



# The –WIND RISK project: nowcast and simulation of thunderstorm outflows

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## Abstract

–WIND RISK is a research project dealing with measurement and modelling of wind fields within thunderstorm cumulonimbus clouds and outflows at the ground (i.e., downbursts and gust fronts). The general objective of the project is to advance the knowledge about the processes occurring inside thunderstorm clouds responsible for strong outflows, and the identification of the environmental (synoptic and meso-scale) conditions favourable to their development. The area under investigation is Northwestern Italy and the Ligurian Sea, which are among the most exposed regions to strong thunderstorms in Europe. Two measurement campaigns using Doppler weather radars and remote-sensing ground-based anemometry, and ad-hoc simulations using the WRF model are carried out to build a database of thunderstorm wind fields with special focus on downdraft and downburst characterization. All measurements and simulations are shared within the scientific community after the end of the project through datasets published on open access platforms.

**Keywords** Thunderstorm outflows · Doppler radar · Doppler lidar · WRF · 3D wind field reconstruction

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## 1 Introduction

Cold-season windstorms generated by extra-tropical cyclones were deeply investigated in the past (Feser et al. 2015; Clark et al. 2018) because they are the most destructive natural phenomenon in Europe, accounting for more than 70% of damages and casualties associated with this kind of events (Ulbrich et al. 2013). On the other hand, warm-season windstorms caused by local convective storms were marginally studied in Europe until few years ago (Gatzen et al. 2020; Pacey et al. 2021). Despite the substantial impacts that these events can cause (Squitieri et al. 2023a), the atmospheric environments responsible of severe convective windstorms in Europe are not well known, and a thorough knowledge of their potential impact on the natural and built environment is still lacking. In this regard, in the last decades the thunderstorm-related surface wind fields have been studied through signal analysis of wind velocity records (e.g., Duranona et al. 2007; Zhang et al. 2018) and vertical profiles (e.g., Canepa et al. 2020; Romanic 2021), ad-hoc wind tunnel experimental campaigns (e.g., Romanic and Hangan 2020; Canepa et al. 2022), and numerical simulations (e.g., Mason et al. 2009; Zuzul et al. 2023). Europe has been funding this field of investigation within its research framework programs (Solari et al. 2012) in an attempt to identify a downburst model suitable for codification (e.g., Jesson and Sterling 2018; Xhelaj et al. 2020).

Although some accepted theories on downburst generation were proposed already a few decades ago (Rotunno et al. 1988; Weisman 1993), there are still many open challenges on downburst dynamics and prediction (Squitieri et al. 2023b). Moreover, a reliable downburst model suitable to simulate their impacts is still missing.

In 2022, the University of Genoa and the Institute of Atmospheric Sciences and Climate of the National Research Council (ISAC-CNR) have been awarded by the Italian Ministry of University and Research with a grant for research projects of relevant national interest (PRIN-2022) for the Project “Thunderstorm outflows measurement and modeling for strong–WIND nowcast and RISK mitigation” (–WIND RISK). The area under investigation is Northwestern Italy and the Ligurian Sea, since this area is among the most affected by severe thunderstorms in Europe (Mateusz et al. 2020). An overview of the project structure is reported in Sect. 2.

The project is intended to provide the scientific community with relevant wind field reconstructions inside thunderstorm clouds with special focus on surface winds, within the region where downdrafts are expected to accelerate due to negative buoyancy and eventually produce strong outflows and related impacts on the ground. A database of wind field retrievals within real thunderstorm clouds that occur during two field campaigns carried out in Piedmont and Liguria regions is expected to be published at the end of the project. During these campaigns, coupled radar and lidar remote-sensing techniques are used to measure Doppler velocities, and proper algorithms are applied to reconstruct the high-resolution 4D (i.e., in space and time) wind fields within cumulonimbus clouds (Sect. 3).

In addition, ad-hoc numerical simulations are performed to analyse a set of case studies that occurred in the past with the aim of finding common meteorological precursors and environmental conditions favourable to the development of gust fronts/downbursts in the area under investigation (Hadavi and Romanic 2024) (Sect. 4).

## 2 Project structure

The project consortium is made up of two research units: the University of Genoa, in charge of organizing the field campaigns, collect and post-process all measurements, and the National Research Council, in charge of performing numerical simulations of downburst-producing thunderstorms.

According to this subdivision of competencies and activities, the project is structured into three main Work Packages (WP) as shown in Fig. 1. WP1 is devoted to thunderstorm measurement and analysis and, in turn, is organized in 4 Tasks (T). T1.1 concerns with the definition of the overall measurement setup, instrument deployment, and data management during the field campaigns. T1.2 includes all the activities needed to carry out the field campaigns during their executive phase. T1.3 deals with the analysis of wind measurements and post-processing to reconstruct the 3D wind fields. T1.4 is a demonstration activity of the algorithms developed in T1.3 applied in real-time in an operational environment for nowcasting purposes.

WP2 is devoted to thunderstorm simulation by means of a state-of-the-art numerical weather prediction (NWP) model, and it is subdivided in three Tasks. T2.1 and T2.2 aim at simulating in hindcast mode some relevant thunderstorms over the area under study that occurred in the past in order to investigate their development mechanisms. In T2.3, the same NWP model are used in forecast mode during the field campaigns in some specific events and compared to measurements.

Finally, WP3 is entirely focused on dissemination and communication activities, including social media, publication of relevant results in journal papers, and presentation in conferences. In addition, the project is expected to publish the database of the thunderstorm-related 3D wind fields extracted from measurements and numerical simulations in open access mode.

## 3 Measurement campaigns

Two measurement campaigns are carried out during the project's lifetime. The first campaign (Jan-Sep 2024) is carried out in Piedmont, centered over the urban area of Turin and its surroundings (yellow box in Fig. 2a), whereas the second campaign (Oct 2024-Mar 2025) is based in Liguria (white box in Fig. 2a).

In both campaigns, remote-sensing measurements based on two fixed C-band Doppler radars (Fig. 2d, e) and one transportable X-band Doppler radar (Fig. 2c) are used to scan the in-cloud wind fields, complemented by two scanning Doppler lidars (Fig. 2b, in Genoa)

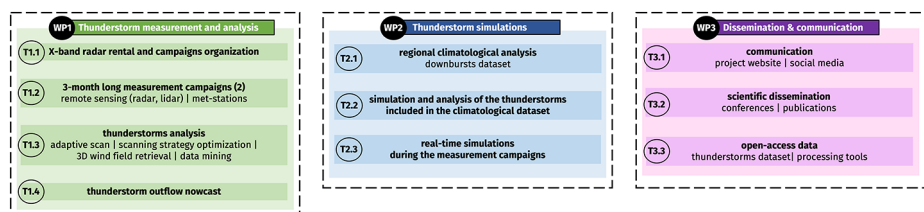
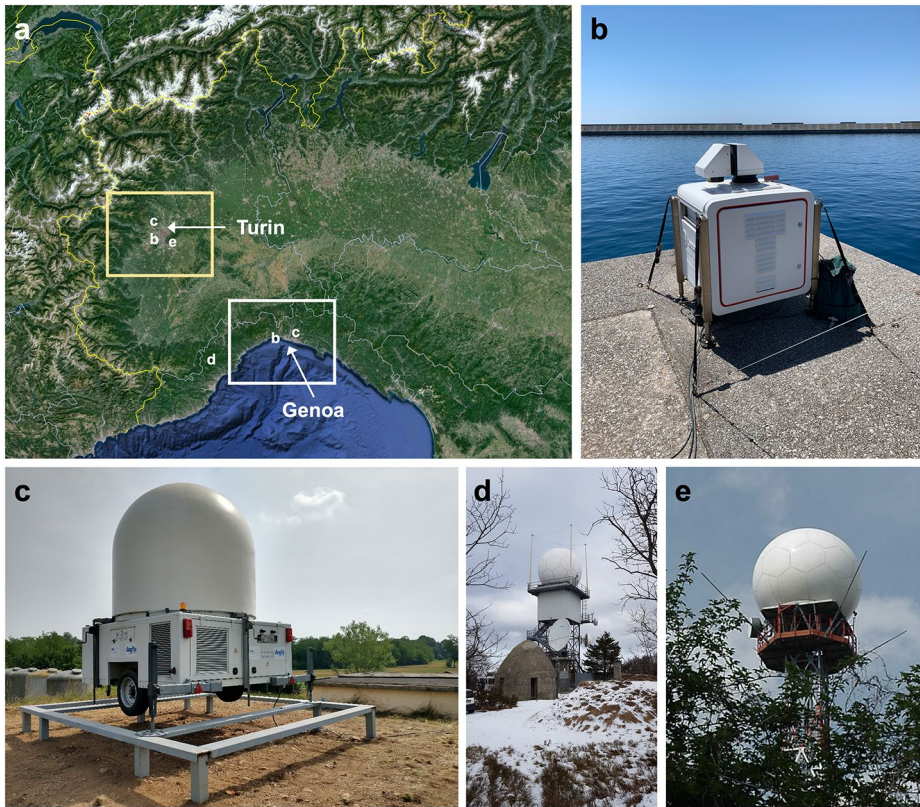


Fig. 1 Structure of project –WIND RISK

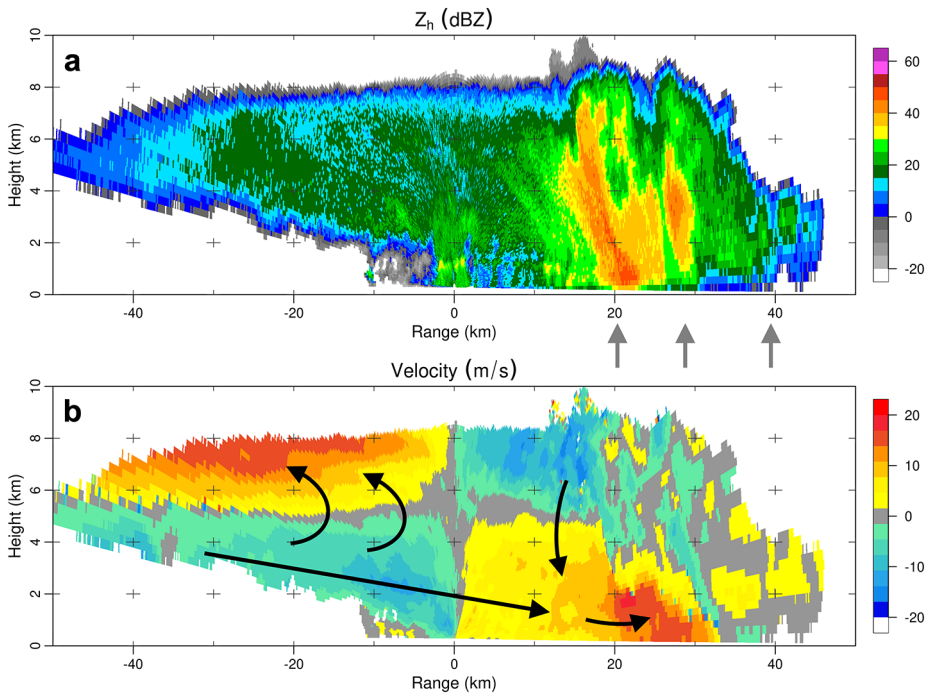


**Fig. 2** (a) Area of the two campaigns in Piedmont (yellow box) and Liguria (white box), and position of: (b) scanning LiDAR in Turin (campaign 1) and in the Port of Genoa (campaign 2); (c) X-band Doppler radar in Druento (campaign 1) and Righi, Genoa (campaign 2); (d) C-band Doppler radar in Mount Settepani, Liguria (campaign 2); (e) C-band Doppler radar in Bric della Croce, Piedmont (campaign 1)

to measure the thunderstorm outflows at the ground at high resolution. In addition, ground-based met-stations belonging to the regional meteorological networks of Piedmont and Liguria are used for rain and cold pool detection, as well as for any other meteorological quantity relevant for the investigation of severe thunderstorms.

The radial velocities recorded by radars and lidars are acquired including partially overlapping scanning volumes in order to collect measurements within a total volume that is continuous from the ground to the cloud top. Since lidars can measure at a resolution that is approximately one order of magnitude finer than that available from radars, and since they are intended to measure the rapidly evolving gust fronts generated below the cloud base after the downdraft touchdown, their scanning path is remotely controlled via the API (Application Programming Interface) system to point adaptively towards touchdown position and maximum horizontal outflows. In addition, the PyDDA software (Shapiro et al. 2009; Potvin et al. 2012) is utilized to retrieve the 3D wind field from post-processing of radar and lidar radial wind components using data assimilation techniques. All relevant thunderstorm wind fields measured during campaign 1 and 2 are intended to be collected in a dataset that will be published in an open access repository according to FAIR principles.

As an example of within-thunderstorm flow field measured during campaign 1, Fig. 3 shows the measurements of the X-band radar in Druento, Piedmont (provided by Arpa Piemonte, Fig. 2c) corresponding to a RHI (Range Height Indicator) scan taken along a vertical section from the azimuthal angle  $110^\circ$  (i.e., approximately eastward, positive values in the  $x$ -axis) to  $290^\circ$  (i.e., approximately westward, negative values in the  $x$ -axis). The scan was taken at 1810 UTC on 5 March 2024 when a severe thunderstorm was over Turin. Reflectivity (Fig. 3a) shows the core of the main cumulonimbus cloud (cb), located about +20 km (see gray arrow) eastward with respect to the position of the instrument, and the extension of hydrometeors and precipitation from the top of the cloud (below the main overshooting top) to the ground. A melting layer, approximately 1 km above the radar, is also discernible. The interpretation of Doppler velocities (Fig. 3b) is supported using arrows that are intended to show qualitatively the main flow structure within the cloud. In the lower half of the troposphere a sheared and drier rear inflow jet from the west contributes drifting the cloud eastward (this is the overall storm motion according to subsequent radar snapshots, not shown) and tilting its updrafts. Furthermore, the inflow jet seems to promote the development of new cells in the front side of the cb (see gray arrows at about +30 and +40 km in Fig. 3a). To the west of the instrument (negative  $x$ -axis values) the anvil shape aloft has positive velocities in the ascending front-to-rear flow (Houze et al. 1989), which suggest possibly strong wind shear from the lower levels (inflow jet) to the higher levels (front-to-rear flow). To the east of the instrument, the downdraft is initiated aloft, where vertical velocities in the order of -10 m/s are measured, and a strong outflow at the lower



**Fig. 3** Reflectivity (a) and Doppler velocity (negative inbound, positive outbound) (b) measured by the X-band Doppler radar in Druento on 5 March 2024 at 1810 UTC. RHI scan from  $110^\circ$  (positive  $x$ -axis values) to  $290^\circ$  (negative  $x$ -axis values)

levels, of around 20 m/s, is observed; the associated cold pool is likely responsible of the initiation of the new cell at +30 km.

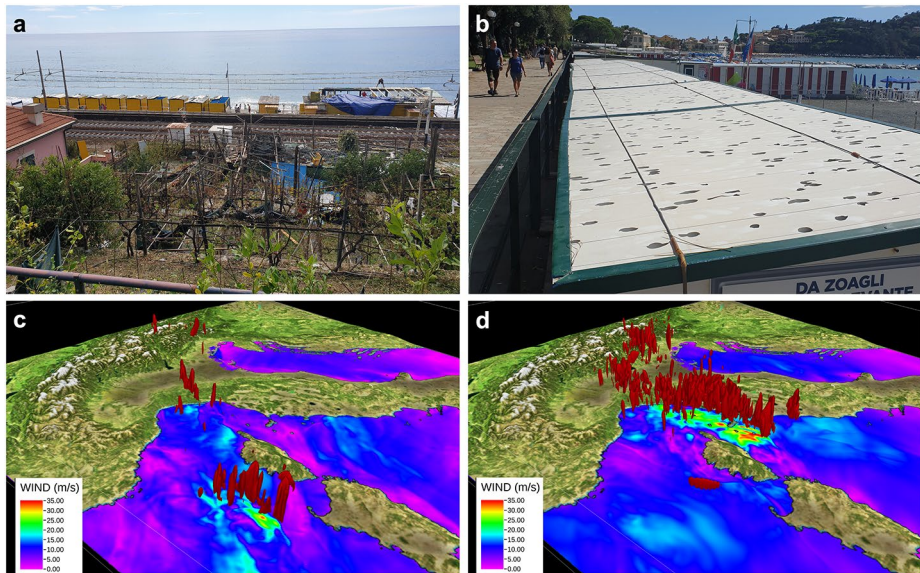
## 4 Numerical simulations

Numerical simulations of relevant thunderstorm events are performed using the Weather Research and Forecast (Skamarock et al. 2019) meteorological model, version 4.1.1, which is a state-of-the-art numerical weather prediction model widely used both for research and operational purposes.

Since a detailed climatology of downburst occurrence is not available in any Italian region (see Pacey et al. (2021) and Taszarek et al. (2020) for some attempts at a European scale), one of the first steps in the project is the definition of a regional climatology of downbursts over Northwestern Italy (Fig. 1, Task 2.1). Since 2018, PRETEMP (De Martin et al. 2023) has been collecting storm reports in Italy, feeding the European Severe Weather Database (ESWD, Dotzek et al. 2009), the most comprehensive database of severe weather events over Europe. That database is the starting point for this analysis. However, since many events are missing in the ESWD before 2018, this will be complemented by additional regional data sources to extend the dataset. For instance, reports available at the Regional Agencies for Environmental Protection (Arpa) of Liguria and Piedmont regions are used. After the dataset of extreme events is collected, the conditions favorable to downburst occurrence are systematically investigated through both numerical simulations and data analysis (Task 2.2). We plan to extend the dataset near the end of the project, since most probably some additional events are going to occur in the region during the project lifetime.

As a first relevant extreme event, the windstorm that occurred early in the morning in central Liguria on 18 August 2022 (González-Alemán et al. 2023) is analyzed and hereafter briefly presented. On the night between 17 and 18 August, a long-living bow-echo system (i.e., a derecho) travelled from the Balearic Islands towards Northwestern Italy, making landfall in Eastern Liguria and Tuscany around 0800 UTC. Wind speeds greater than 25 m/s were recorded all along the windstorm track (Pucik 2022) with maximum wind gust of 62.2 m/s measured by Météo France at Marignana, Corsica. However, earlier in the morning (around 0500 UTC), when the derecho had yet to land over Corsica (about 250–300 km southwest of Liguria), an exceptionally strong downburst possibly associated to a supercell (Arpa Liguria forecasters' personal communication) occurred in central Liguria, with 37.5 m/s wind gusts measured in the marina of Chiavari by a met-station installed in the framework of the European Project I-CHANGE (<https://cordis.europa.eu/project/id/101037193>, last accessed May 2024) and radar-estimated rainfall of around 80 mm/h in the mountainous inland. The entire coastal area suffered large damage due to the strong wind and hailstones (Fig. 4a, b): some roofs and parts of wood cabins were uplifted and fell on the railway, blocking and limiting the train transit for a few days; many trees were uprooted; widespread hail damage was recorded mainly along the coastline in Sestri Levante.

This event was simulated by CIMA in hindcast mode using the WRF model, adopting the same configuration described in Poletti et al. (2024). In short, three two-way nested domains are utilized, the finest one covering all Italy with  $430 \times 469$  grid points in the horizontal and 2.5 km grid spacing, and 50 vertical levels up to 50 hPa. For details concerning the adopted parametrizations (e.g., soil model, PBL scheme, radiative processes, convection, etc.) the



**Fig. 4** Photos taken by the University of Genoa during the post-event damage survey: wood-framed roof uplifted and fallen partially over the railway line and an orchard (**a**); hail damage to plastic roofs of beach cabins (**b**). WRF model simulation of the windstorm on 18 August 2022 in Liguria: updrafts (red isocontours) and surface (10 m height) wind speed over the sea (shaded contours) during the pre-derecho phase at 0500 UTC (**c**); same as (**c**) at the time of derecho landing in eastern Liguria and Tuscany at 0800 UTC (**d**)

reader is referred to Poletti et al. (2024). Both radar reflectivity and lightning are assimilated using a 3-h cycle 3DVAR technique.

Overall, the timing of the derecho is well-captured by the WRF model, as well as its spatial extension and evolution. Figure 4d shows that the simulated landing occurs correctly at 0800 UTC and only Eastern Liguria and Tuscany are affected by strong surface winds, up to about 35 m/s, and heavy precipitations. Conversely, at the time of the downburst-producing thunderstorm at 0500 UTC (Fig. 4c), WRF is not able to detect the initiation of the deep convective cell that develops in central Liguria, demonstrating that relatively small and short-living cells cannot be properly simulated despite the model is run in hindcast mode and forced through data assimilation. This issue is probably a consequence of the limitation in meteorological models to correctly reproduce the triggering mechanism of this kind of very local phenomena despite an environment prone to deep convection.

## 5 Conclusions

This paper provides a general overview of the research project –WIND RISK, which at the time of writing is still ongoing and is being carried out by the University of Genoa and the National Research Council (as leading partners), and supported by Arpa Piemonte (IT), ARPAL (IT), the University of Bologna (IT), CIMA Research Foundation (IT), and the McGill University (CA).

Some preliminary results are already available and presented in this paper. The radar measurements of a relevant thunderstorm that occurred in Piedmont during the field campaign 1 are shown and briefly described in Sect. 3. This was a multicellular thunderstorm cluster propagating eastward. Doppler velocities provide some insights of the overall flow field within the system as well as quantitative information regarding the position of downdraft initiation (around 8 km above the ground), and the order of magnitude (10 m/s) of vertical velocities aloft. Unfortunately, the vertical velocity associated to the downdraft approaching the ground, which usually corresponds to the maximum intensity, is not available since the touchdown position is too far east (somewhere between +15 and +20 km), and the Doppler velocity measured along line-of-sights with low elevation angles does not provide reliable information on the vertical velocity component. However, the horizontal divergence of the downdraft is clearly captured in the layer below 2 km above the ground, and a second cell developing at +30 km is initiated by the low-level convergence along the gust front. Again, despite direct measurements of surface winds are not available for this event, the order of magnitude of the outflow can be inferred to be stronger than 20 m/s, and there is no evidence of an axisymmetric radial outflow while the gust front shows a prevalent eastward direction. In perspective, the post-processing of Doppler velocities using PyDDA algorithms is expected to better clarify and detail all these aspects through the 3D reconstruction of the wind field inside the clouds.

A high-resolution WRF model simulation of the derecho that occurred in Liguria on 18 August 2022 has been shown in Sect. 4. This event caused severe damage to structures and infrastructures in eastern Liguria and northern Tuscany due to strong winds as well as large hailstones. However, most of the damage, which has been documented in great detail through a post-event damage survey carried out by the University of Genoa, was brought about by a supercell at 0500 UTC, well before the derecho landing that occurred 3 h later. This suggests an origin of the supercell independent of the derecho, likely related to a combination of atmospheric thermodynamic and kinematic conditions prone to the development of organized deep convection and some kind of very local forcing/lifting mechanism needed to the storm initiation. While the WRF model shows good skills in simulating the larger-scale derecho, even if only after assimilation of radar reflectivity and lightning observations, it fails to simulate the smaller thunderstorm that occurred in the pre-derecho phase. This points out the importance of the present project to better understand the physical reasons behind the formation of this kind of smaller but very dangerous storms, also in the perspective of improving the capability of modern numerical weather prediction models to forecast extreme events.

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**Author contributions** B.M. and M.M.M. equally contributed to the conception, design, and supervision of this work. B.M. drafted the original manuscript. All authors edited/revised critically the manuscript. B.R. provided radar measurements. L.M., M.M., and P.A. run the WRF simulations.

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**Data availability** No datasets were generated or analysed during the current study.

## Declarations

**Competing interests** The authors declare no competing interests.

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