fig. 7** Cumulative precipitations estimated by radar from 02/10/2020 to 03/10/2020 on the border between Cuneo province, Liguria and France (from ARPA Piemonte)

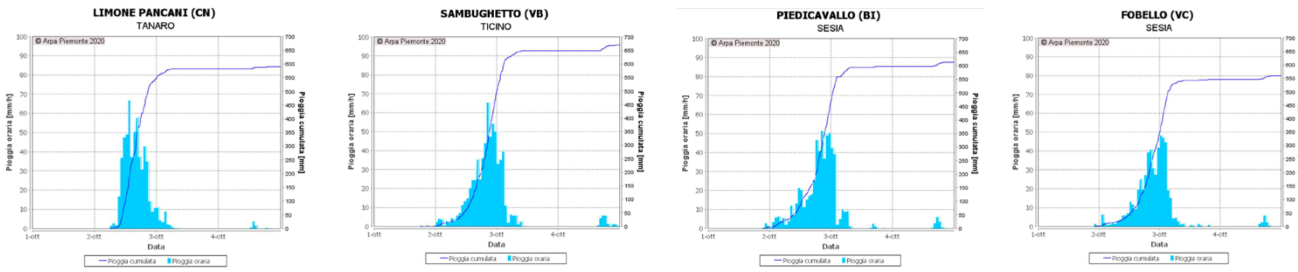


**Fig. 8:** ARPA Piemonte network rain gauges, cumulated and hourly precipitation values for the period $1^{st}$-$4^{th}$ October 2020

As shown in figure 8, which is related to the entire rainfall event (from $1^{st}$ to $4^{tn}$ October 2020), the highest values were recorded in the second half of $2^{nd}$ October, confirming what was foreseen by the model. An exception is represented by Limone Piemonte that, located further south than the other stations, was affected by the arrival of the most intense rainfall before northern Piedmont.

The model correctly evaluated the convective nature of the rainfall that affected the Maritime Alps, as demonstrated by satellite images and lightning maps. Figures 9a-b show two different MSG satellite products. If the MSG HRV Clouds RGB allows to recognize some cumulonimbus (Cb) clouds top (pointed out by the black arrow) approaching the Maritime Alps, the MSG Convection RGB clearly identifies them in yellow, which means severe convection, as the result of a combination of high red (high overshooting of Cb clouds), high green and low blue (both standing for strong updraft and high presence of small ice particles).

The lightning maps in figures 10a-b show the high number of strikes recorded in the area between the France-Italy border, especially in the Italian provinces of Cuneo, Savona and Imperia. Figure 10b, particularly, demonstrates how the storm has slowly moved eastward by the late night of $2^{nd}$ October (the yellowish dots represent the lightnings registered after 20:30 UTC).

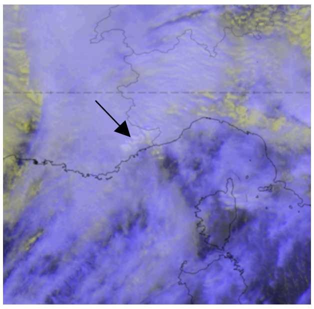

**Fig. 9a** MSG HRV Clouds RGB at 12 UTC, 02/10/2020 (from Eumetrain ePort)

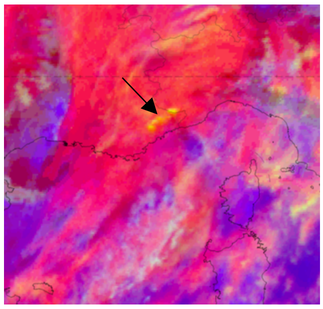

**Fig. 9b** MSG Convection RGB at 12 UTC, 02/10/2020 (from Eumetrain ePort)

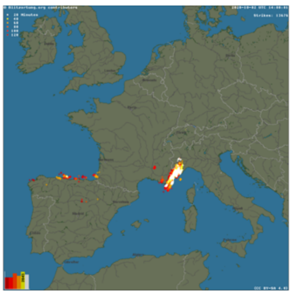

**Fig. 10a** Lightning strikes at 14 UTC, 02/10/2020. The white and yellow stand for strikes detected within the last 40 minutes (from Blitzortung)

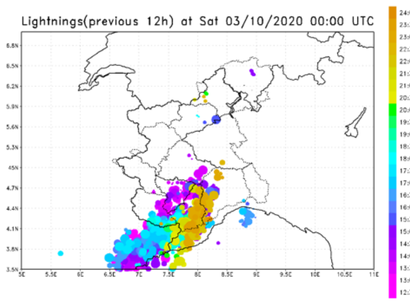


**Fig. 10b** Lightning strikes recorded from 12 UTC, 02/10/2020, to 00 UTC, 03/10/2020 (from ARPA Piemonte)

With some important exceptions, MOLOCH has generally proved to be quite effective in estimating the amount of expected precipitation on Piedmont, in foreseeing the timing and localization of the rainfalls and in predicting atmospheric parameters with high resolution. One example is the correct forecast of the surface low formed downwind of the Maritime Alps on Cuneo province (fig. 11a-b), which probably contributed to the intense precipitation in the Ossola Valley during the afternoon of $2^{nd}$ October and the following night.

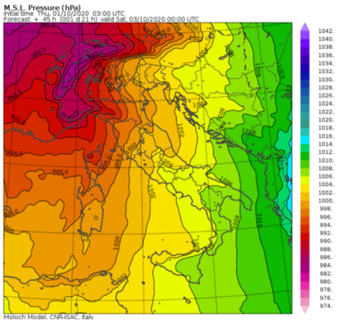


**Fig. 11a** MOLOCH Forecast +45: mean sea level pressure (hPa), 00 UTC, 03/10/2020 (from Eumetrain ePort)

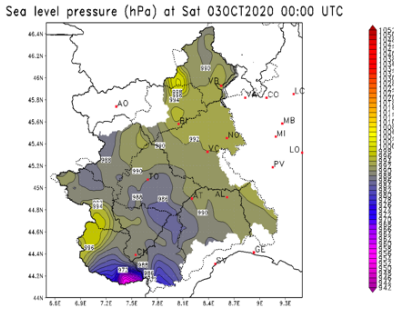


**Fig. 11b** Sea level pressure (hPa), registered by the Piedmont monitoring network at 00 UTC, 03/10/2020 (from ARPA Piemonte)

CAPE (Convective Available Potential Energy) accurate forecast (fig. 12a) probably allowed BOLAM to predict convection over the Ligurian Gulf. In figure 12b a comparison with the forecast by ECMWF is shown.

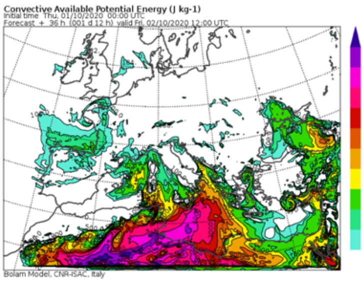


**Fig. 12a** BOLAM Forecast +36 h: CAPE, 12 UTC, 02/10/2020 (from CNR-ISAC)

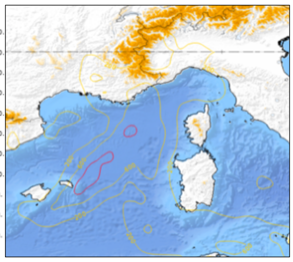

**Fig. 12b** ECMWF Forecast +12: CAPE, 12 UTC, 02/10/2020 (from Eumetrain ePort)


**Fig. 12c** ECMWF Forecast +12: SSI, 12 UTC, 02/10/2020 (from Eumetrain ePort)

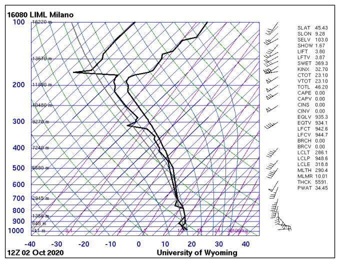


**Fig. 12d** Milano Linate sounding at 12 UTC, 02/10/2020 (from University of Wyoming)

The errors in forecasted precipitation, especially for the Maritime Alps, might be related to an underestimate of convection and of the orographic obstacle set by the Alps to strong, southerly winds. As suggested by satellite images, actual convection may have been stronger than the one predicted by the model. This may have also been favored by the instability of the air masses approaching the Maritime Alps, as suggested by the Showalter Stability Index (SSI), a severe weather index that takes into account differences in temperatures of an air parcel and the environment at different levels. Values of SSI between 0 and 3 suggest chances of thunderstorms, while values between -3 and 0 mean high potential of heavy thunderstorms (source: Eumetrain). In figure 12c, forecasted values of SSI by ECMWF are shown; in figure 12d, the sounding at Milano Linate outlines a relatively stable atmosphere observed over the Po Valley, which may explain the lower thunderstorm activity on the Ossola Valley.
The inaccuracy of the model for central Piedmont may be related to an overestimate of the rainshadow effect on the leeward side of the Maritime Alps. The high elevation of this chain, whose peaks frequently exceed 2500 m a.s.l., generally acts as an effective obstacle to storms approaching from south. In this case, very strong upper wind may have forced precipitations to overcome the mountain ridge and fall over central Piedmont, more than the model was able to predict in terms of rain amount. The high rainfall over Piedmont may also be linked to a general slowness of the front, whose shift eastward has been contrasted by the persistent easterly winds on central Po Valley. This situation may have forced the precipitation to remain over the same area for several hours.

## 4. Event 2: thunderstorms along the coast of southern Latium. Synoptic context

On 14th November 2020 a ridge, extended from the subtropical latitudes with an associated high pressure field at the surface, affected the Mediterranean and the Italian Peninsula. The ridge was only partially lapped, in its northern portion, by a weak trough, which represented the easternmost flap of a deeper trough located west of the British Isles (fig. 13a). Centered on the Balearic Islands, a weak cyclonic circulation around a surface low affected the western Mediterranean Sea, triggering moderate southeasterly winds and a related warm advection on mid Tyrrhenian (fig. 13b). At 850 hPa, the isotherm of 8°C, which in the middle-low Tyrrhenian Sea took on a trend parallel to the coastline, separated milder air on the central-western Mediterranean from cooler air on the Italian Peninsula (fig. 13c).

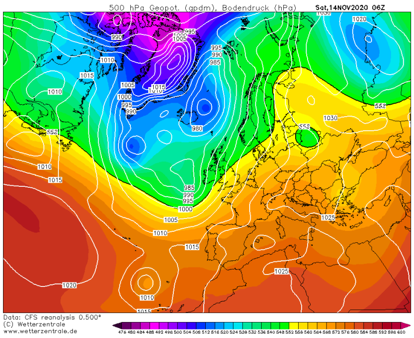


**Fig. 13a** CFS reanalysis: geopotential height (dam) at 500 hPa and ground pressure, 06 UTC, 14/11/2020 (from Wetterzentrale)

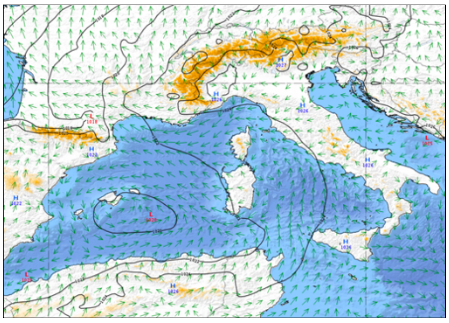

**Fig. 13b** ECMWF Forecast +6: mean sea level pressure and 10 m wind at 06 UTC, 14/11/2020 (from Eumetrain ePort)

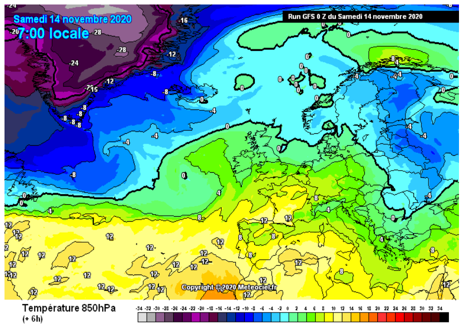


**Fig. 13c** GFS analysis: temperature at 850 hPa, 06 UTC, 14/11/2020 (from Meteociel)

In such context, thunderstorms developed along the coast of southern Latium, which was affected by quasi-stationary systems that produced some damage on the ground (roads flooding, above all).

Quasi-stationary systems are mesoscale systems that tend to remain over the same area, generally between the sea and the coast, where sea-land inhomogeneities, especially in terms of temperature, tend to trigger and maintain them. A relatively warm sea can generally act as a high moisture source to them. These convective systems are composed of different storm cells, in various stages of their life cycle, which move very slowly, mainly as an effect of the contrast in the direction of lower and upper winds. Each of these cells have their own trajectories that carry them repeatedly over the same area, with the effect of producing heavy rain and consequent floods once they reach the land (Chappell 1986; Ferrari et al. 2020).

### 4.1 Forecasts and recorded data

Focusing on Latium only, MOLOCH provided, as shown in figures 14a-b, two different forecasts, depending on the initial run. The most recent one, and thus the closest to the event, did not foresee, at 9 UTC on 14th November, any significant precipitation cumulated within the previous 3 hours. The run of the previous day, for the same time, instead, had shown some sign of precipitation on the area (at most 10 mm expected in 3 hours from 6 UTC to 9 UTC, with local values up to 25 mm, especially just off the coast of Cape Anzio). In the same way, BOLAM, on the run of 00 UTC of 14th November, reported substantially negligible convective precipitation slightly further offshore, while the previous day the forecast had showed some more, but always weak, convection along the mid-Tyrrhenian coasts (fig. 14c-d).

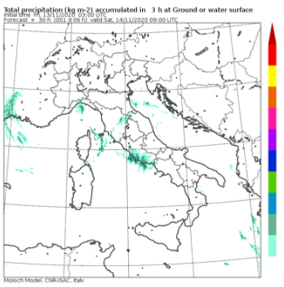

**Fig. 14a** MOLOCH Forecast +30 h: 3 hours cumulated precipitation at 09 UTC, 14/11/2020 (from CNR-ISAC)

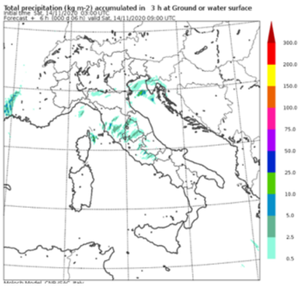

**Fig. 14b** MOLOCH Forecast +6 h: 3 hours cumulated precipitation at 09 UTC, 14/11/2020 (from CNR-ISAC)

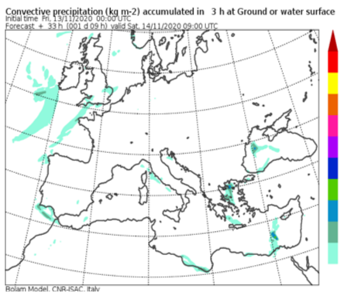


**Fig. 14c** MOLOCH Forecast +33 h: 3 hours cumulated convective precipitation at 09 UTC, 14/11/2020 (from CNR-ISAC)

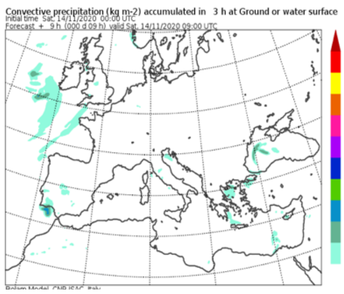


**Fig. 14d** MOLOCH Forecast +9 h: 3 hours cumulated convective precipitation at 09 UTC, 14/11/2020 (from CNR-ISAC)

Radar maps from DPC in figures 15a-d show what happened during the early morning of 14th November, when thunderstorms developed right in front of the coasts of Anzio and Nettuno, standing over that area some hours long with alternate but frequent ingressions into the inland. The system slowly moved southeastward only starting from the early afternoon, affecting the areas south of Latina (especially the municipality of Terracina and surroundings). The yellow and orange color in the radar maps mean high reflectivity values, standing for intense and strong intensity, respectively.

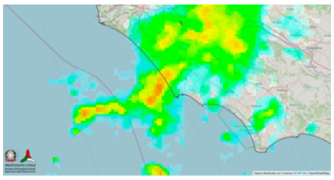

**Fig. 15a** VMI (Vertical Maximum Intensity, in dBZ) at 06 UTC, 14/11/2020 (from Civil Protection Department Radar)

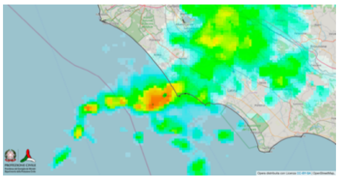

**Fig. 15b** VMI (Vertical Maximum Intensity, in dBZ) at 07 UTC, 14/11/2020 (from Civil Protection Department Radar)

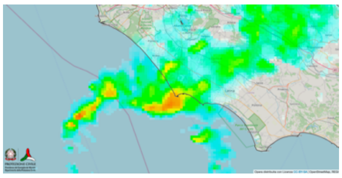

**Fig. 15c** VMI (Vertical Maximum Intensity, in dBZ) at 08 UTC, 14/11/2020 (from Civil Protection Department Radar)

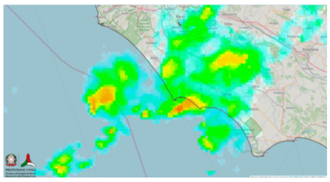

**Fig. 15d** VMI (Vertical Maximum Intensity, in dBZ) at 09 UTC, 14/11/2020 (from Civil Protection Department Radar)

Rainfall amounts recorded by Meteonetwork weather stations (fig. 16a) show average values of cumulative daily precipitation of about 30 mm, with a storm duration of about 6 hours. The highest value has been recorded by the station of Terracina-Borgo Hermada (LT, 50 mm), followed by Velletri-Cinque Archi (RM, 43.40 mm). Some weather stations from the official network of Latium Region (SIARL) registered even higher amounts of precipitation: Sonnino-Frasso (LT), 89.4 mm, Sabaudia-Acquaviva (LT), 82 mm. However, the highest values of rainfall were allegedly recorded by two stations belonging to an amateur meteorological association network, in the municipalities of Nettuno and Anzio, where, respectively, 124.9 mm and 115.5 mm were reached. Such high values may be considered reliable because they are quietly consistent with what is shown by radar maps and with the effects occurred on the ground, as reported by some local newspapers (widespread roads flooding).

Precipitation has been mainly of convective type, as demonstrated by the high number of lightning strikes recorded (fig. 16b) and by satellite products (fig. 16c-d). At 09 UTC of 14th November, the image of MSG Day Microphysics RGB (fig. 16c) shows, over the analysed area, bands of thick clouds (the pinkish color derives from high values of red in the combination of red, green and blue). The image from Terra/MODIS Cloud Optical Thickness (fig. 16d), relative to the morning of the same day, shows a narrow band of clouds with almost 100% content of ice phase, standing for high clouds. Both these characteristics (high values of clouds' thickness and height) represent signs of a probable strong convection over the study area.

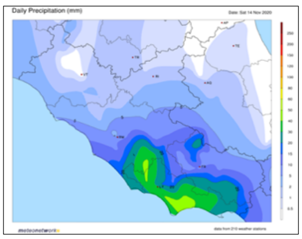

**Fig. 16a** Daily precipitation (mm), 14/11/2020 (from Meteonetwork)

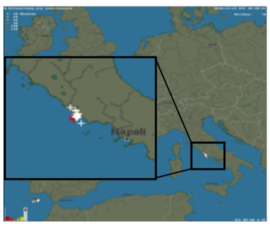

**Fig. 16b** Lightning strikes at 06 UTC, 14/11/2020 (from Blitzortung). In white: strikes detected in the last 20 minutes. On the left, a zoom on the study area

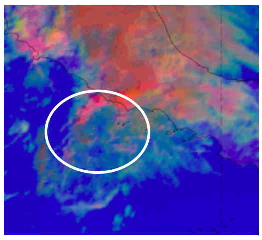

**Fig. 16c** MSG Day Microphysics RGB, 09 UTC, 14/11/2020 (from Eumetrain ePort). The white circle identifies the study area

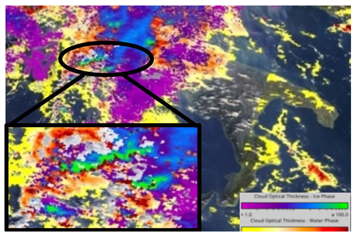

**Fig. 16d** Terra/MODIS Cloud Optical Thickness, 14/11/2020 (from EOSDIS Worldview). On the lower left, a zoom on the study area

The atmospheric parameters forecasted in the two different runs were fundamentally comparable to each other and did not suggest any chance for convection. Some differences appear in the maps of wind at 06 UTC (fig. 17a-d), considered at 10 m and at 850 hPa. At 03 UTC of 14th November, this being the most updated run, the main direction of winds on the ground, at the sea-land interface, seems to suggest less low-level convergence, compared to the previous run (03 UTC of 13th November). In the latter, upper forecasted wind speed at 850 hPa was about 8-10 m/s, lightly stronger than what the next run forecasted (about 3-7 m/s). Figures 18a-b show a comparison with ECMWF forecasts of wind at 10m and 850 hPa, at 06 UTC of 14th November 2020. Their results are basically comparable to the ones by MOLOCH.

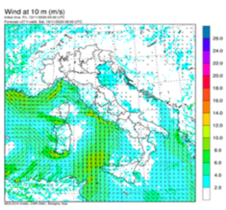

**Fig. 17a** MOLOCH Forecast +27 h: wind at 10 m, 06 UTC, 14/11/2020 (from CNR-ISAC)

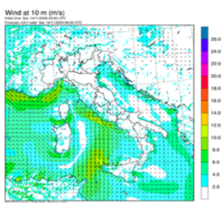

**Fig. 17b** MOLOCH Forecast +3 h: wind at 10 m, 06 UTC, 14/11/2020 (from CNR-ISAC)

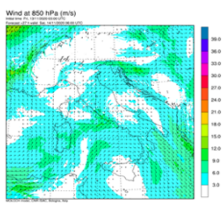

**Fig. 17c** MOLOCH Forecast +27 h: wind at 850 hPa, 06 UTC, 14/11/2020 (from CNR-ISAC)

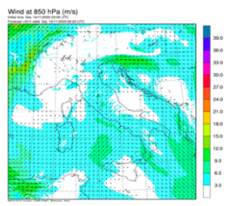

**Fig. 17d** MOLOCH Forecast +3 h: wind at 850 hPa, 06 UTC, 14/11/2020 (from CNR-ISAC)

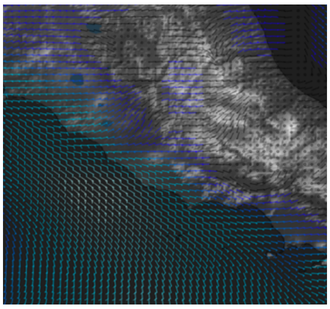

**Fig. 18a** ECMWF Forecast +6: wind barbs at 10 m, 06 UTC, 14/10/2020 (from Eumetrain ePort)

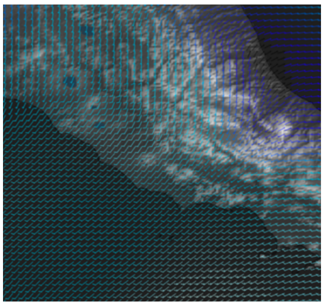

**Fig. 18b** ECMWF Forecast +6: wind barbs at 850 hPa, 06 UTC, 14/10/2020 (from Eumetrain ePort)

Some indication of favorable conditions for convection can be drawn from the evaluation of CAPE and Lifted Index indices. The global model GFS (fig. 19a-b) provided, in the two runs of 13th and 14th November, values of CAPE and Lifted Index comparable to each other. The only differences consisted in the fact that, compared to the run of 13th November, the run of 14th November forecasted some more convective potential energy (higher CAPE values) on a wider area in mid Tyrrhenian Sea (up to 700-800 J/kg), and lower Lifted index values over central Italy (highest value 8 K, instead of 10).
BOLAM, instead, (fig. 19c-d) predicted higher values of CAPE (up to 1000 J/kg) over a wider area of Tyrrhenian Sea for both runs, with a light reduction of the expected values in the run of 14th November. Unfortunately, no Lifted index forecast is provided by this model. In figure 20a CAPE values forecasted by ECMWF are shown for a comparison. Values higher than 500 J/kg up to 1000 were predicted in a very little portion of sea between Sardinia and Sicily; the small pointer in the figure identifies the CAPE value, equal to 50 J/kg, predicted over sea just in front of the coasts of Anzio and Nettuno. In figure 20b, the atmospheric sounding at Pratica di Mare (RM) at 00 UTC of 14th November, representing the observed situation over land, shows a Lifted Index value of 1.07 K and a CAPE value of 47.11 J/kg.

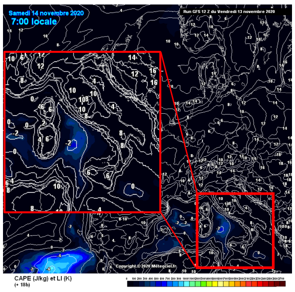

**Fig. 19a** GFS 12Z run, 13/11/2020: CAPE and Lifted Index (from Meteociel)

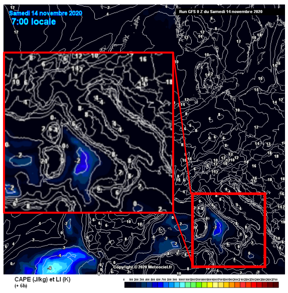

**Fig. 19b** GFS 0Z run, 14/11/2020: CAPE and Lifted Index (from Meteociel)

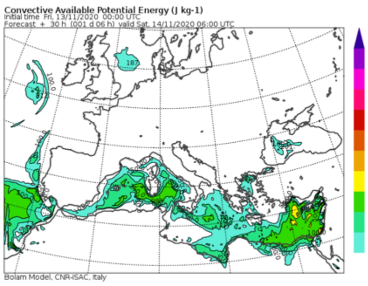

**Fig. 19c** BOLAM Forecast +30 h: CAPE at 06 UTC, 14/11/2020 (from CNR-ISAC)

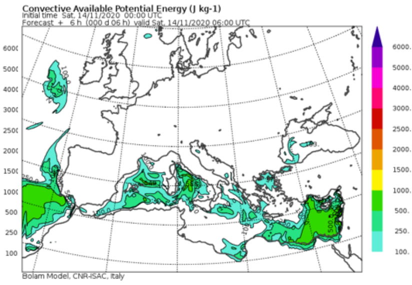

**Fig. 19d** BOLAM Forecast +6 h: CAPE at 06 UTC, 14/11/2020 (from CNR-ISAC)

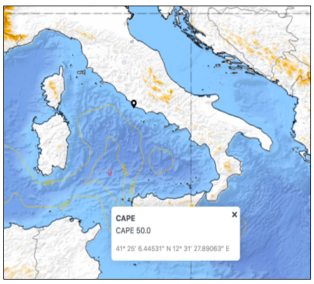

**Fig. 20a** ECMWF Forecast +6: CAPE at 06 UTC, 14/11/2020 (from Eumetrain ePort)

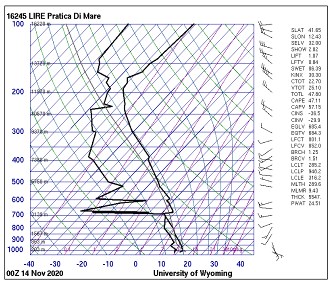

**Fig. 20b** Roma-Pratica di Mare sounding at 00 UTC, 14/11/2020 (from University of Wyoming)

### 4.2 Discussion

Both the examined runs someway missed the forecast, but the most up-to-date one surely failed the most. The run of 13th November predicted some precipitation on central-southern Latium coasts and immediately offshore, but strongly underestimating its intensity. The run of 14th November, instead, proved to be affected by greater errors, consisting in an actual missing in forecasting precipitation. The reasons for such mistakes can be many and not easy to understand. One reason may be related to the so-called "spin up" period, during which the model attempts to stabilize its calculations. Consequently, the initial results may be unreliable, frequently, but not exclusively, due to uncertainties or errors in observed data.

The analysis of selected parameters may provide some clues about the causes for the triggering of thunderstorms. Comparing the forecasted CAPE with the one by ECMWF, BOLAM likely proved to be quite accurate. Both its runs showed CAPE values between 500 and 1000 J/kg (standing for marginally unstable atmosphere) where ECMWF predicted them, too. In the second run, the highest CAPE values were forecasted by BOLAM over a smaller area, compared to the previous run, further off the Tyrrhenian Sea, where thunderstorms have likely developed. Although LI forecasts made by the GFS (about 0 K over sea and 5 K on the coast, standing for stable atmosphere) have proved to be a little overestimated if compared to observations from the atmospheric sounding, in both cases (forecasted and observed) the values obtained do not provide indications of particular atmospheric instability. This is also suggested by the low CAPE observed and forecasted over the same area (47.11 J/kg at Pratica di Mare; 50 just off the coast in the ECMWF forecast).
The origin of convection may be studied by analysing two other indices. As shown in the atmospheric sounding in figure 20b, significant values were reached by the Total Totals index (47.80) and by the K index (30.30), both suggesting chances for convection and severe weather (source: National Weather Service). The values reached by the TT and K indices are the ones that could likely hint at the development of thunderstorms in the area.
The role of wind, instead, seems harder to understand. By examining the chart of predicted 10 m wind in the run of 13th November, some more low-level convergence appears, compared to the chart of the following day. This may have helped the model in predicting convection. Wind may have had a key role also in the evolution of the quasi-stationary thunderstorms developed in the morning of 14th November. The weak warm advection affecting the mid Tyrrhenian may have favored vertical motions, contributing to remove the convective inhibition (the so-called CIN) and enhancing convection.
One major factor in the development of quasi-stationary systems is generally represented by the convergence in the direction of winds at different heights. As shown in the maps and in the sounding, wind at 10 m was mainly coming from south and southeast, while the upper winds were largely from west and southwest. Wind in the lower boundary layer may hence have contrasted the movement of the developing thunderstorms, thus impeding them to shift eastward and creating the right conditions to keep them over the same area for about 6 hours. This has consequently caused the high amount of rainfall, due to the alternation of a series of storms developing on the sea and then approaching the land.

**5. Conclusions**

In both the examined case studies, the LAMs showed some errors in forecasting the amounts of precipitation and, in the second event, in foreseeing precipitation itself.
In the first case the model correctly identified the locations affected by the highest rainfall. In an operational weather forecasting activity, for example aimed at assessing alert situations, such results, even if not completely accurate, can anyway be considered effective. Underestimates in forecasted precipitation have been likely due to errors in interpreting mesoscale factors and, particularly, orographic effects. The latter may have increased precipitation both on Lepontine and, above all, Maritime Alps. Here, the unstable nature of air masses coming from the Mediterranean Sea, as shown by severe weather indices, has probably favored a strong uplift operated by the mountain range, enhancing convection and leading to a strong thunderstorm activity.
On northern Piedmont, precipitation was mainly of the advective kind. Rainfall may have been enhanced by two main features: the convergence between easterly winds on Po Valley and southerly winds on central Piedmont; a surface low formed on the lee side of the Maritime Alps as a likely consequence of the advancement of the front. This situation may have contributed to direct precipitation towards the Ossola Valley and the Lepontine Alps, where very high rainfall was recorded. In this case, too, orography may have helped in reaching the extreme amounts of precipitation that were locally observed.
In the second case the model was not able to predict the development of quasi-stationary thunderstorms along the coast of southern Latium. The instability of the atmosphere, shown by some severe weather indices, probably enhanced convection. The accuracy of the model has likely been affected by spin-up problems and by local factors, such as low-level convergence, which probably also had a role in the development of convection. At present, such situations still represent a limit for weather models, whose operation, especially at high resolutions, is usually affected by uncertainties in initial and boundary conditions. This means that it is not yet possible to localize thunderstorms and foreseeing their severity with high chances of success and/or with great advance, and this represents one of the main issues affecting the assessment of thunderstorm alerts.
In the next future, technological and computational advances will likely overcome these limitations and allow weather models to correctly predict local thunderstorms in terms of timing, localization and severity.

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- CEAM: http://www.ceam.es/ceamet/SST/index.html

- CNR-ISAC: https://www.isac.cnr.it/dinamica/projects/forecasts/

- DPC radar: http://www.protezionecivile.gov.it/

- Eumetrain ePort: http://www.eumetrain.org/eport.html

- Meteociel: https://www.meteociel.fr/

- Meteonetwork: https://www.meteonetwork.it/

- NASA EOSDIS Worldview: https://worldview.earthdata.nasa.gov/

- National Weather Service: https://www.weather.gov/

- University of Wyoming, Dept. of Atmospheric Science: http://weather.uwyo.edu/upperair/sounding.html

- Wetterzentrale: https://www.wetterzentrale.de/