A Nowcasting Model for Severe Weather Events at Airport Spatial Scale: The Case Study of Milano Malpensa

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***Abstract*— One of the challenges for meteorologists is to forecast severe weather events developing at small spatial and temporal scales. The H2020 SESAR project "Satellite-borne and IN-situ Observations to Predict The Initiation of Convection for ATM" (SINOPTICA) aims at improving the performances of the numerical weather prediction model to nowcast severe weather events developing in the vicinity of airports. In the project, these new prediction technologies are used to integrate weather events into an Arrival Manager (AMAN) for approach controllers to visualize the actual meteorological development and to support arrival sequencing and target time calculation. We defined the users' requirements through a questionnaire distributed to air traffic controllers to find design solutions for additional controller support system functionalities. We are now developing a nowcasting model for air traffic controller support based on a dense network of ground-based sensors. The focus is on Milano Malpensa airport because it is located in a region with high risk of severe weather development and in which we have an easy availability of high-quality data. The results show that, for this specific case, the use of radar, lightning and Global Navigation Satellite System data greatly improve the prediction of the extremes while the weather stations alone are not essential for this purpose.**

Keywords: nowcasting; severe weather; Weather Research and Forecasting; Malpensa; ATM; ATC.

I. INTRODUCTION

Climate change is intensifying the water cycle [1], thus bringing more intense rainfall and associated flooding, as well as more intense drought in many regions. It is expected that climate change through its impact on atmospheric processes, especially on short-lived and highly localized phenomena (thunderstorms, hailstorms etc.), will also affect air traffic management activities. The changes in precipitation and temperature, sea-level rise, wind changes and the impacts of more extreme weather events are the projected climate impacts expected to affect more directly aviation [2], thus calling for different management strategies [3]. These considerations are supported also by some recent meteorological episodes affecting aviation: on 4 July 2021 S7 Airlines flight S71146, an Airbus A320-214, flew through a hailstorm after departure from Chelyabinsk Airport. The aircraft suffered damage to the nose cone and cracks to the outer cockpit windscreen panes. A safe landing was made at the destination airport (Moscow-Domodedovo Airport) at 17:48 UTC, two and a half hours after takeoff from Chelyabinsk; on 13 July 2021 the Emirates Airlines flight EK205, a Boeing 777-31HER, flew through a hail storm after departure from Milano-Malpensa Airport (MXP), Italy. The flight entered a holding pattern for about 50 minutes and turned back for a safe landing. The aircraft sustained damage to the nose cone, outer pane of the captain's windshield, engine inlet cowling and wings.

In this respect, the H2020 Satellite-borne and IN-situ Observations to Predict The Initiation of Convection for ATM (SINOPTICA) [4] project aims to demonstrate that very high-resolution and very short-range numerical weather forecasts, benefiting from the assimilation of radar data, in situ weather stations, GNSS and lightning data, can improve the prediction of extreme weather events to the benefit of Air Traffic Management (ATM) and Air Traffic Control (ATC) operations. Furthermore, SINOPTICA weather forecast results are being integrated into air traffic controllers' (ATCO) decision-support tools, visualizing weather information on the air situation display, and generating aircraft specific 4D trajectories to avoid severe weather areas. To find the best solution for the optical and planning integration of the new functionalities into the ATCO's support systems, a survey was conducted with professional controllers. They were presented with different solutions for static and dynamic representation of extreme weather areas for evaluation and selection. In addition, preferences for the use of the display control and the level of detail for visual and guidance support were queried.

The SINOPTICA project selected four different severe events to be addressed from a joint meteorological and ATM perspective. These events correspond to episodes that occurred in Italy during 2019/2020 and that somehow affected at least one Italian airport: Milano Malpensa airport, 11 May 2019 with a squall line hitting the airport between 14-15UTC, hail and 8 planes diverted to other airports; Venice Marco Polo airport, 7 July 2019, with general instability with two different thunderstorms affecting the airport at 13UTC and 16UTC, strong wind gusts and 8 planes diverted; Bergamo Orio al Serio airport, 6 August 2019: high atmospheric instability with thunderstorms and hail hitting the airport around 19 UTC, 7 planes diverted to other airports; and finally Palermo Punta Raisi airport, 15 July 2020: unstable conditions in the area, with a self-regenerating cell hitting the city of Palermo, nearby the airport, between 16-18UTC. This paper presents the results of the assimilation of the aforementioned observations into the Weather Research and Forecasting (WRF) model and the related ATM implications, for the Milano Malpensa case study on 11 May 2019, proving that it is possible to get a better prediction of this kind of events in line with the expectations and requirements of ATC.

The Malpensa airport is located in a hotspot area for severe weather events development. According to [5], northern Italy is characterized by high frequency of lightning, large hail and strong wind events and, together with the Balkan area, it is also the only European region in which the trend per decade of the modelled number of lightning, large hail and strong wind, is increasing. Malpensa is the only large airport (top 20 for passengers' number and freight in the 2019 ranking) located in the weather riskiest regions of Europe.

II. The Data Assimilation System

Weather radar reflectivity, in situ weather stations measurements, Global Navigation Satellite System (GNSS) estimations and lightning data are assimilated into the WRF model [6] at high spatio-temporal resolution. With this purpose, a 3-hourly cycling assimilation system based on the WRF model three-dimensional variational data assimilation system (3D-VAR) is developed. WRF is a next-generation mesoscale atmospheric model, developed at National Center for Atmospheric Research (NCAR), which uses a fully compressible non-hydrostatic set of equations, Arakawa C-grid staggering, terrain-following hydrostatic-pressure vertical coordinates, and multiple-nesting capabilities. Three domains (Fig. 1) in two-way nesting with respectively 22.5 km (domain D1, 216 × 191 grid points) 7.5 km (domain D2, 523 × 448 grid points) and 2.5 km (domain D3, 430 x 469 grid points) grid spacing are adopted for the numerical experiments. For each domain, 50 unequally spaced vertical levels are used, from ground level up to 50 hPa. The WRF model offers a very rich portfolio of physical options, but we set the same configuration as the hydro-meteorological chain at CIMA [7]. Shortwave and longwave radiation processes are addressed through the Rapid Radiative Transfer Model for Global Climate

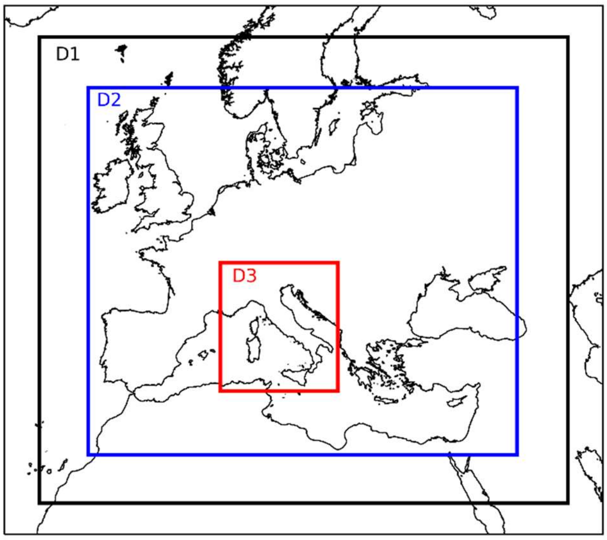

Figure 1. The domains used for the numerical simulations: D1, D2 and D3 with a spatial resolution of 22.5 km, 7.5 km and 2.5 km, respectively.

Models (GCM) [8] parameterization. The very well established WRF single-moment six-class scheme [9] with six different types of hydrometeors is applied for the microphysics, whereas the boundary layer approximation Yonsei University [10] scheme is used for the Planetary Boundary Layer. Furthermore, the land surface is parameterized by the Rapid Update Cycle land surface model [11], which is a recommended for very short range and nowcasting applications. Finally, the New Simplified Arakawa–Schubert scheme [12] is chosen for the convection, consistently with the convection parameterization adopted by Global Forecasting System (GFS) forcing model, except in the inner domain (domain D3 with 2.5 km grid spacing) where it is explicitly resolved. The WRF 3D-VAR assimilation method is largely employed in Numerical Weather Prediction (NWP) to improve the initial conditions and, as result, the forecast skill. The method finds the optimal estimate of the atmospheric state, called 'analysis', by minimizing an appropriate cost function that weights the background atmospheric state (coming from a NWP model run) and the observations, by their uncertainties through the minimization of a cost function reported in (1):

$$J(\mathbf{x}) = \frac{1}{2}\{(\mathbf{x}-\mathbf{x}_b)^T\mathbf{B}^{-1}(\mathbf{x}-\mathbf{x}_b) + [\mathbf{y}_0 - \mathbf{H}(x)]^T\mathbf{R}^{-1}[\mathbf{y}_0 - \mathbf{H}(\mathbf{x})]\} \quad (1)$$

where **B** and **R** are the background and observation error covariance matrices, $\mathbf{y}_0$ is the observation vector, $\mathbf{x}_b$ is the background vector field, **x** is the model state vector, and **H** is the observation operator. The 3D-VAR is applied every three hours in cycling mode, considering a 6h assimilation window. The **B** matrix plays a key role in the assimilation method because it weighs the errors in the background field adjusting the impact of observations. The matrix can be estimated through a statistical method because the correlation between the variables is unknown, so the National Meteorological Center method [13] is used. The method evaluates the differences between different sets of 24- and 12-hour forecasts being verified at the same time. For this work, the **B** matrix is computed over a period of one month.

The radar reflectivity data are assimilated using the reflectivity operator developed by Lagasio et al. [7]. It modifies the direct assimilation operator [14] considering all the hydrometeors (snow, hail/graupel) and not only the rainwater like the default direct operator does. In addition to the reflectivity data, also the Zenith Total Delay (ZTD) from GNSS, are assimilated using the ZTD operator [15] implemented in WRF-3D-VAR. The Lightning Data Assimilation (LDA) is also a useful tool to improve the short-term forecast (0-3h), however, several studies have shown a rapid decrease (1-3h) of the positive impact of LDA on the forecast. For this reason, the nudging method [16] is used with a fast LDA technique [17]. Nevertheless, the nowcasting of convection is highly impacted by the LDA because:

- The flashes are precisely detected in space (the position error is of the order of 100 m and the spatial precision is higher compared to the horizontal resolution of models) and time (the detection of the strokes is almost instantaneous and much lower than the time step used in meteorological models);
- The flashes are generated during severe convective events, so the precise positioning of the lightning in space and time also provides a precise positioning of the convective cells;
- The process to compute the lightning position from electromagnetic signals detected by sensors is fast, making lightning observations available in real time;
- The lightning data are simple to transfer and do not require wide band network connection.

III. Definition of User Requirements to Display Adverse Weather

Assimilated nowcasting data of convection areas should be visualized to support air traffic controller (ATCO) and to reduce controller's workload. For the definition of user requirements to display adverse weather, a survey with air traffic controllers was conducted within the SINOPTICA project. The goal of the survey was to get an overview about controller's requirements and preferences in order to enhance acceptance and usability of adverse weather visualization. The results of the survey allow us to introduce suggestions to improve the presentation of adverse weather areas (like convective cells) on a radar display for aircraft guiding and flight trajectory calculation with target times at significant waypoints. These insights should be used for development of an individually configurable adverse weather display to increase acceptance of the support system by controllers.

The survey was provided to participants as a twelve-page questionnaire and contained ten different structured main questions, some of which were subdivided into small sub-questions. There were questions about the display variants in which the participants could answer in seven levels and there were questions that could be answered with "yes" or "no". The latter ones had the additional option of specifying one's answer or limiting its validity and scope via an associated comment field. The survey began with general questions about the person. In the second section, five display variants were presented, for which the participants were asked to give an estimate of the support quality of the display, as well as a possible order regarding their personal acceptance of the display modes. In the third section, the participants were asked to answer to what extent the activation of the display should be automated or manual and whether they wanted a weather display at all. This was followed by questions about dynamic and static weather visualization and about a possible forecast period when integrating nowcasts. The final section then addressed ideas about additional symbols on the aircraft labels on the radar display to mark aircraft affected by adverse weather, and around the integration of additional safety zones around measured and predicted convection cells in the airspace. The questionnaire was prepared and created by the German Aerospace Center (DLR) and sent to Austrian and German air traffic controllers with homogenic distributed work experience between one and more than 21 years. This allowed us to get inside in the bright spectrum of requirements depending on the controller's work experience.

Although the integration of adverse weather is intended as a support for an advanced scheduling and sequencing, it was usually perceived by controllers as a taking over of additional responsibility. Some of the respondents emphasized the responsibility of the pilot for the safe flight including evasive maneuvers due to adverse weather. On the other side, the respondents stressed that display of extreme weather is good in order to have better planning and less interference into traffic flows. Current and accurate weather radar images including their sophisticated representation are certainly of great use for an Air Traffic Control Officer (ATCO). Due to the large differences in the reaction of the pilots, respondents assumed impossibility of a meaningful and realistic categorization with regard to the dangerousness of a weather situation. One of the most often given comments is regarding a possible overload of the controller's display either with additional information or with its colored presentations. The next point was that the controller’s display may only represent the actual state at any time and not a forecasted one. Also, weather presentation should not be overrated. Experience shows that one aircraft can fly on the left side of a convective cell, the next one on the right side and the last one through some severe weather area depending on the experience of the pilot and interpretation of the available onboard weather radar. Generally, this supporting tool is conceivable for a planning controller. For executive controllers, there might be a risk of visual overload on the radar display. Basically, it is a very good approach to show current weather data in the radar image. However, there should be a possibility to switch-on or -off this information manually with a button. It should be used by ATCO if necessary for better planning of traffic in relation to sequence creation. The represented information should always match the actions of the controller. For instance, airspace is "usable" or "not usable" means that a display with two possible states should be used.

The resume of the results from the requirements analysis for the development of the controller support system in the SINOPTICA project can be summarized very well with the phrase "*less is more*". Overall, most controllers welcome a way to access weather information that is relevant to them quickly and directly. One of their basic requirements is that any type of information, whether it is provided graphically or numerically, must be able to be activated and deactivated quickly and easily on the display. These requirements build basis for visualization of adverse weather on the controller display.

However, during evaluation of the survey, it also became apparent that the project principle of timely and automatic use of weather information by an arrival planning system for early route rescheduling – so that pilots do not even have to ask for a last-minute diversion in the case of adverse weather – could not, or not sufficiently, be communicated to the controllers. For the development of support functionalities in SINOPTICA project, this means that since about half of the participating controllers considered support in adverse weather situations desirable, it is important to make these graphical support functions individually activatable and customizable. It is also important that, if possible, automatic appearing display elements should never obscure or distract from essential aircraft information. Thus, an additional symbol in the aircraft label to display a route rescheduling is rejected. However, there is obviously nothing to be said against designing this label by changing the color of individual display elements within the label, since this would not result in additional information being covered up. Furthermore, when choosing between reliability and prediction time, they rather opted for a shorter one in the period of 10 to 15 minutes, but more reliable prediction. A restrained animated weather development display based only on the reliable forecast period of around 10 minutes, which is only visible at the request of the controllers, thus turns out to be a desirable development solution within the project.

IV. The Case Study of Milano Malpensa

A. Synoptic analysis

On 11 May 2019, the Po Valley was affected by a strong convective activity causing several economic damages and a seriously injured person in Lombardy region. At 06:00 UTC the synoptic analysis at 500 hPa showed a stretched trough, extending from northern Europe to the Mediterranean basin, that was approaching to northern Italy. Also, at 500 hPa a weak anticyclonic ridge was still affecting central and southern Italy bringing atmospheric stable conditions and clear sky. Instead, at the 12:00 UTC there was advection of a cold air mass over north-western Italian Alps at 500 hPa as well as an intense south-westerly flow that increased the vorticity of the air column over the plain (Fig. 2, upper panel). In the afternoon hours, the cold air mass at 500 hPa reached the Po Valley with values around -26 °C and consequently the winds shifted to northwest. On the other hand, the strong south-westerly flow at low levels, moved a large amount of water vapor from the Ligurian Sea to the inland, increasing the convective instability (Fig.2 lower panel). These meteorological factors produced favorable conditions for the triggering of convective cells over northern Italy. In this context, a squall line hit the Malpensa airport between 14:00 UTC and 16:00 UTC producing intense precipitation and heavy hail formation. The large quantity of hail over the runaways caused the closure of the airport for 40 minutes and some flights were delayed. In addition, nine aircrafts were diverted to other airports. The heavy precipitation also produced several floods in the city of Milan, where some

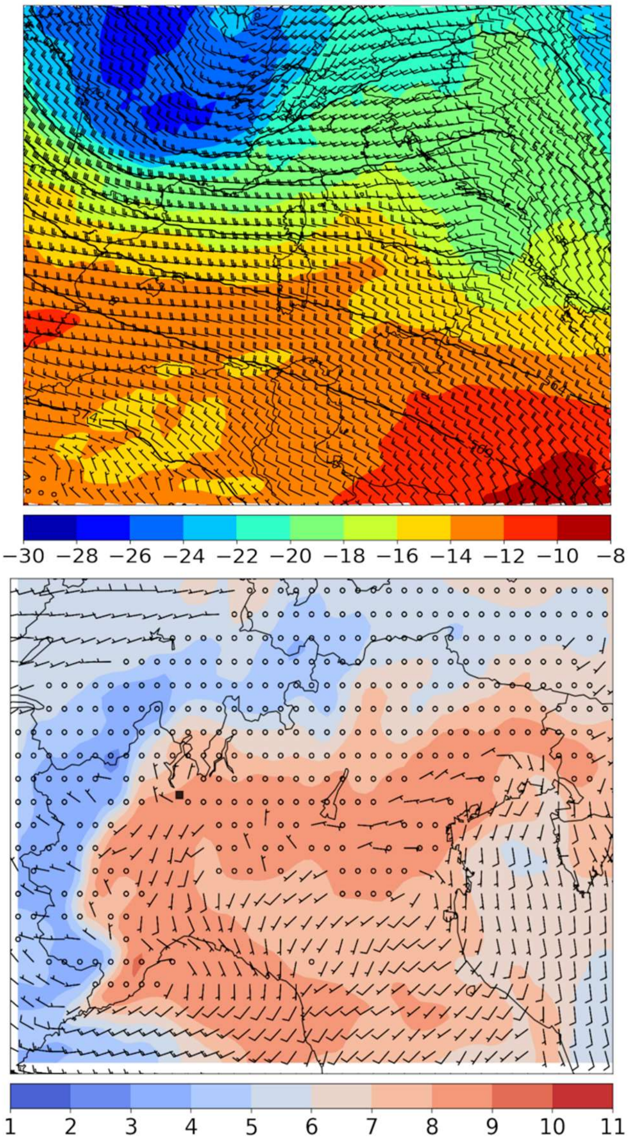

Figure 2. Upper panel: European Centre for Medium-Range Weather Forecasts (ECMWF) high-resolution analysis (HRES) of geopotential height (dm, contours), temperature (°C) and wind (barbs) at 500 hPa the 11 of May 2019 at 12:00 UTC. Lower panel: ECMWF-HRES forecast of specific humidity (g/kg) and wind (barbs) at 950 hPa the 11 of May 2019 at 12:00 UTC +3h. The black rectangle indicates the location of Malpensa airport.

underpasses and metro stations were closed. Instead, the strong downburst winds caused the fall of some trees and billboards and the intervention of firefighters was required. The nearest rain gauge station (managed by the Italian Civil Protection Department), Arconate, recorded 10 mm of precipitation in 10 minutes while the 10-minute average wind gusts of 20 km/h were measured by the anemometer.

We analyzed a combination of two radar products, the Vertical Integrated Liquid (VIL) and the Echo Top Maximum (ETM) of 20 dBZ. The VIL shows the total amount of liquid water in a vertical column of the atmosphere while the ETM

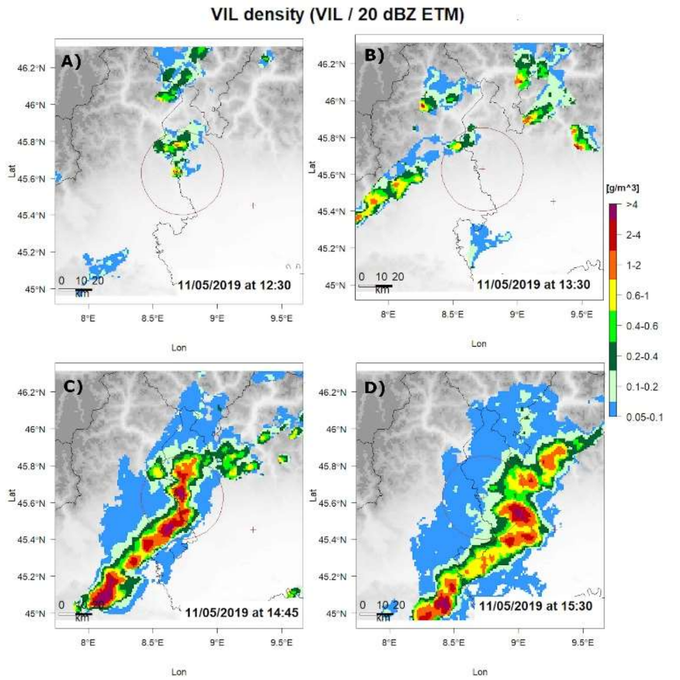

Figure 3. VIL density (DVIL) of the storm system impacting MXP. Time evalution (A-B-C-D) of the convective system from 12:30 UTC to 15:30 UTC, each image shows the maximum DVIL value in the following fifteen minutes.

provides information about the maximum height reached by the storm. Combining both products, we can obtain the VIL density (DVIL):

$$DVIL=VIL/ETM \quad [g/(m^3)] \qquad (2)$$

At 11:20 UTC the first echoes appeared on the radar mosaic, forming individual storm cells in the Alpine region near to the Italy-France border. These storms began to move to the east reaching the Malpensa Airport about an hour later (Fig. 3A). At the same time another storm structure started its convective organization in the same place. This second storm rapidly increased its organization from 12:30 to 13:00 UTC, growing in extension from about 10 km of major axis to more than 50 km. The axis of the storm continued to grow in the North-East direction, reaching 100 km around 13:30 UTC and the intensity of the storm also increased with the most intense part near Turin (Fig. 3B). The already organized storm system moved to the East and reached the surroundings of MXP at about 14:00 UTC. The storm intensity increased reaching the maximum at 14:45 UTC (Fig. 3C), impacting the Malpensa airport for at least 30 minutes with DVIL greater than 4 g/m^3 highlighting large hail size or high hail intensity. After 15:30 UTC, the system started weakening and moving away from the airport area (Fig. 3D), splitting into two different storms.

B. Model simulations

A total of four simulations were carried out in order to improve the nowcasting of the case study (convective cells, hailstorms and wind gusts) in terms of localization and timing. The radar data (RDR), more specifically the Constant Altitude Plan Position Indicator (CAPPI) reflectivity at 2000 m, 3000 m and 5000 m above mean sea level, were assimilated alone or in combination with GNSS ZTD (GNSS), in-situ weather stations from Civil Protection network (WS) and lightning data (Ligh), respectively (as shown in Tables 1-2). Finally, a control run (CTL) without assimilation was performed. The initial and boundary conditions for all experiments were provided by the National Centers for Environmental Prediction (NCEP) Global Forecast System (GFS) with a horizontal resolution of 0.25°x0.25°. All simulations started the 11 of May 2019 at 12:00 UTC and lasted for 6 hours. To assess the performance of data assimilation, an object-based verification was performed by using the Method for Object-Based Evaluation (MODE) [18,19], developed by NCAR. In addition to the DVIL, also high VIL values may denote intense convective cells. Thus, two VIL thresholds, 10 mm and 15 mm were considered for the statistical analysis. The verification was performed over a sub-region of the inner domain (D3 in Fig. 1), including MXP, and covered by the extended arrival Manager (Extended AMAN). The objects and their attributes were identified applying a convolution filter to the observed and predicted VIL fields. Many attributes are computed by MODE tool, but they can be grouped in four main categories: area, distance, intensity, and ratio. To summarize the results and perform the merging and matching between the objects, a fuzzy logic approach is adopted. In this regard, a function, called interest map, is computed to reduce the attribute value in a number ranging from 0 to 1. Next, scalar weights are assigned to the attributes to tune their importance than the other. Finally, the weights and interest maps for each attribute are combined in a scalar value, the total interest, that has been used in this study. The total interest ranges between 0 and 1, with 1 being the best score. To perform this test, the maximum of VIL in the period from 14:30 UTC to 15:30 UTC (when the convective cell was approaching the airport) is taken into account. The attributes obtained through the MODE for a VIL threshold of 10 mm in an observed area of 875 km^2 are summarized in Table 1.

TABLE 1

Experiment	**Centroid distance [grid units]**	**Forecast area [grid units]**	**Intersection area [grid units]**	**Total interest**
CTL	37.45	1479	33	0.78
RDR	62.41	1342	0	0.69
RDR+GNSS	50.10	1947	75	0.80
RDR+WS	70.53	1451	0	0.68
RDR+Ligh	21.92	3500	822	0.91

The experiment including the lightning data shows the lower values in terms of centroid distance, so the best performance in the convective structure localization. Furthermore, the interest parameter confirms the good result obtained with lightning assimilation, in fact the interest value reaches 0.91 (best values) compared to 0.69 and 0.80 of RDR and RDR+GNSS simulations, respectively. Conversely the RDR+Ligh shows a forecast area much larger than the other experiments suggesting an overestimation of the precipitation in the study despite the best value in terms of intersection area. The GNSS-ZTD and lightning data assimilation improves the convective cell forecast compared to the simulation with only radar reflectivity assimilation. Finally, the simulation with radar in combination with temperatures shows a similar behavior to RDR experiment in terms of interest, but a worsening of centroid distance.

The results for the VIL threshold of 15 mm in an observed area of 593 km^2 are reported in Table 2.

TABLE 2

Experiment	**Centroid distance [grid units]**	**Forecast area [grid units]**	**Intersection area [grid units]**	**Total interest**
CTL	48.41	795	0	0.75
RDR	62.18	931	0	0.65
RDR+GNSS	57.50	689	12	0.78
RDR+WS	71.03	1057	0	0.60
RDR+Ligh	19.00	2376	546	0.92

The statistical analysis using a stricter threshold proves that the use of GNSS and lightning data further improve the localization of the convective event. The interest value increases from 0.65 with the RDR experiment to 0.78 when the GNSS-ZTD are assimilated in combination with radar reflectivity. In addition, the centroid distance between the observed and predicted VIL clusters reduces from 62.18 to 57.50 grid units pointing out the positive impact of GNSS data. On the other hand, the RDR+WS experiment shows a slight worsening both in centroid distance and interest, but temperatures only are considered because a quality check is needed before assimilating humidity and wind data. Finally, the simulation with lightning and radar data shows the best results in terms of both interest and centroid distance, in agreement with the lower threshold values.

C. *Model output visualization*

The SINOPTICA data visualization for the meteorological data is a ground map with the DVIL (or other relevant parameters) superimposed in transparency. The color scale goes from light blue (low intensity) to dark red (high intensity) covering the whole area interested by the severe weather event (Fig. 3). This type of visualization, according to the users' requirements, is too complex. We are now working to convert this visualization in a simpler polygon highlighting the area in which we are able to nowcast the severe event with very high confidence.

V. Conclusions

This paper reports parts of the results obtained by the H2020 project SINOPTICA, focusing on the definition of user - i.e. air traffic controller ATCO - requirements and on the assimilation of radar, weather stations, GNSS and lightning observations into the WRF numerical model.

The user requirements analysis concluded that visualization of weather information on ATCOs' displays would be welcome, assuming that the controller can activate/deactivate it quickly and easily. An important point that also emerged, is that some controllers perceived the addition of weather information as taking over of additional responsibility for them. A requirement strongly highlighted is that the graphical visualization should be as essential as possible in order not to clutter the display. We are now working in this direction, defining a possible threshold to be used as reference for "high confidence" severe weather nowcast commonly accepted by ATCOs and meteorologists, and displaying this information with a graphically polygons on the controller's radar display.

As regards the data assimilation experiments, one of the four case studies analyzed within SINOPTICA, namely the Milano Malpensa case study, was described in detail from a meteorological perspective. Four numerical experiments were performed for this case study, assimilating radar observations only, radar and weather stations, radar and GNSS, radar and lightning into the WRF model. Results, evaluated using the object-based method MODE, indicate an improvement of convective cell forecast, in terms of centroid distance and interest value, when assimilating GNSS or lightning data, compared to radar-only assimilation. Conversely, assimilation of weather stations data shows a slight worsening of the forecast in terms of both centroid distance and interest value.

The results obtained in the other three case studies, namely those focused on Venice Marco Polo, Bergamo Orio al Serio and Palermo Punta Raisi airports, as well as the results that will be obtained in the project progression, will be presented in future papers.

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