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Severe convective weather in Italy: Current understanding and Research Priorities in the TIM campaign

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Abstract. The status and priorities of research on severe convective storms in Italy are outlined here, with particular attention to the upcoming Thunderstorm Intensification from Mountains to Plains (TIM) observation campaign. The increased intensity of events induced by climate change is attracting growing attention from the Italian scientific community on this topic. While northern Italy is the most studied, with numerous papers analyzing intense events such as tornadoes, hailstorms, and flash floods, the central and southern regions are less explored, even though they are also occasionally subject to intense events modulated by mesoscale circulations, sea-land interactions, and complex orography. The TIM campaign represents a unique opportunity to improve the understanding, monitoring, and forecasting of severe storms. The campaign, led by the European Severe Storm Laboratory, represents a first-of-this-kind pan-European campaign aimed at obtaining coordinated data on severe convective storms, and is a key step toward improving warnings, forecasts, climate change impact estimation, and adaptation measures. The value of the campaign for Italy is indicated by the participation of several institutions, both from the academic and the operational community. Among the planned initiatives, the use of two Italian airborne platforms will allow for a more complete characterization of the environments associated with convective storms, including an improvement in our understanding of the role of aerosols and storm-scale modeling.

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1. Introduction

Convective storms result from a complex interplay between thermodynamics and dynamical processes at different scales, ranging from the synoptic scale to the microscale. Therefore, their forecast is still challenging due to the complexity of the physical processes, which are still only approximately accounted for in numerical weather prediction models, and the scarcity of high-resolution observations within the pre-storm environment, which limits the representativeness of the initial conditions in model simulations. Improving our understanding of these processes requires a coordinated strategy that combines in-situ microphysics observations, thermodynamic profiling, remote sensing of clouds, precipitation, winds and aerosols, turbulence measurements, together with modelling activities.

Severe convective storms are responsible for injuries and even fatalities (e.g., De Martin et al., 2025b), as well as for a substantial amount of damage across Europe. Their growing impact (Battaglioli et al., 2025) highlights the importance of research and a better understanding of their effects to adopt appropriate loss mitigation measures.

Unfortunately, focused field campaigns in Europe were relatively small (Kunz et al., 2022). Conversely, several observational campaigns on severe convection have been performed for several decades in the USA. Considering the complex morphology of the Italian territory, where land-sea transitions and complex orography may especially affect the meso-gamma scale circulation, the conceptual models developed for the USA should be at least modified or adapted to the peculiar Mediterranean environment. This was shown, for example, in Miglietta et al. (2016) or, more recently, in De Martin et al. (2024), in which the triple point configuration typical of tornadogenesis in US Midwest was observed in the Po Valley, but with very different time and spatial scales. In particular, the role of the increasingly warmer Mediterranean Sea and the presence of a very long and complex coastline should be properly included in this framework, together with the complex orography of the region, as demonstrated in recent studies of extreme convective weather (e.g. De Martin et al., 2025a).

In the Mediterranean region, only a limited number of extensive observational campaigns was performed, but none was focused on small-scale convective storms. In northern Italy (and partly central Italy), severe weather was investigated during the Mesoscale Alpine Program (Bougeault et al., 2001) and the HyMeX program (Ducrocq et al., 2012), but both projects were mainly focused on the large scale and mesoscale conditions conducive to severe weather, heavy rain in particular (Miglietta and Davolio, 2022).

In recent years, one major observational effort was the observational campaign on Monte Baldo (Italian Alps), managed by the University of Trento under the DECIPHER project. This activity was part of the summer Extended Observation Period of TEAMx (Serafin et al., 2020; Rotach et al., 2022), during which nine research teams from various European countries provided a remarkable number of different instruments and personnel to the observational activities from June to October 2025. The Adige valley target area and its experimental setup are shown in Figure 1. Although the project focused on planetary boundary layer (PBL) processes in a complex Alpine environment, some attention was posed to air-surface exchange processes and ventilation mechanisms towards the free atmosphere, possibly conducive to the initiation of atmospheric convection. Through in situ observations-including flux towers, Doppler and Raman Lidar, ceilometer, aerosol sensors and disdrometers–, the TEAMx-DECIPHER campaign was a great opportunity to consolidate a high level of logistical and organizational expertise in the management of complex observation campaigns with many partners involved. Various turbulence regimes, slope and valley circulations were observed, allowing to investigate their role in transport and mixing, and indirectly their potential influence on convective initiation through the distribution of humidity, aerosols and atmospheric tracers, leading to a rich dataset in the Alpine area.

Together with convective initiation, another important issue is the predictability of severe thunderstorms. In the Po valley, it is known that predictability is generally high in the presence of a strong synoptic forcing (e.g., a cold front advancing from the northwest), but it is much lower during the convective season, when severe storms may locally occur without any substantial large-scale driver. To make the picture more complex, storms over the Alps and Prealps follow a strong diurnal cycle, associated with diurnal heating, while those near the coasts or offshore are mostly associated with the annual cycle of sea surface temperature (SST; Manzato et al., 2022a). Consequently, the distribution of thunderstorms is not uniform in the area, showing a strong maximum in the northeastern Prealps (Fig. 2).

Any approach based uniquely on synoptic analysis (e.g., a simple “weather-type” classification) is insufficient for severe weather forecasting in the Po Valley. Even any approach based on simple mesoscale “environmental conditions” would not be very helpful, because potential instability is present on most summer days in the Po Valley (Manzato, 2003; Manzato, 2023); hence, it is not obvious that the instability (e.g., estimated by CAPE) has a direct proportionality to the storm probability or even to the storm intensity (Manzato et al., 2025).

Finally, severe convective weather events, particularly supercell thunderstorms and hailstorms, constitute a significant hazard and have accounted for the costliest natural disasters in recent years (Bowen et al., 2023). These phenomena pose substantial risks to populations, infrastructure, and sectors such as agriculture and transport. These issues illustrate how timely is the planning of the field campaign on Thunderstorm Intensification from Mountains to plains (TIM; see Fischer et al., 2025 for further details on the motivation of the campaign and its research topics). The campaign, led by the European Severe Storm Laboratory (ESSL), represents a first-of-its-kind pan-European campaign on severe convective storms aimed at obtaining coordinated and dense data on orographically driven storms, and is a key step toward improving warnings, forecasts, climate change impact estimation, and adaptation measures. The value of the campaign for Italy is indicated by the participation of several institutions, both from the academic and the operational community.

This paper represents a summary of the contribution that the Italian community could and is willing to provide to the forthcoming TIM campaign, planned in the 2027-2029 years. Section 2 presents the state of the art of severe convective weather research in Italy. Issues worth studying during the campaign are reported in Section 3. Section 4 describes which tools are available or would be necessary for better understanding the dynamics and microphysics of severe convective storms. Conclusions are drawn in Section 5.

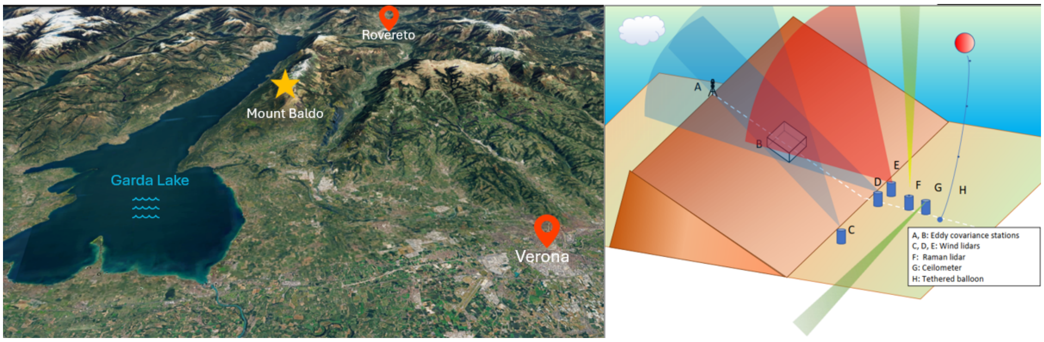

Figure 1: Geographical location of Monte Baldo (left; Imagery © 2025 NASA, Map data © 2025 Google); sketch of the experimental setup on the Monte Baldo slope during the TEAMx campaign (right).

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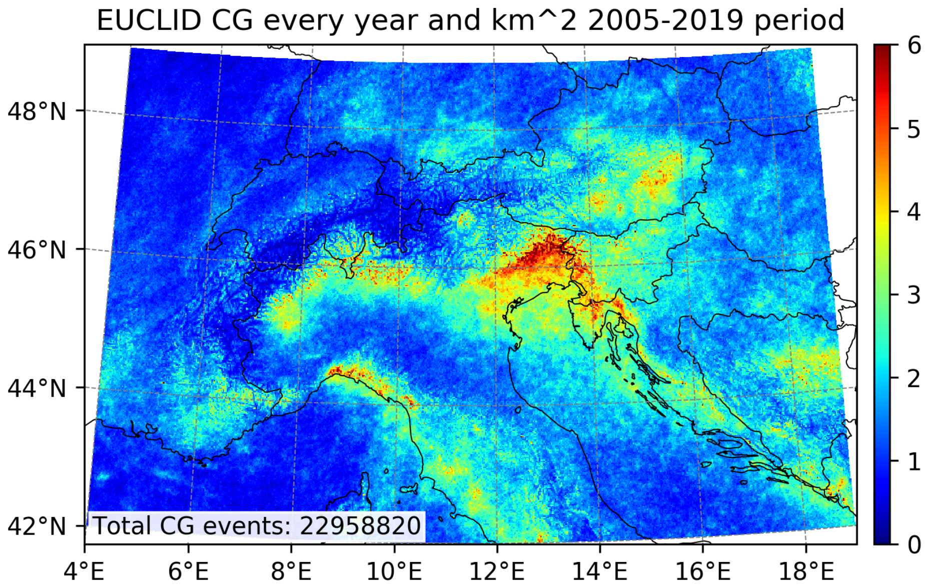

Figure 2: Spatial distribution of Cloud-to-Ground lightning (per km^2 yr) based on EUCLID data from 2005 to 2019 (adapted from Manzato et al., 2022a).

2. State of the Art

2.1 Northern Italy

The Liguria region, characterized by complex orography and proximity to the sea, every year experiences intense meteo-hydrological events, such as flash floods, severe thunderstorms, hail, downbursts and strong winds. These events are generally localized and typically develop in correspondence with the convergence between the southerly flow over the Ligurian Sea with the northerly cold outbreak from the Po valley across the gaps in the orography (Buzzi et al., 2014; Fiori et al., 2017). They can cause significant socio-economic impacts, occasionally even casualties, while their predictability is still quite limited. The available observations from the Regional Agency for the Environmental Protection of Liguria region (ARPAL), including a dense network of weather stations, enriched by open hardware ACRONETWORK stations (Loglisci et al. 2024), operational radars, and continuous satellite monitoring, combined with numerical simulation analysis, have highlighted the key role of orography, sea-breeze interactions and SST patterns in enhancing convective activity (e.g., Cassola et al., 2016, Meroni et al. 2018), but the understanding of small-scale processes remains limited. In particular situations to be further investigated, storms originating from mesoscale convergence over the Ligurian Gulf or northern Tyrrhenian Sea can move further inland in the Tuscan hinterland and, more rarely even downwind the main orographic barrier, even affecting the Emilia-Romagna region, as happened on 13-14 September 2015 during the devastating flash floods in Val Trebbia and Val di Nure (Segadelli et al., 2020).

In the Veneto and Friuli Venezia Giulia (FVG) regions, a series of particularly intense phenomena, such as supercells and intense convective systems, have occurred in the last decades. Remarkable examples are shown in Fig. 3: the EF4 Mira-Dolo tornado of July 2015 (Zanini et al., 2017); the violent downburst in Verona in August 2020; the recurrent summer hailstorms, which peaked in July 2023, when the European record for hailstone size was broken (De Martin et al., 2025a).

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Other severe weather events were directly or indirectly related to cyclonic activity, such as the famed Vaia storm of 2018 (Davolio et al., 2020; Sioni et al., 2023), the impressive "acqua alta" in Venice on November 12, 2019 (the second highest level in the historical record; Ferrarin et al., 2021; Miglietta et al., 2023), the intermediate-duration floods (12-24 hours long) over the pre-Alpine area near Vicenza that tested the efficiency of the recently implemented operational detention basins, and the back-building storms responsible for flash floods in eastern FVG in November 2025. A statistical study by the Regional Agency for the Environmental Protection of Veneto region (ARPAV) has identified a marked increase in high precipitation threshold exceedances during the last 30 years for what concerns the short and very short accumulation timescales (5 min - 12 hours), while no significant trend was found in extreme precipitations in FVG (Manzato et al., 2025). The increased interest in intense events has brought ARPAV to maintain a register of intense rainfall events and tornadoes in the region, as part of its weather forecasting practice. ARPAV continuously monitors these episodes with its ground-based high-resolution observational network, including over 300 hydro-meteorological stations, 2 C-band radars, 8 disdrometers, a 10-km temperature and humidity profiler, and a historical archive of images from installed webcams.

Overall, the Alpine region appears to exhibit increased hydrogeological sensitivity, emerging during several heavy downpours during the summer season in the form of recurrent debris flows. In fact, the increased frequency and intensity of extreme weather events (e.g., Dallan et al., 2022) resulted in a rise in hydrogeological risk and in the vulnerability of ecosystems and infrastructure. These phenomena, often characterized by strong spatial and temporal variability and very difficult to predict, are particularly impactful in urban areas (Gambini et al., 2025). For example, the Milan hydraulic node represents an emblematic case, where the Seveso, Olona, and Lambro rivers cause recurrent inundations in the metropolitan area, leading to widespread damage to infrastructure and urban mobility (Ceppi et al., 2022). Furthermore, wide urban areas (such as Milan) may alter the dynamics of local severe storms, by intensifying updrafts and shifting storm tracks (De Martin et al., 2025c), thus adding an additional level of complexity.

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Figure 3: Photos of recent severe weather events in northern Italian regions: supercell with downburst in Verona – hundreds of trees fallen in urban areas (August 23, 2020; top left); Mira-Dolo F4 tornado (July 8, 2015; top right; Photo: Alberto Gobbi); hailstorm (hailstone diameter: 16 cm) in Carmignano del Brenta (July 19, 2023; bottom left; Photo: "Associazione Meteo in Veneto"); flash flood in Meda due to severe rainfall in Brianza province (September 22, 2025; bottom right).

2.2 Central and Southern Apennines

While northern Italy has been the subject of several studies and some conceptual models are now available to identify conditions conducive to severe weather, the central and southern Apennine range remains largely under-researched, although they constitute a steep, coastal-proximal mountain range occasionally subject to heavy precipitation, strongly modulated in terms of timing and persistence by mesoscale circulations, land-sea contrasts and complex topography. In the Apennine setting, modest but steep relief modulates convective initiation by: (i) channeling low-level flow through gaps and valleys, (ii) forcing ascent on the windward flanks, and (iii) focusing near-shore convergence where the marine boundary layer impinges on the coastal range. The efficacy of these pathways depends on the synoptic flow, boundary-layer stability, shear, and sea-land thermal contrasts, which together set diurnal phasing and storm organization. The available literature clearly documents how the interaction between coastal orography and marine inflows over Italy prolongs event duration and shifts precipitation peaks relative to the upstream forcing (see Miglietta and Davolio, 2022, for a review), leading to intense inland flooding (Rosso and Ceppi, 2022).

Across the Apennines, orographic precipitation encompasses both cold-season events, driven by moisture transported from the sea (stratiform or embedded convection in the presence of long-fetch advection) and warm-season events, characterized by convection initiated by the orography, including hail-producing storms. Capozzi et al. (2023a) identified a limited set of recurrent heavy-precipitation spatial patterns for Campania region (southern Italy) that are systematically associated with synoptic types and the regional orography; importantly, such patterns occur in autumn-winter under long-fetch maritime moisture transport impinging on the mountain ranges, highlighting the key role of moisture-fluxes in organizing and sustaining heavy rainfall events (Fig. 4).

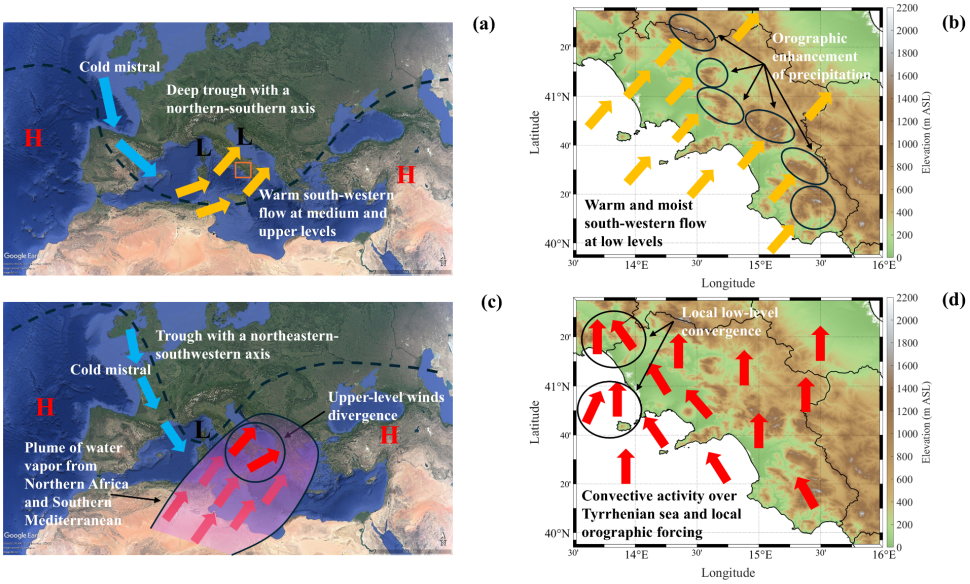

Figure 4: Schematic illustration of two of the six large-scale configurations associated with heavy-precipitation events in the Campania Region (southern Italy) identified by Capozzi et al. (2023a). Panels (a)–(b) show Pattern 1 (warm and moist southwesterly flow and orographic enhancement of precipitation along the main Apennine ranges); panels (c)–(d) represent Pattern 6 (convective activity over the Tyrrhenian Sea and the northern sector under local low-level convergence). In (a) and

(c), the black dashed line marks the approximate position of the 552-dam 500-hPa geopotential-height contour, while the orange box in (a) locates the Campania region, zoomed in b) and in d). Images credit: © Google Earth, Data Sio, NOAA, U.S. Navy, NGA, GEBCO.

2.3 Atmospheric Rivers

Atmospheric rivers (ARs) have emerged as one of the most relevant global drivers for extreme hydro-meteorological events in many areas of the globe. Defined as narrow corridors of enhanced horizontal transport of low-level moisture, ARs typically form over midlatitude regions pulling up water vapor charge also from subtropics and feeding precipitation systems in the areas where they make landfall and are forced to raise over the orography. Whilst the science of ARs is well developed in the US, where they have been recognized as responsible for extreme precipitation especially along the Pacific coast, only in the last decade the role of ARs has become evident over Europe (Lavers and Villarini, 2015). Over the Mediterranean basin, ARs were found relevant for recent extreme rainfall and major floods over southern Spain (Lorente-Plazas et al., 2019), southern France (Francis et al., 2022), the Dinaric Alps (Martinković et al., 2017), the eastern basin (Bozkurt et al., 2019) and over northern and central Italy (Davolio et al., 2020; Davolio et al., 2023; Sioni et al., 2023).

Focusing on the Alpine chain southern slopes, the presence of moisture transport, which may originate from either remote or local sources, is critical for the development of orographic rainfall and convection. Heavy precipitation often develops eastward of an advancing upper-level disturbance, a trough or a cyclone deepening over the basin. The latter is responsible for steering warm and moist low-level (unstable) air from the sea towards the steep slopes of the Alps and the Apennines (Miglietta and Davolio, 2022). At the mesoscale, precipitation systems are likely triggered by the direct orographic uplift or by the deflection or blocking action exerted by the orography (Miglietta and Buzzi, 2004), which can also renew convection triggering at the same location.

2.4 Tornadoes and downbursts

Italy is among the European countries with the highest tornado occurrence and intensity. Most Italian tornadoes fall within the categories of damage EF0 and EF2 of the Enhanced Fujita scale, but intense cases (EF3, EF4 or even EF5) have also been reported, as documented by the European Severe Weather Database (ESWD; Dotzek et al., 2009). Some climatological studies (Miglietta and Matsangouras, 2018; Avolio and Miglietta, 2022) have shown that the Italian areas most prone to tornado development include some southern areas (Ionian regions and Sicily), the Po Valley (in particular, its eastern part), and the Tyrrhenian coasts (Fig. 5). These events occur predominantly in autumn (in the southern regions) and summer (in the northern regions).

Some recent studies have improved our understanding of tornadic environments in Italy. The conditions typically identified include the presence of strong wind shear (especially in the low-level) and significant Convective Available Potential Energy (CAPE) (Ingrosso et al., 2020). In southern Italy, SST anomalies also play a key role (Miglietta et al., 2017a; Bagaglini et al., 2021; Avolio and Miglietta, 2021) as well as the convective initiation by the orography (Miglietta et al., 2017b). More recently, a conceptual model based on the proximity of three air masses with different characteristics has been proposed for the Po valley (De Martin et al., 2024), showing some similarities with the US Midwest tornadic environments, although at a much smaller spatial scale. Due to its small-scale, this feature was not identified earlier in reanalysis studies. A detailed analysis of a recent EF3 tornado in the same area reaffirmed the applicability of this conceptual model (De Martin et al., 2025d).

Significant field campaigns in Italy, focused on observations of high-resolution surface wind fields during thunderstorms, has been conducted using a wind monitoring network, which integrates ultrasonic anemometers, three LiDAR profilers, and one scanning LiDAR, installed in the commercial ports of the Ligurian Sea (Solari et al., 2012; Repetto et al., 2018). This system has captured numerous thunderstorm-related wind events over the past few decades (e.g., Burlando et al., 2017, 2018, 2020; Canepa et al., 2020; Solari et al., 2015; Zhang et al., 2018). Canepa et al. (2024) include a database of 29 thunderstorm wind records acquired by ultrasonic anemometers within the monitoring network. Several of these events were simultaneously captured by multiple instruments located within the same area, enabling spatiotemporal cross-correlation analyses and providing a depiction of different thunderstorm outflows. This level of spatial and temporal resolution makes the dataset unique in the national context.

However, in terms of direct measurements of thunderstorm outflows and their potentially destructive impacts on the ground, full-scale wind observations remain scarce due to the limited spatial and temporal extent of the phenomenon. When available, high-sampling anemometric records capture only a single, event-specific realization, shaped by both the intrinsic characteristics of the downburst (e.g., size, intensity, duration, and interaction with background flow) and the relative position of the measuring instrument with respect to the evolving phenomenon. Consequently, field data seldom provide a complete description of the spatial flow structure or of its temporal evolution, particularly when the parent storm moves relative to the sensor. In-situ measurements alone do not permit a quantitative reconstruction of the interplay between the various flow components that collectively define the downburst system. As a result, much of the research on downburst dynamics relies on laboratory-scale physical modelling and numerical simulations. Recent large-scale experimental campaigns have produced valuable datasets, enabling statistical analyses of the spatiotemporal evolution of downburst flows and their interaction with the near-surface PBL and the translating storm system . Subsequent experiments incorporated thermodynamic effects by imposing temperature differentials between the downdraft and ambient air, highlighting the key role of thermal gradients in shaping the downburst structure and dynamics (Canepa et al., 2025). Nevertheless, the quantitative influence of thermal processes in natural conditions remains largely unresolved.

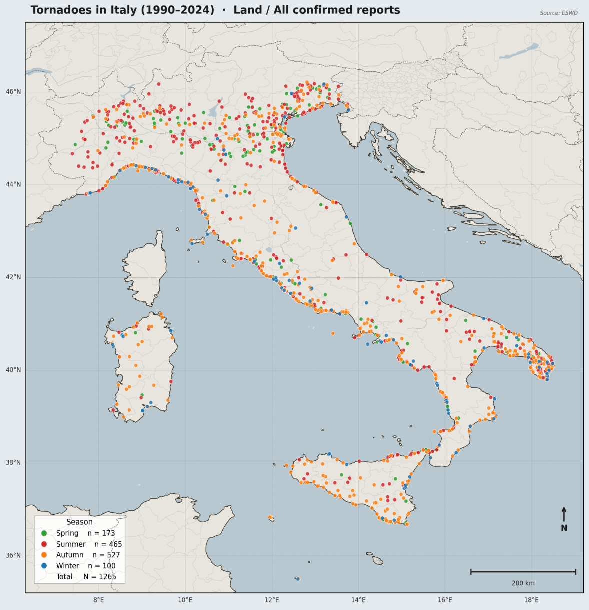

Figure 5. Map of selected Italian tornadoes crossing "land" for the period 1990–2024; different colors represent the seasons (data derived from ESWD).

2.5 Role of aerosols

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Aerosol particles play an important role in the climate by controlling the radiative budget of the atmosphere (aerosol-radiation interaction; ARI) and by directly modifying the microphysical properties of clouds (aerosol-cloud interaction; ACI). The high uncertainty of the latter leads to a limited consensus on the impacts of aerosol particles on precipitation, making microphysics parametrization in numerical models a critical issue (Stier et al., 2024).

Aerosols are the seeds upon which cloud droplets and ice crystals form. Their ability to act as ice-nucleating particles (INPs) or cloud condensation nuclei (CCN) regulate microphysical processes, e.g. increasing the number of liquid droplets (Twomey, 1977) or initiating cloud glaciation (Murray et al., 2021). However, the impact of ACI on cloud formation and precipitation is nonlinear (Zhao et al., 2024), leading to contrasting effects, invigorating or weakening microphysics effects at cloud base accelerating or delaying precipitation. Overall, the microphysical effect of aerosol on cloud formation and precipitation is ultimately controlled by atmospheric dynamics, being the complex interplay of aerosol and dynamics extremely sensitive to local perturbations (Stier et al., 2024).

Within the Mediterranean, climate-change induced desertification and heatwaves modify the local concentration of aerosols (e.g. Cristofanelli et al., 2013; Vogel et al., 2025), hence the availability of CCN and INPs. Even though numerical modelling studies correlate these aerosol perturbations with changes in convective systems (Ferrari et al., 2024), the inability of reconciling observations and modelling data complicates the attribution of observed changes to aerosol-cloud interactions (Stier et al., 2024).

2.6 Hail

Currently, there is considerable interest within the research community in hail over Italy for several reasons. While Italy has emerged as a hail hotspot in Europe over the last decade (e.g., Punge et al., 2017), the most recent hail climatologies show remarkable differences across the country. Some studies indicate a frequency peak over the foothills of Northern Italy (e.g., Giordani et al., 2023; Cui, 2025; Manzato et al., 2022b), while others show a maximum over the sea (e.g., Laviola et al., 2022; Kahraman et al., 2024), suggesting that further work is needed to clarify the spatial distribution of hailstorms. Furthermore, there has been growing awareness of the substantial economic damage caused by hail to crops, buildings, and vehicles (Púčik et al., 2019; Panosetti and Tomassetti, 2023). Extending hail climatologies to include economic hail damage in Italy —potentially involving insurance companies— is therefore encouraged, both to improve hail risk maps and to lay the groundwork for impact-oriented hail warnings.

2.7 Numerical weather prediction models and data assimilation

Despite the progress made in the model resolution and physical parameterizations, the forecast of convective events is challenging for numerical weather prediction (NWP) models because of the multitude of physical processes and scales involved (Hu and Franzke, 2020) and the intrinsic limited predictability of convection.

Improved model performance can be achieved by advancing the physics of the model and/or steering the model using observations, such as by applying data assimilation. The purpose of data assimilation (DA) is to accurately describe the state of the atmosphere using observations and a gridded data field coming from a NWP model (Kalnay et al., 2024).

Current weather and climate models are progressing towards ever finer spatiotemporal scales, which is largely due to the increased computational capabilities that have become available. In many cases, DA is applied at convective scales. Convection permitting DA refers to DA at regional scale with horizontal grid-length at around 1-4 km, where convection is explicitly resolved rather than parametrized. There are several operational systems around the world using convection permitting DA (e.g. Ballard et al., 2016). These systems provide improved nowcasts and short-term (0-24h) forecasts particularly suitable for convective storms (Milan et al., 2020).

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Several studies have been conducted over Italy focusing on the assimilation of different data sources, often at the convection resolving resolution, as radar (Gastaldo et al., 2021; Maiello et al., 2017; Lagasio et al., 2019b; Mazzarella et al., 2020), GNSS (Lagasio et al., 2019a; Torcasio et al., 2023; Faccani et al., 2005), lightning (Federico et al., 2024; 2026), weather stations (Maggioni et al., 2023), rain-rate (Davolio et al., 2017; Torcasio et al., 2024), among others. These studies used different DA techniques namely 3DVar, 4DVar, nudging, and Ensemble Kalman filter.

3. Open Issues

Observational networks in Italy are mostly managed at regional scale. Although some fields (e.g. precipitation), especially in northern Italy, are densely monitored, several challenges and significant limitations persist, due to sparse and heterogeneous observational coverage and reporting (e.g., for tornadoes and hail) and the complex topography.

For example, flash floods in small catchments are often poorly observed because of their rapid and highly localized nature. Existing observational networks may miss peak showers because measurements are either insufficiently frequent or too sparse to adequately cover the affected areas, and the accuracy of numerical models is not always satisfactory (Ceppi et al., 2023). These limitations, together with the lack of specific measurements needed to better understand convective initiation and development, make the need for a dedicated field campaign urgent. Some key issues are outlined below.

3.1 Convective initiation

The difficulty in predicting localized convective storms requires a better understanding of the local conditions leading to *convective initiation*. Although some recurrent patterns for heavy rain have been recently identified in Italy (e.g., Capozzi et al., 2023b; Grazzini et al., 2020, 2021; Iacomino et al., 2025), and the role of equilibrium and non-equilibrium conditions has been analyzed (Molini et al. 2011), the characteristics of the synoptic and mesoscale conditions associated with other severe storms should be clarified, identifying the observational/model-based precursors for intense convection in the different regions. This investigation will allow improving the capacity of forecasting severe thunderstorms and combined with observational analysis, should help identify the typical trajectories followed by the storms in their evolution.

Within the framework of orographic convection in the Alpine areas, the experience gained during the TEAMx–DECIPHER campaign has emphasized the need to better understand the PBL mechanisms leading to convective initiation and, in particular, any mechanism that may produce vertical motion sufficient to lift high-θ_e air mass to the level of free convection. In particular, Manzato et al. (2022a) provided the first climatology of convective initiation over northern Italy based on lightning strikes.

The campaign stimulated several scientific questions, both methodological and operational: which dynamic and thermodynamic preconditions govern the initiation and lifecycle of *orographic cumulus clouds*? which atmospheric and terrain factors govern their location and persistence? how do local slope/valley circulations, atmospheric stability, and direction of the synoptic flow interact to determine the stationarity or propagation of convective clouds?

Different initiation mechanisms may favor the development of convective systems, such as convergence induced by local breeze systems, land-coast gradient boundaries, sunrise-sunset induced thermal gradients, moisture gradients due to advection (e.g., from the Adriatic Sea). In addition, cold-pools, bores and gravity waves may trigger new convective events (the so-called “secondary convection”). However, it is difficult to discriminate which initiation mechanism is effective. This issue is related to a key question: why on days with similar instability and “weather-type” conditions, do severe storms sometimes occur and sometimes not? This point should be analyzed for heavy rain events both in the convective season (summer), in the period characterized by “strong flux of rain” (autumn), and in the transition between the two regimes (Manzato, 2007a; Davolio et al., 2016). In the past, Manzato (2007b) and Manzato et al. (2019) developed a neural network–based scheme to perform a multivariate analysis for forecasting the occurrence and intensity of rainfall events using multiple sounding-derived indices in the Friuli-Venezia-Giulia region. Building on this work, the present research project aims also to better understand whether a relationship between instability indices and severe precipitation that can lead to flash flood episodes may exist. Given the limitations identified in this kind of studies, new aspects should probably be incorporated in research, in particular the role of aerosol concentration and of warm rain in enhancing storm dynamics and rain efficiency. At a later stage of development, another issue is the transition of convective storms from mountains to plains, which seems neither well understood from a storm-dynamics perspective nor generally well predicted by numerical models (Fischer et al., 2025).

The presence of the *Mediterranean Sea* introduces an additional degree of complexity, making the prediction of convective initiation and evolution particularly challenging, especially in the case of stationary or back-building convective systems, as identified in some heavy rain events in the Liguria region (Cassola et al., 2016). A better understanding of the role of SST anomalies has implications not only for a better detection of observed events, but also in terms of reduction of false alarms.

3.2 Role of aerosols

Variations in *aerosol properties* can dramatically affect convective storms as they may: modify droplet activation and warm-rain formation; shift the height and temperature of primary glaciation; influence secondary ice processes such as rime-splintering; determine the number and type of ice particles, graupel, and hail embryos; affect latent heating profiles, updraft strength, and storm intensity; control the rate and efficiency of precipitation development; modulate storm electrification and lightning activity. Extreme convective storms often form in environments characterized by strong horizontal and vertical aerosol gradients—for example, dust intrusions, biomass-burning plumes, polluted boundary layers, or marine aerosol inflow. The ability to detect these gradients over large areas is essential for interpreting storm initiation and spatial evolution.

Unfortunately, the understanding of *microphysical processes* leading to hail formation and extreme precipitation is still incomplete. Despite recent progress, wide observational gaps limit our knowledge of aerosol-cloud interaction and their influence on Mediterranean severe storms: do aerosols act as CCN and/or as INP? Do they promote the formation of rain and/or graupel, and if so, through which mechanisms and relationships? Recently, the role of aerosols was identified in modulating the precipitation in Mediterranean areas exposed to Saharian dust advection (e.g., Ferrari et al., 2024); however, the generality of these results is still uncertain and requires further investigation.

Along similar lines, Napoli et al. (2022) showed through cloud-permitting simulations over the Great Alpine Region (GAR) that the lifetime of low-pressure-system clouds and orographic clouds is generally increased at high levels of aerosols, while convective clouds (typical of the summer season) can decrease at high levels of pollution as a result of the reduction in strong updrafts associated with an increased air column stability. All in all, it is crucial to study observations related to the 3D distribution of aerosol in connection with convective initiation (e.g., Brennan and Wilhelm, 2025 for hail in Switzerland, have identified an "optimal concentration" of aerosol to maximize hail probability).

A central challenge is to disentangle aerosol-driven microphysical effects from dynamic forcing. Accordingly, open questions are: what are the background aerosol states (composition, CCN/INP abundance, vertical structure) that do not promote storm intensification, and how do they differ from perturbations associated with Mediterranean severe convective weather? Under which dynamical and thermodynamic conditions (CAPE, shear, humidity, synoptic forcing) do

Mediterranean aerosol perturbations transition from weakening to invigorating convective storms? How can in-situ observations be used to attribute observed storm variability to aerosol–cloud interactions rather than to meteorological dynamics alone?

3.3 Convective storm changes in future climate

The potential changes in storm frequency and intensity under future climate scenarios is an open question that is still subject of strong debate in the scientific community. While there are strong evidences that potential instability increased in recent years (Cavalleri et al., 2026), and will be enhanced in a warmer climate, the signal in rainfall observations from regional network is not so clear (e.g. Manzato et al., 2025 found no significant trend of precipitation during the convective season), emphasizing the need for the analysis of multi-decadal trends in different data to detect possible shifts in precipitation regimes (Mazzoglio et al., 2025). Conversely, attribution studies based on pseudo-global warming simulations have clearly identified the role of a warmer atmosphere and sea in enhancing the intensity of severe convective events (Gonzalez-Aleman et al., 2023; Calvo-Sanchez et al., 2026). The fact that the observed super-Clausius–Clapeyron scaling of extreme precipitation may be explained by a shift from stratiform to convective rain type (Da Silva and Haerter, 2025; Haslinger et al., 2025) opens new questions on the role of climate change in modifying the precipitation formation pathways (Hawkins et al., 2023). In this framework, and following recent evidence for the Apennine areas that the intensity and frequency of heavy precipitation events are increasing, particularly during autumn (Capozzi et al., 2023b), it is worth investigating how this result applies to different types of precipitation (e.g., autumn-winter orographic rainfall episodes driven by long-fetch maritime moisture transport in the Apennines).

Some studies report a marked increase in large hail events in the Po Valley (Battaglioli et al., 2023), others over the Alps (Cui et al., 2025), while in the plain of Friuli Venezia Giulia region, located in north-eastern Italy, no significant hail trends were observed from 29 years of data, collected by a network of about 300 hailpad stations, except for hail size (Manzato et al., 2025). These inconsistencies may ultimately be related to the scarcity of systematic ground-based hail observations, a limitation that could only be addressed through an extensive and dense network of automated hailpads (e.g., Kopp et al., 2023) and disdrometers (Jameson et al., 2015).

3.4 Conceptual models for central Italy

While conceptual models for precipitation have been developed in the Alpine areas, for other regions specific conceptual models need to be developed. The open issues include: (i) better investigating the convective initiation along the Adriatic/Tyrrhenian flanks, discriminating between terrain-forced convergence versus synoptically-forced cases; (ii) identifying under which combinations of SST anomalies, stability and shear, orographic channeling most effectively trigger convection and favors hail growth in central Italy; (iii) assessing the transferability of hail proxies calibrated in other Mediterranean regions, such as the Alps and northeastern Italy (Manzato, 2012; Giordani et al., 2024), to the interior Apennine basins with different relief scales and coastal geometry.

3.5 Atmospheric rivers and severe convection

The role of *ARs* in heavy precipitation has been recently disclosed in a climatological framework over northern Italy (Davolio et al., 2025), as well as in case study analyses (Davolio et al., 2020, Sioni et al., 2023), providing evidence of a strict connection between extreme organized water vapor transport and extreme events affecting both the Alps and the Apennines (Grazzini et al., 2020). Conversely, it is well known that the thermodynamic characteristics of the impinging moist flow are fundamental to determine the interaction with the orography (Miglietta and Rotunno, 2014, among others), thus the intensity and distribution of rainfall.

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In this context, ARs have been so far described as characterized by moist-neutral stratification in the lowest layers (~ 3 km) of the atmosphere, as observed from dropsondes released during many field campaigns over the Pacific (Ralph et al. 2020). This weak stability makes AR prone to rise over mountain barriers, producing orographic precipitation where convection is likely embedded, which can greatly amplify the amounts of precipitation. However, ARs associated with severe organized convective storms, over or at some distance from the orography, have been rarely documented. For example, Moore et al. (2012) analyzed a heavy rainfall event that occurred over the Central US, where an AR fed two quasi-stationary MCSs, linearly organized and exhibiting back-building mechanisms. Recent events affecting the Mediterranean basin revealed the presence of intense convection associated with ARs, as in the case of the dramatic flood in Valencia in October 2024 or the record-breaking rainfall over Liguria and Piedmont in October 2020 (Davolio et al., 2023). Therefore, given the availability of various AR datasets, both global and Mediterranean-specific, it is timely and worthy to investigate whether, and to what extent, ARs are associated with severe convective storms that develop near the Alpine chain during different seasons.

3.6 Tornadoes and downbursts

Significant limitations persist in monitoring and predicting rapidly evolving storms, such as tornadoes or downbursts, hence raising key challenges. These include: i) sparse and heterogeneous observational coverage, including radar gaps and non-uniform scanning strategies, that limit the monitoring of mesocyclones and small-scale storms; ii) underreporting and inconsistent intensity classification; iii) the intricate geomorphology of Italy and the Mediterranean, which can enhance or hinder small-scale circulations, including sea–land and orographic interactions; iv) the absence of tornado-specific forecasting or warning systems in Italy, as discussed in Miglietta and Rotunno (2016).

While some progress has been made in identifying the tornadic environment (Bagaglini et al., 2021; De Martin et al., 2024), more attention should be paid to radar patterns associated with severe convection. A climatology and a systematic analysis of the environments conducive to downbursts is also missing, although they represent a significant cause of damage in some Italian regions (Burlando et al., 2025). Future advances in downburst understanding will require integrated observational networks combining high-frequency anemometry, Doppler LiDAR and radar systems, and thermodynamic profilers capable of resolving temperature, humidity, and pressure gradients at fine spatial and temporal scales. The coupling of these measurements with numerical weather prediction (NWP) models and Computational Fluid Dynamics (CFD) simulations could enable real-time reconstruction and nowcasting of downburst structures.

3.7 Hail

Understanding of the physical processes leading to hail formation remains limited, particularly for giant hail events (Allen et al., 2020). In Italy, this issue is further complicated by complex topography, as recently demonstrated by De Martin et al. (2025a) for northeastern Italy, and Ricchi et al. (2023a, 2023b) for a giant hail event in Central Italy, where the Apennine topography, together with SST anomalies, guided the low-level flow and focused coastal convergence, effectively preconditioning convective initiation. This uncertainty has important implications. For instance, why does large hail appear to be a rare phenomenon along the Ligurian and Tyrrhenian coasts, despite the very high frequency of severe thunderstorms? Conversely, why is large hail so common along the Alpine foothills? Uncertainty in the mechanisms leading to large hail production also affects hail forecasting. For example, how important are environmental kinematics with respect to thermodynamics? Generally, hail is not explicitly forecast by regional and national weather services and is generally treated as one of several possible hazards associated with severe storms. While this approach is partly justified by the uncertainty in hail prediction, other weather services (e.g., NOAA in the United States) issue daily hail outlooks, suggesting that such forecasts are feasible and could be tested during the TIM campaign. Notably, OSMER-

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ARPA FVG mentioned in their forecast for 24 July 2023 the possible occurrence of severe hailstorms, a few hours before a record-breaking hail event occurred.

Beyond direct hail observation and forecasting, substantial effort is currently devoted to estimating hail size using remote sensing, like radar data (Allen et al., 2020; Areggeret et al, 2025). An effective hail size detection algorithm, combined with a tracking algorithm, could represent a powerful tool for early warnings of severe hailstorms. Regional weather services in Emilia-Romagna and Piedmont are testing several algorithms for this purpose (Fornasiero et al., 2024), and the data collected during the TIM campaign could significantly support their calibration.

3.8 Numerical weather prediction models and data assimilation

As stated, there are some publications over Italy addressing the problem of DA at the convective scale. However, there are many challenges requiring further work and the TIM campaign can help to cope with some of them: i) quantifying the observation impact of different data sources to guide future observing network design for the prediction of convection; b) quantifying the impact of a background correlation matrix, which is aware of the "error of the day", compared to climatological approaches in order to better designing DA system for the convective scale; c) using different observations at high spatio-temporal resolution to consider explicitly the correlation among observations; d) refining the use of currently available observations, and assimilating new observation types.

4. Required Tools

Observational tools and modelling techniques available nowadays make it possible to better investigate at unprecedented resolution severe convective weather features.

4.1 Satellite data

Satellite observations are limited by their relatively coarse space and time resolution; however, the integration of geostationary and polar data remain a privileged tool to explore and monitor storm evolution, from pre-storm conditions and convection initiation to the mature and decaying stages of the systems. The data provided by the new satellite constellations (e.g., Meteosat Third Generation, MTG), including vertical profiling, represent a tremendous opportunity to better characterize the environment where convective storms develop and to track their evolution. In addition, flash observations from the Lightning Imager onboard MTG are very useful to identify, track and forecast convective storms.

New satellite techniques are available to identify and monitor hailstorms. The Multi-sensor Approach for Satellite Hail Advection (*MASHA*) is a new multi-instrument blended technique conceived for real-time detecting of hail-bearing clouds. MASHA (Fig. 6) identifies hail clouds from satellite measurements and monitors the evolution of hail-bearing systems every 5 min by combining the strength of the MicroWave Cloud Classification-Hail (MWCC-H) method, which detects hail through the whole Global Precipitation Measurement (GPM) sensor constellation (Laviola et al., 2020a,b), with the high temporal rate of the Meteosat Rapid Scan Service (MSG-RSS). MASHA has been applied to various case studies demonstrating strong capability in identifying severe events and high robustness to detect small-scaled hailstorms in mountain catchments. These results open new perspectives for investigating hailstorms and hydro-meteorological events in mountain areas, whereas traditional methodologies often miss events or underestimate their severity. Although further experiments are needed, MASHA's performance paves the way towards pseudo-operational applications in support to hailstorm nowcasting and assimilation in regional numerical weather predictions and appears mature for application during the TIM campaign.

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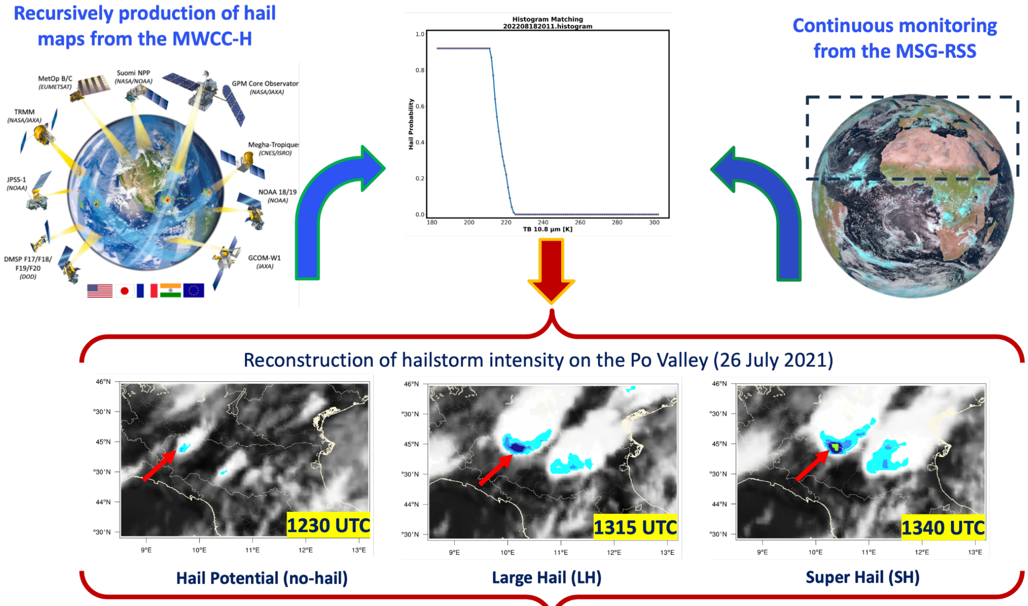

Figure 6: MASHA conceptual scheme (top images; Credit: NASA and EUMETSAT) and highlights of hailstorm evolution affecting Northern Italy on 26 July 2021 (bottom bracketed images).

4.2 Radar

Investigating convective initiation requires high-temporal resolution observations of the vertical velocity and moisture distribution in the lowest part of the troposphere (first 2-3 km). *Doppler radar* wind data with overlapping scan domains (at least every 5 minutes) would be necessary to estimate the *vertical* velocity spatial distribution using the classical continuity equation method (Dual-Doppler Analysis, DDA) or more modern techniques (e.g. Lopez-Carrillo et al. 2011, Tsai et al. 2025). For northeastern Italy, these techniques can be applied to the Loncon and Fossalon C-band Doppler radars. In the Emilia-Romagna region, an X-band radar will be soon installed and two C-band radar sites updated.

The Italian Civil Protection Department (DPC) expressed its willingness to join the TIM campaign, being particularly interested in analyzing the ground impact of severe convective storms and in integrating the damage surveys with radar data. A mobile X-band radar (2m high antenna) may be made available for the campaign but requires power supply stations in the target areas and some funds to assure the transport of the instrument. Also relevant for the campaign will be a radar situated on mount Zoufplan at 2000 m height, at the border with Austria.

The recent installation of two X-band dual-polarization radars in the Lombardy Region (Desio and Flero) aims to strengthen the regional monitoring network and enhance nowcasting capabilities using machine learning models (Franch et al., 2025). In addition to supporting operational forecasts (Xu et al., 2025), these radar-based estimates can serve as inputs for hydrological models, whether physically based and spatially distributed (hybrid systems) or entirely AI-driven (full AI systems). Consequently, integrating AI-based radar nowcasting with hydrological models represents a significant advancement in improving the effectiveness of operational warning systems and the dynamic management of structural mitigation measures, providing reliable and accurate short-term forecasts, particularly for summer convective events (Ceppi et al., 2025).

AEROLAB (AERosol mObile LABoratory) is a CNR-ISAC mobile platform designed for deployment in remote and non-instrumented areas for the study and characterization of atmospheric particulate matter through in situ sampling. AEROLAB is housed in an ISO10 container, certified for operation also on-board research vessels, temperature-controlled, and equipped with dedicated sampling lines for multiple instruments. The remote sensing operational observational capability of the mobile platform consists of a co-located Doppler wind lidar, a 35-GHz cloud radar, and a lidar, enabling an integrated characterization of convection-relevant processes from the surface layer to the cloud column. Together, the suite links aerosol structure, inflow kinematics, and near-cloud vertical motions to the cloud and precipitation response, enabling process studies and model evaluation of triggering, microphysics–dynamics feedbacks, and aerosol-mediated convective intensification.

4.3 Integration of remote sensing and surface data

A possible correspondence between severe storms and ARs can be identified based on the exploitation of satellite analysis and ground-based observations. Being characterized by large-scale moisture transport, ARs can be identified using analysis fields and detection algorithms. However, to describe precisely the low-level thermodynamic profiles of the impinging moist flow and infer the precipitation characteristics, the availability of on-demand *radio-soundings*, *dropsondes* and vertical moisture/wind measurements, including weather *drones*, especially upstream of convection, would be critical. Additional instruments, like *optical lidar* and powerful *wind profilers*, which have been extensively employed during the TEAMx campaign, should monitor the PBL at high-resolution, and the low-level wind, including its vertical component.

A substantial upgrade of in-situ observations is also needed, mainly in areas which have been excluded from the mainstream scientific interest, such as the Apennines. Dense, elevation-stratified *raingauges* with ≤10-min logging along coastal-to-ridge transects and windward crests should be complemented by a disdrometer network (Adirosi et al., 2023) to resolve drop size distributions, phase and fall speeds in mixed-phase and convective events. An extensive *hail monitoring network is* also necessary to document occurrence, size spectra and kinetic energy, ideally co-located with disdrometers for cross-validation.

4.4 Aerosol and cloud in-situ observations

ACI in-situ observations are rarely coordinated with large scale dynamic campaigns (Kunz et al., 2022). The Italian contribution to TIM aims to provide systematic observations of both aerosol properties and cloud microphysics at the WMO/GAW observatory of Monte Cimone (CNR-ISAC), a facility representative of the Mediterranean troposphere. However, without vertical profiles of wind, stability, humidity, and aerosol distribution (Fig. 7), it remains impossible to separate microphysical aerosol effects from dynamical forcing. Implementing remote-sensing and profiling capabilities in parallel to in-situ aerosol-microphysical observations during the TIM campaign is therefore essential to enable robust attribution of aerosol impacts on Mediterranean severe storms.

Airborne platforms are the only way of providing vertically and horizontally resolved observations of aerosol properties, thermodynamic structure, and cloud development in the vicinity of convective systems. To address this need, we propose the integrated deployment of two Italian research aircrafts: the SkyArrow ERA and the Piper Seneca III in coordination with aerosol remote sensing (Lufft CHM – Nimbus 15k).

Used in combination, the Cimone observatory and the two mobile platforms may characterize the environmental conditions from the surface to the mid-upper troposphere with complementary measurements. This yields a 3D, multi-scale picture of the storm environment over a wide geographic domain, capturing horizontal gradients in aerosol concentration, shifts in aerosol types, thermodynamic stability, moisture and temperature gradients, all of which are critical for convective initiation and strongly modulate the spatial evolution and intensity of convective storms.

5. Conclusions

The TIM campaign offers a unique opportunity to improve our understanding of severe weather in Italy. This objective needs, however, a fine data coverage, which includes: high-resolution dual-polarization radars, with short scan times, and improved overlapping coverage for storm detection and tracking; integration of high-frequency satellite and radar data to support effective nowcasting; dense networks of rain gauges and hydrological sensors for real-time monitoring of flash floods; radiosondes and weather drones to better understand the local conditions favorable to deep convective initiation; convection-permitting numerical limited-area models, either deterministic or probabilistic, potentially combined with advanced convective-scale data assimilation methods, providing severe convection indices as outputs to give sufficient guidance in forecasting localized severe convection and in concentrating the observational capabilities in specific areas; post-event damage survey analysis techniques for correlating storm dynamics and ground impacts; development and improvement of nowcasting algorithms in identifying and reproducing the dynamics of propagating, stationary and back-building systems, including the use of data-driven AI algorithms.

The national radar reflectivity mosaic, of which we will encourage the full integration in the OPERA European mosaic, may be combined with the data from the available mobile radar and (hopefully) from weather drones (Leuenberger et al., 2020), representing a great opportunity to discover signatures and monitor the detailed evolution of severe weather directly in the areas affected by the most intense events, solving the weaknesses over complex terrain, due for example to radar beam blocking. The recent development of AI methods paves the way to new applications, in terms of both nowcasting and forecasting capabilities, and of pattern-recognition tools trained on radar, satellite, and reanalysis datasets. Finally, the campaign can be crowdsourced, using the platforms where weather amateurs already share the information in real-time (e.g., PRETEMP, De Martin et al., 2023, and Meteonetwork, Giazzi et al., 2022).

The proposed dual-aircraft strategy will allow, for the first time in Italy, to deliver one of the most comprehensive environmental characterizations ever obtained for European deep convective storms. This combination will allow to directly link aerosol spatial gradients to microphysical evolution (glaciation, hail, precipitation); to improve storm-scale modelling, especially microphysical parameterizations; to advance the understanding of aerosol–convection coupling, a major climate uncertainty. The dedicated airborne measurements, combined with the data from the observatory of Monte Cimone, offers a unique opportunity to better investigate the troposphere during severe convective events and to improve our understanding of the role of aerosols in enhancing or reducing severe storm activity.

Therefore, we believe that the TIM campaign, under the coordination of ESSL and the involvement of many institutions across Europe, may represent a tremendous boost for: (i) moving ahead the understanding of severe weather over Italy; (ii) improving the monitoring and forecasting capabilities; (iii) creating more comprehensive, and generate detailed and (iv) accurate statistics for the intensity and distribution of severe convective events, which is partially missing over Italy (e.g., downbursts); enhancing resilience of the population.

Finally, the communication activities planned aside the campaign should be able to increase the awareness about severe weather in the framework of climate change and to explain to the population how to deal with alerts. While the recurring floods over Italy in the last few years have surely improved the situation and made clear the need to adopt more precautionary behavior, unfortunately public education on severe convection storms is still limited, and there is a long way to go to reach an acceptable level.

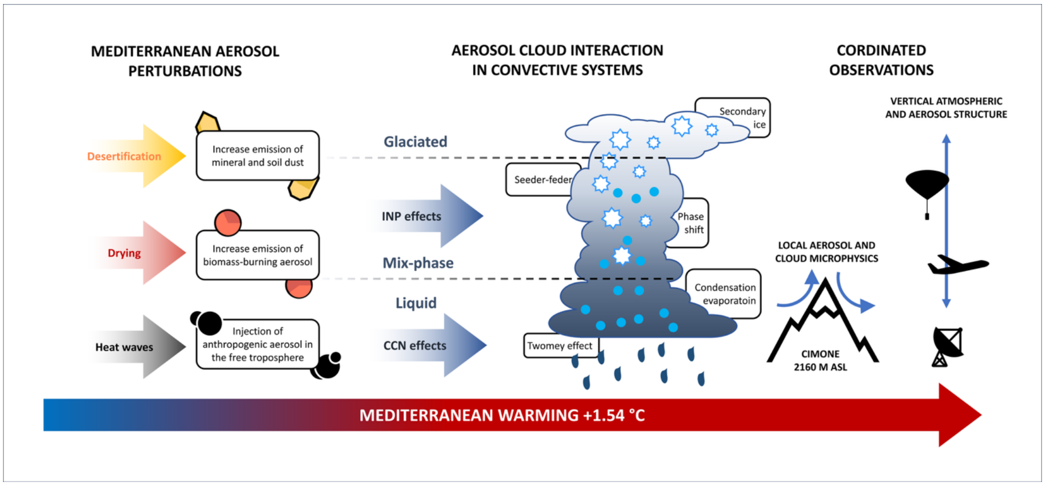

Figure 7. Schematic representing the aerosol cloud interactions (ACI) under the warming scenario in the Mediterranean. The cloud condensation nuclei (CCN) and ice nucleating particles (INPs) trigger different processes during severe storm development. To isolate the ACI contribution, observations of aerosol and cloud microphysics must be coordinated with vertically resolved dynamics observations.

Data availability

Not relevant for the present paper.

Authors contributions

All Authors contributed to the writing of the paper.

Conflicts of interest

The contact author declars that none of the authors has any competing interests.

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