Invited perspectives: Thunderstorm Intensification from Mountains to Plains

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Abstract. Severe thunderstorms are among the most damaging and impactful weather phenomena. In Europe, notable clusters occur in the vicinity of complex terrain. These areas not only experience frequent thunderstorms but also show a strong climate change signal with an increasing storm frequency. Despite the relevance of the subject, our understanding of severe convection in complex terrain, particularly in a changing climate, remains incomplete. This ~~review~~ White Paper presents the current state of the research on thunderstorms in complex orography, covering storm severity, modification of pre-storm environments, convection initiation, storm-scale interactions with complex terrain, impactful hazards, numerical modeling and forecasting, climatologies and climate change signals, as well as innovative storm observations. Highlighting the gaps in our understanding, this review underscores the need for a coordinated European field campaign on Thunderstorm Intensification from Mountains to Plains (TIM). Initial plans for the TIM campaign built by participating authors and institutions of this article are briefly outlined. Obtaining coordinated and dense data on orographically driven storms is a key step toward improving warnings, forecasts, future climate projections, and adaptation measures.

1 Introduction

Severe convective storms (SCS) with hail, flash floods, ~~hail, severe~~ wind gusts, lightning, and tornadoes cause a significant and increasing amount of damage across Europe and other mid-latitude regions ~~(e.g., ?)~~(e.g., SwissRe, 2024). In 2023 alone, a new record hail size was set for Europe with 19 cm (ESSL, 2023c) while in the US the insured loss from severe convective storms reached 60 billion USD, thereby also setting a new record and dominating the global total loss from Natural Catastrophes (Bowen et al., 2024). These facts highlight the importance of research on all aspects of severe convective storms to better understand where and why these hazards occur.
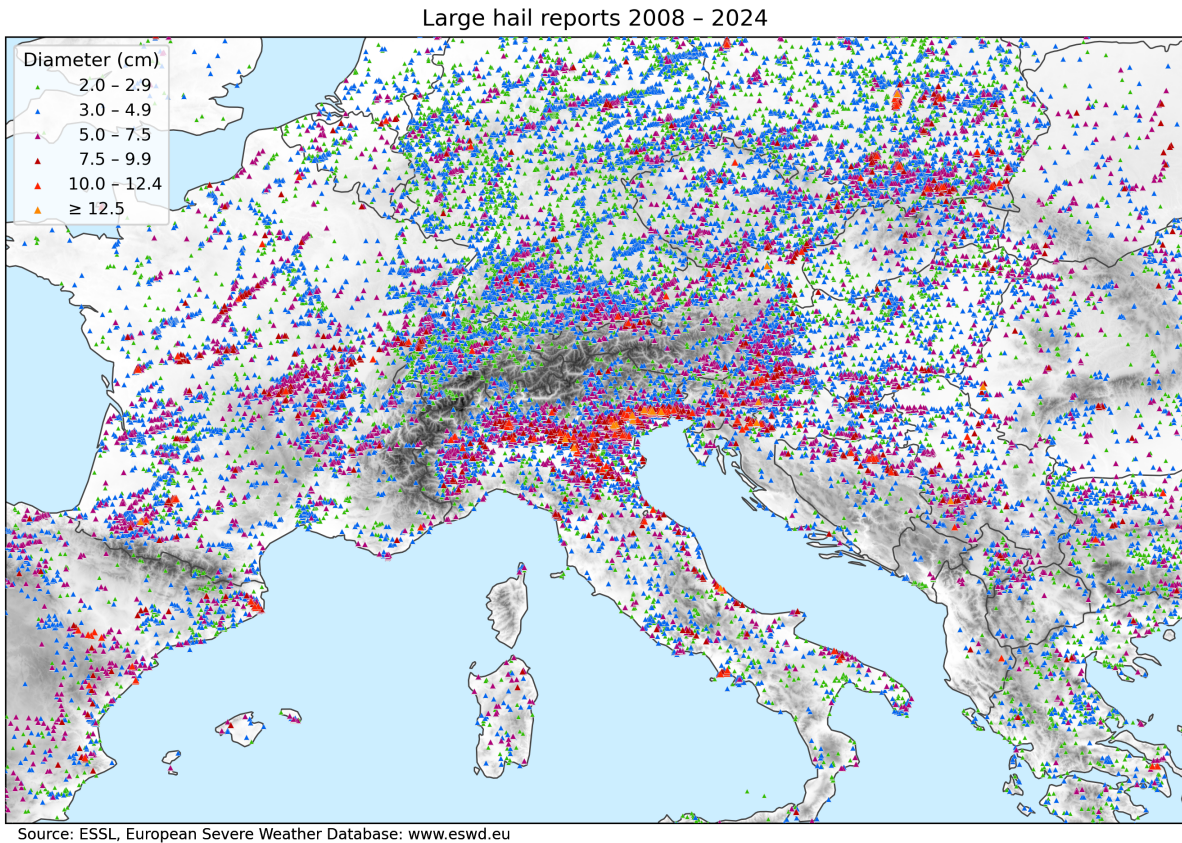
Figure 1. Severe hail reports between ~~2008-2023~~ 2008-2024 in the European Severe Weather Database (ESWD; accessed 10 March 2025). The topography is qualitatively underlayed in gray with darker shading indicating higher terrain. For more topographic detail and the locations of partner institutions see Fig. 7.

Reports of severe weather in the European Severe Weather Database ~~(Dotzek et al., 2009, accessed 10 May 2024)~~ (Dotzek et al., 2009)

20 suggest that particularly severe ~~convective storms are more~~ thunderstorms are most frequent over the flanking slopes of mountain ranges and the plains that straddle them~~rather than directly over the mountains~~. As an example, Fig. 1 shows the clustering of severe hail reports north and south of the Alps and predominantly on the eastern or northeastern flanks of lower mountain ranges ~~. This pattern~~ (the reader may skip ahead to Fig. 7 for more topographic detail and regions of interest). This clustering of reports is supported by indirect but spatially ~~uniform~~ less population-biased measures of storm severity than reports, such as

25 overshooting storm tops (Punge et al., 2017; Giordani et al., 2023), lightning frequency (e.g., Manzato et al., 2022b), and radar-based climatologies ~~in individual countries (e.g., Kaltenboeck and Steinheimer, 2015; Punge and Kunz, 2016; Wapler, 2021; Schröer et al.~~ (e.g., Kaltenboeck and Steinheimer, 2015; Punge and Kunz, 2016; Wapler, 2021; Fluck et al., 2021; Feldmann et al., 2023). The same geographic regions ~~include highly-vulnerable population centers and are projected to experience the strongest increases in severe weather occurrence~~ show a strong past and projected increase in SCS prone atmospheric conditions as a result of
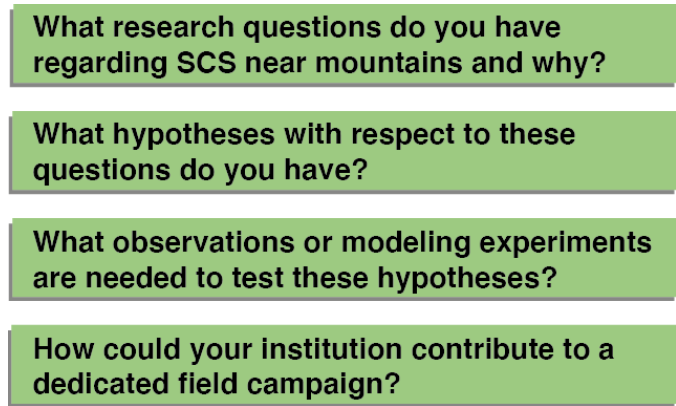
Figure 2. Questions from the White Paper survey conducted for this article with the European partner institutions listed further below.

30 global warming (Púčik et al., 2017; Rädler et al., 2019; Battaglioli et al., 2023). ~~Thus, an important question arises: Why are~~ In addition, many of these parts of Europe are highly vulnerable because of dense population or specialized agriculture (e.g., Púčik et al., 2019). Thus, there is both a need and an opportunity to study SCS in these regions.

One key question in this regard is why storms in the vicinity of ~~mountain ranges more severe?~~ European mountain ranges are more severe. As reviewed in section 2.1, there are several possible explanations in the literature. However, our understanding

35 of thunderstorm dynamics and mesoscale atmospheric processes is still incomplete. One reason is that observational datasets to validate existing theories ~~in different regions and scenarios~~ are scarce and, where available, distributed across many institutions and data archives.

~~Questions from the White Paper survey conducted for this article with the European partner institutions listed further below.~~

This lack of understanding and of shared data is echoed throughout the research field of severe convective storms. As

40 basis for this article, the European Severe Storms Laboratory (ESSL) conducted a survey with institutions in the European atmospheric science community, asking for their perspectives on the most crucial research topics on severe convective storms near mountains (Fig. 2). The contributors to this survey also took part in the writing of this article and are listed in the extended Co-author section. The survey outcome was a pool of over 40 research questions, which are sorted by topic and discussed in detail in section 2. A recurring theme in the responses is that a better understanding of the physical processes controlling

45 severe convective storms and their impacts is needed. Public authorities, research institutions, the aviation industry, and the reinsurance sector share the need to better estimate the frequency, magnitude, and predictability of severe weather.

Presently, a wealth of new sensors and data types is emerging to cater to these needs, ~~including next-generation high-resolution satellite data from~~ for example the Meteosat Third Generation satellite programme (Holmlund et al., 2021), numerical modeling within the DestinE project (Wedi et al., 2022) and the proliferation of polarimetric Doppler radars across Europe (Saltikoff

50 et al., 2019). Validation of these datasets is key, and requires that they are shared among scientists with the least possible restrictions. This validation is especially important near mountain ranges, not only because of the high severe weather frequency

(Fig. 1), but also because the lack of observations of basic meteorological parameters in the boundary layer and in complex terrain[1] is critical to advance forecasting and nowcasting skill (Bojinski et al., 2023).

~~The~~ This prominent need for shared data and research~~on severe storms~~, especially near mountains, can partly be explained
by the prevailing focus of past field campaigns either on thunderstorm dynamics away from mountain ranges *or* on terrain influences on the atmosphere but not on the scale of individual ~~severe~~ storms. For instance, several large field campaigns in the United States, such as VORTEX1/2/SE (Rasmussen et al., 1994; Wurman et al., 2012), PECAN (Geerts et al., 2017), TORUS (Houston et al., 2020), PERILS (Kosiba et al., 2024) and TRACER ~~(Jensen et al. 2024)~~ (Jensen et al., 2022) led to advancements in our understanding of thunderstorm dynamics, microphysics, and processes leading to severe weather. ~~Meanwhile,~~
Convection-focused campaigns in Europe such as Swabian MOSES (Kunz et al., 2022) and LIFT (Kunz et al., 2024) were relatively small. Meanwhile, larger convective-season field campaigns in ~~the Alpine region~~mountainous regions, such as MAP (Bougeault et al., 2001), COPS (Wulfmeyer et al., 2011), HyMeX (Ducrocq et al., 2016) and, currently, TEAMx (Rotach et al., 2022), ~~greatly~~ improved numerical models and process understanding with respect to large-scale orographic flow, boundary-layer exchange processes, autumn convective floods, and processes occurring prior to convection initiation (CI),
but much less so regarding the dynamics of individual thunderstorms (e.g., Rotunno and Houze, 2007). Exceptions are RELAMPAGO and its sister campaign CACTI, which took place in Western Argentina where some of the most intense storms worldwide are heavily influenced by the Andes and Sierras de Cordoba mountains (Nesbitt et al., 2021; Varble et al., 2021). However, the setting of RELAMPAGO in the lee of a long meridional mountain range and with the Amazon Basin as a moisture source differs greatly from Europe and other severe storm regions of the world with respect to larger-scale environments, geography, ~~and climatology(e.g., Zhou et al., 2021). Furthermore, South America does not have the wide spectrum of existing instrument networks , institutions, and research possibilities that could be used in central Europe~~climatology, and meteorological instrument networks (e.g., Zhou et al., 2021).

~~Thus~~Therefore, a field campaign investigating individual thunderstorm dynamics near complex terrain in the densely-observable regions over Europe seems overdue, particularly given the potentially escalating storm activity attributed to climate change in densely populated regions (Battaglioli et al., 2023). To this end, ESSL is coordinating an effort for an international field campaign in Europe under the name TIM (Thunderstorm Intensification from Mountains to plains). In this article, we summarize the most pressing research questions ~~on the basis of an overview of recent scientific studies. The paper is organized as follows. Section 2outlines key research topics of TIM~~based on the White Paper survey and the existing literature (section 2). Section 3 then provides a ~~synergy for how these~~ summary and briefly outlines how this wide range of topics can be ~~combined in one field campaign and briefly outlines the preliminary campaign strategy, including focus regions and instrument setups~~addressed in TIM.

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[1]The terms "complex terrain" and "orographic" will be used in this article when referring to the vicinity of mountains.

2 Research topics

Our survey within the community has revealed a large pool of research topics regarding severe storms near mountain ranges. These topics are condensed in the following subsections. Section 2.1 starts with an overview of the physical processes important for thunderstorm intensification near mountains. The following sections describe the related research topics ~~more in depth~~that present main foci in TIM.

2.1 Increased storm severity near high terrain

~~Severe~~ As established above, severe convective storms tend to be frequent near European mountain ranges~~as shown by the clustering of severe weather reports (see Fig. 1), and~~, which is underscored by the documented cases of impactful supercells that tracked through such regions (Kaňák et al., 2007; Kunz et al., 2018; Trefalt et al., 2018; Šinger and Púčik, 2020; Wilhelm et al., 2021; Kopp et al., 2023). That said, it is difficult to disentangle to what extent high storm frequency and stronger average intensity are each driving these near-mountain severe weather maxima.

Thunderstorm frequency is largely related to convection initiation (CI) or the lack thereof. Mesoscale orographic processes dominate CI mechanisms in mountainous regions, in contrast to synoptic-scale processes, such as fronts, which are more important over flat terrain (e.g., Pacey et al., 2023). As illustrated in Figure 3 and discussed in more detail in section 2.3, orographic CI can occur where terrain-induced flows converge and cause deep continued lift in the atmospheric boundary layer (e.g., Kirshbaum et al., 2018), especially if these flows transport and vertically mix boundary-layer moisture and thereby decrease convective inhibition (CIN) and dry air entrainment near the convergence zones (e.g., Scheffknecht et al., 2017; Serafin et al., 2020; Marquis et al., 2021; Nelson et al., 2022; Göbel et al., 2023). Hence, mountain ranges strongly influence where thunderstorms form (e.g. Nisi et al., 2018; Manzato et al., 2022b). Although severe storms can move ~~quite long distances after CI~~several hundreds of kilometers (e.g., Scheffknecht et al., 2017; Kunz et al., 2018), CI-prone regions tend to have a much higher frequency and coverage of severe storms (e.g., Feldmann et al., 2023; Kvak et al., 2023). Nevertheless, for Switzerland, Feldmann et al. (2023) demonstrated that while the regions of highest storm frequency and highest storm intensity strongly overlap, they are not identical (see also; Nisi et al., 2018; Manzato et al., 2022a). Thus, CI is likely an important but not the only factor.

Severe storm intensity is largely determined by the vertical distribution of temperature, moisture and horizontal winds. Most reports of severe weather occur where certain atmospheric "ingredients" (e.g., Doswell et al., 1996) are met, which can be boiled down to (1) high convective available potential energy (CAPE) which drives deep convective updrafts and which is found where tropospheric temperature lapse rates and low-level moisture are large, and (2) strong vertical change of wind speed and/or wind direction, i.e., vertical wind shear (e.g., Thompson et al., 2003; Taszarek et al., 2020a). Given CI in regions where these ingredients are met, storms tend to become more intense, more organized, and longer-lived, often forming mesoscale convective systems (MCS) or supercells (e.g., Markowski and Richardson, 2010). Thus, one likely reason for the accumulation of severe reports near orography (Fig. 1) is that these ingredients are enhanced there. Several mechanisms exist in that regard, which are summarized in the rest of this section. Figure 3 illustrates the respective key processes.
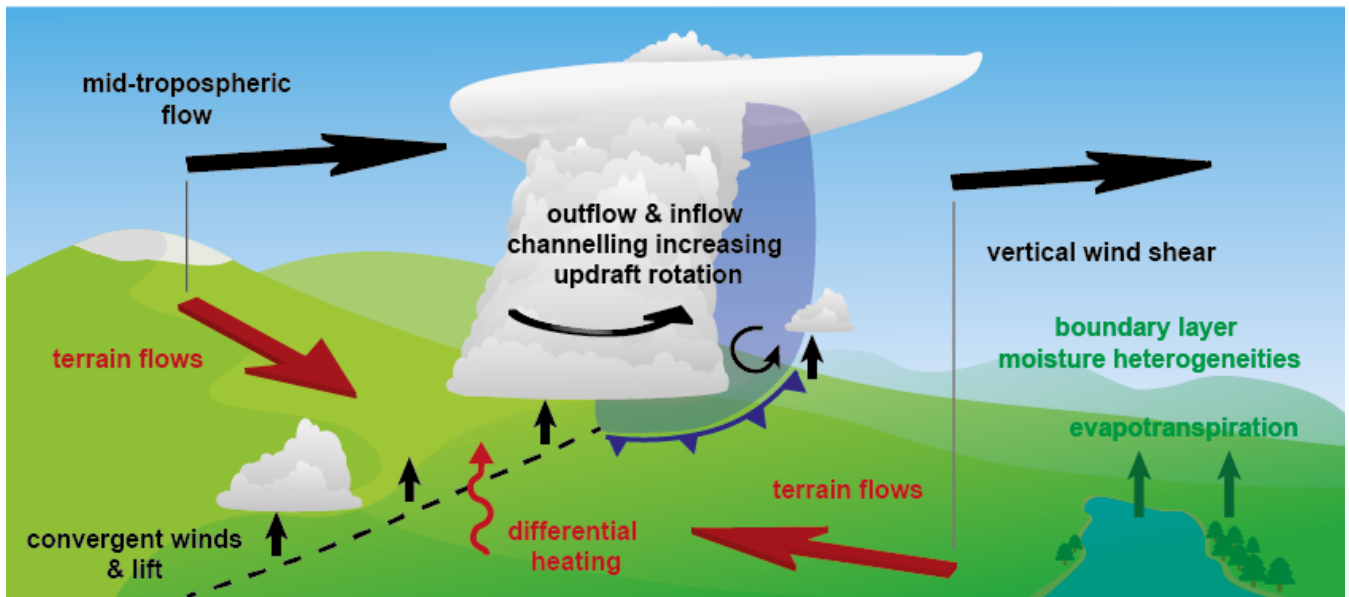
Figure 3. Conceptual illustration of processes influencing severe convective storms near and over complex terrain as explained in the text. The term "terrain flows" encompasses all possible terrain-induced near-ground flow perturbations, such as thermally-forced circulation caused by differential heating, mechanically forced ascent or channeling, upstream blocking, and lee-side convergence (e.g., Kirshbaum et al., 2018).

115   Local terrain-induced flow systems such as thermal slope winds and Alpine Pumping (Ćurić and Janc, 2012; Soderholm et al., 2014; Trefalt et al., 2018; Mulholland et al., 2020; Trapp et al., 2020; Katona and Markowski, 2021), wind channeling (Whiteman and Doran, 1993; Hannesen et al., 1998; Ćurić et al., 2007; Geerts et al., 2009; Tang et al., 2016; Feldmann et al., 2024), or lee cyclogenesis (e.g., McGinley, 1982) can cause perturbations in the atmospheric ~~boundary-layer~~ lower-tropospheric winds. This can increase the vertical wind shear and thereby severe storm potential. Furthermore, the wind

120   profile influences storm structure and propagation (e.g., Houze et al., 1993). Terrain flows depend on the thermodynamic stability of the atmosphere ~~(e.g., Houze, 2012), but also~~ as well as the terrain shape and dimensions ~~, and the surface use such as cities or cropland~~(e.g., Houze, 2012). As a result, typical flow systems seem to exist for individual mountain ranges (e.g., Dotzek, 2001; Kunz and Pusskeiler, 2010), but more universal conceptual models for what processes dominate in what ~~situation and location could be not~~ scenario have not been developed thus far.

125   Another factor is the spatial distribution of low-level moisture across complex terrain. Moisture is often relatively low directly over mountain ridges, leading to less CAPE compared to the surrounding slopes and valleys ~~. Local increase in~~ (e.g., Katona and Markowski, 2021). However, water vapor content ~~can be found along convergence lines, near lakes, or other regions where moist air can be transported or accumulated, which would lead to larger CAPE, all else being equal. Processes that favor this are large-scale,~~ and CAPE can be increased by near-ground up-slope moisture flux ~~(e.g., from the~~

130   ~~Mediterranean) or evapotranspiration from local water bodies or vegetation (Laiti et al., 2014; Feldmann et al., 2024). In the same vein~~(e.g., from the Mediterranean; De Martin et al., 2024, 2025), evapotranspiration from lakes or vegetation (e.g., Laiti et al., 2014;

, or along airmass boundaries and convergence lines (e.g., Maddox et al., 1980). Because of these effects, the distribution of water vapor in complex terrain is often spatially heterogeneous, which can play a role in the formation of thunderstorms (Adler et al., 2016; Marquis et al., 2021; Nelson et al., 2021; Calbet et al., 2022). ~~Research~~ More research is needed to ~~analyze if storm severity could also be linked to these~~ understand the storm-scale impacts of such heterogeneities and to ~~derive~~ reliably detect them with remote-sensing~~retrievals of water vapor that could be used in weather forecasts~~.

The interpretation of the thermodynamic profile near ~~complex terrain is somewhat~~ mountains is complicated by the ~~local modifications from~~ heterogeneous heat and moisture fluxes. Nevertheless, ~~studies~~ the studies below have suggested that with increasing elevation near-surface air parcels that enter a thunderstorm cloud originate higher relative to the background thermodynamic profile that is advected over the terrain, i.e., inflow air does not originate near the surface. At intermediate elevation, this can lead to an increase in convective energy because the most unstable parcels are being lifted (Markowski and Dotzek, 2011; Scheffknecht et al., 2017; Katona and Markowski, 2021; Feldmann et al., 2024). At increasingly higher elevation or on the leeward side (with respect to the deep-layer winds) of a mountain ridge CAPE is typically diminished because lifted parcels from higher in the atmosphere are drier and the depth of the CAPE layer decreases (Markowski and Dotzek, 2011; Mulholland et al., 2019; Katona and Markowski, 2021; Feldmann et al., 2024). However, ~~all~~ these studies have only considered specific mountain ranges or idealized scenarios and hence it remains unclear how significant these effects are in different geographic regions. ~~For instance, upslope moisture flux on the leeward side of a mountain range may lead to CAPE actually being larger than on the windward side. In this or similar ways, the geographic location and terrain dimensions likely determine the typical scenario at an individual location.~~

The above-mentioned convergence regions from terrain-induced flows may also overlap with moisture gradients and take characteristics of dryline-like boundaries (e.g., Pistotnik et al., 2011; LeBel et al., 2021). Such boundaries are known to have an impact on storm severity, mainly through locally enhanced low-level vertical wind shear, moisture, and lift (e.g., Maddox et al., 1980). However, mesoscale boundaries have not been well documented in Europe, although case studies ~~show they can play a key role in the development of severe weather near mountains (e.g., ?Komjáti et al., 2023)~~indicate at least some importance for supercells that produce large hail and tornadoes (e.g., Komjáti et al., 2023; De Martin et al., 2024, 2025).

Lastly, complex terrain also influences the internal structure and processes within existing thunderstorms. This can include channeling of the outflow and inflow of a thunderstorm (Fig. 3), which in turn can feed back to storm intensification via increased storm-relative winds or baroclinic generation of horizontal vorticity (e.g., Feldmann et al., 2024). As discussed in section 2.4, these storm-scale influences are complex and not well-researched. Hence, much research in the storm scale is needed to better understand them, in addition to the larger-scale, environmental influences in the previous paragraphs.

As suggested by Feldmann et al. (2024), it is the interplay of the factors described in this section that may cause ~~severe storm~~ SCS potential to be enhanced over the slopes of mountain ranges compared to flat terrain or directly over the mountains (Fig. 1). Even slight enhancements are especially relevant in regions like Europe where ~~severe storm~~ SCS potential is often marginal (e.g., Taszarek et al., 2020b). However, what processes are typically at play in which weather situation and in which sub-regions remains largely unclear and is considered one research focus of TIM.

2.2 Orographic modification of the mesoscale environment

The influence of orography on the atmosphere and parameters like CAPE and wind shear opens up several follow-up questions. What influence does the prevailing mid-tropospheric flow direction and speed have on the modification of convective parameters? Why are there regions along the Alps and other mountain chains much more prone to severe storms than others~~(Fig. 1)~~? What are preferential paths for severe storms? At which elevations are environments most or least favorably modified? How significant is the impact of vegetation, water bodies, snow cover, or urban areas in mountainous regions?

Related to these topics is also how storms ~~behave~~ evolve when either crossing or moving away from mountains and hence ~~encounter~~ encountering either abrupt or continuous changes in the mesoscale environment. Situations have been documented for both decay or intensification in these scenarios (e.g., Scheffknecht et al., 2017; Trapp et al., 2020; Klaus et al., 2023; McKeown et al., 2024), but more research is necessary. By documenting ~~exemplary~~ example cases within a field campaign such as TIM, detailed observations could help our understanding of these opposing changes.

Furthermore, it is well-established that the ~~characteristic environments for different~~ atmospheric environments of hazards are statistically different, e.g., between tornadoes and hail (Púčik et al., 2015; Nixon and Allen, 2022). Similarly, Zhou et al. (2021) showed that statistically different hailstorm environments exist, with one of the main differentiating factors being terrain elevation. Hence, the impact of orographic modifications is likely hazard-dependent. Several studies have shown that channel winds in relatively narrow valleys improve the conditions for supercell tornadoes even if the background environment is otherwise unfavorable (Fujita, 1989; Dotzek, 2001; Bosart et al., 2006; Tang et al., 2016). Whether there are similar mechanisms specifically for hail or other hazards ~~, as is suggested by observations (Fig. 1; Feldmann et al., 2023), is~~ is relatively less researched. Targeted observations and measurements as well as simulation studies (e.g., Katona et al., 2016) over different Alpine sub-regions as part of the TIM campaign could provide deeper insights into the processes of orographic modification.

2.3 Convection initiation

Due to its importance for thunderstorm evolution, CI has been a focus of past research. The reader is referred to Houze (2012) and Kirshbaum et al. (2018) for reviews on the topic. Large low- to mid-level relative humidity, dry air entrainment, and strong as well as deep ascent have been shown to be among the most crucial factors for CI (e.g., Nelson et al., 2022; Marquis et al., 2023). Whether near-ground convergence and ascent occur upstream, over, or downstream of a mountain ridge (Fig. 3) broadly depends on the speed of the flow impinging on the terrain obstacle, the stability of the atmosphere, and the shape and dimensions of the ridge (e.g., Kirshbaum et al., 2018; Imamovic et al., 2019). However, in reality, individual flow and moisture perturbations are extremely complex and subject to strong diurnal cycles (e.g., Zardi and Whiteman, 2013; Adler et al., 2016). On this local scale, terrain-induced flows (e.g., Schmidli, 2013; Panosetti et al., 2016), land use and urban heat islands (e.g., Niyogi et al., 2006; Zhao and Wu, 2018; Liu and Niyogi, 2019), as well as outflow from existing storms (e.g., Soderholm et al., 2014) strongly influence the convergence regions in addition to the larger-scale flow. Furthermore, mountain slope has a strong influence on the advection of moisture and thereby on CI likelihood (Göbel et al., 2023).

These processes make CI more "reliable" over mountains compared to flat terrain and thereby increase the predictability of convective precipitation in forecast models (e.g., Bachmann et al., 2020; Khodayar et al., 2021). However, this is not the case for other SCS hazards. Since small details in CI timing and location can have a profound impact on the evolution and organization of severe convective storms, failure to resolve all relevant processes in numerical models remains a main cause for forecast error. For that reason, CI is an important topic to the weather services who contributed to this article and a focus of current and recent research (e.g., the past COPS and RELAMPAGO campaigns and the current TEAMx campaign; Wulfmeyer et al., 2011; Nesbitt et al., 2021; Serafin et al., 2020; Rotach et al., 2022).

By focusing explicitly on SCS conditions, TIM can make an important contribution to the research on CI. This includes a better understanding of CI location relative to mountains (e.g., Nisi et al., 2018; Manzato et al., 2022b) by documenting the boundary layer evolution, thermal circulations, and convergence lines before and during CI. The interplay of dry lines and triple points (De Martin et al., 2024), cold fronts (e.g., Pacey et al., 2023), sea-breeze circulations (e.g., Jensen et al., 2022), frontal waves, and gravity waves (e.g., Mulholland et al., 2020) with complex terrain requires further research as well. For instance, the maximum in large hail reports over Northern Italy (Fig. 1) and the occurrence of tornadoes in the same region appear linked to the combined effects of mesoscale boundaries and sea-breezes separating the dry mountain boundary layer from the marine boundary layer over the warm Adriatic and Ligurian Seas (Bagaglini et al., 2021; De Martin et al., 2024, 2025).

Another important scientific question concerns scenarios in which CI is suppressed. Several White Paper survey participants noted that on days with high severe weather potential and predicted SCS activity in forecast models, the storms frequently fail to occur or are forming delayed. Some participants pointed out that this often happens on days with high concentrations of Saharan dust, which is typically advected over Europe together with conditionally unstable airmasses (e.g., Seifert et al., 2023; Brennan and Wilhelm, 2024). This dust can decrease radiative warming at the surface, thereby suppressing boundary layer mixing and CI, and increases warming aloft, which may reduce CAPE (Stanelle et al., 2010). These processes are not implemented in most operational forecast models (e.g., Seifert et al., 2023). Assimilating in-situ aerosol measurements (e.g., Eirund et al., 2022) or remote sensing data from lidars or the recently launched EarthCARE satellite (see section 2.8) could therefore reduce forecast errors of severe convection.

More generally on the topic of aerosols, their role in cloud microphysics and dynamics is a focus of current atmospheric science research ~~from a variety of angles~~ and still somewhat uncertain (e.g., Morrison et al., 2020). Regarding severe convection, aerosol concentrations can for example have a direct influence by acting as cloud-condensation or ice nuclei (CCNs or INPs), thereby influencing hydrometeor concentrations and thus storm dynamics ~~(e.g., Allen et al., 2020; Varble et al., 2023; Barthlott et al., 2024)~~ (e.g., Loftus and Cotton, 2014; Allen et al., 2020; Varble et al., 2023; Barthlott et al., 2024; Brennan and Wilhelm, 2024). Based on this mechanism, cloud seeding for hail suppression is still widely used in Europe, despite the majority of scientific evidence pointing against its effectiveness ~~(e.g., Browning and Foote, 1976; Knight et al., 1979; Auf der Maur and Germann, 2021). Also disproved but still used are~~ as it is used now (e.g., Browning and Foote, 1976; Knight et al., 1979; Auf der Maur and Germann, 2021). Much more dubious is the use of hail cannons (Wieringa and Holleman, 2006). ~~Given the dramatic increase of hail damage in recent years, more~~ More effective ways of damage prevention should be pursued~~and funds re-allocated~~. A better understanding of aerosol effects, as well as outreach and education as part of TIM (section 2.5), could help in that regard.

2.4 Storm-scale interaction with complex terrain

How the internal structure of thunderstorms changes in reaction to terrain shape is not well understood due to the lack of high-resolution observations within or around thunderstorms. Some insights exist from idealized modeling studies. Based on qualitative experience with storms in the southern pre-Alps, Feldmann et al. (2024) ~~recently~~ analyzed the interaction of a supercell storm with a simplified ridge and sloped terrain in highly idealized simulations. They showed that channeling of storm-generated outflow and inflow can affect baroclinic horizontal vorticity generation, low-level wind shear, and storm-relative inflow, all of which have an influence on supercell structure and intensity (e.g., Rotunno and Klemp, 1985; Peters et al., 2020). These findings are largely consistent with previous idealized simulations (e.g., Markowski and Dotzek, 2011; Scheffknecht et al., 2017) and the general observation that supercells can traverse and intensify over mountain ranges (e.g., Kvak et al., 2023; McKeown et al., 2024). What seems most needed now is to validate the simulated dynamical processes in real supercells over a large spectrum of cases and types of terrain, an endeavor that requires considerable effort and coordination. Similarly interesting are some non-supercell storms, such as pulse storms (Miller and Mote, 2017), which can produce large amounts of hail for a short time for unknown reasons and which are difficult to anticipate.

On larger spatial scales than individual storm cells, several studies have investigated the interaction of mesoscale convective systems (MCS) with orography. These systems are typically driven by lift along the gust front of the cold pool (Markowski and Richardson, 2010, chapter 9), which can be decelerated, accelerated, or blocked by mountains, thereby leading to phases of updraft and precipitation intensification and weakening, respectively (Frame and Markowski, 2006; Reeves and Lin, 2007; Letkewicz and Parker, 2011; Smith et al., 2014; Pucillo et al., 2019; Wu and Lombardo, 2021; Lombardo and Kumjian, 2022). Hence, mountains play important roles in upscale growth from single cells to MCS formation, the system's movement, and in some cases also its decay.

The precipitation enhancement of MCSs over orography is one of the reasons for flooding events in mountainous regions (e.g., Saharia et al., 2017). Another reason is that the lift mechanisms near terrain can lead to repeated re-formation, i.e., "backbuilding" of convective cells, which means that precipitation accumulates over the same location over a long time (e.g.,

Soderholm et al., 2014; Panziera et al., 2015; Kirshbaum et al., 2018). The additional lift along gust fronts of storm outflow, which is influenced by the terrain slope and the environmental temperature and wind profile, plays an important role in these scenarios (e.g., Miglietta and Rotunno, 2014).

Even though past research has helped to increase forecast accuracy, high-precipitation events remain difficult to predict and are in the focus of many weather services in the Alpine and Mediterranean region based on our partner institution survey. Unfortunately, they are also difficult to observe accurately. For example, ~~the good radar coverage over central Europe is essential in monitoring high-precipitation events. However, radars~~ radars are used for Quantitative Precipitation Estimation (QPE, Ryzhkov et al., 2022) but have weaknesses over complex terrain. Radar beam blocking (e.g., Kaltenboeck and Steinheimer, 2015) as well as large vertical gradients of precipitation below the melting layer (e.g., Chen et al., 2023) often lead to underestimates of the ~~Quantitative Precipitation Estimation (QPE, Ryzhkov et al., 2022)~~QPE. As discussed further below, high-resolution precipitation surface and vertical profile measurements as well as gap-filling radars, aimed to be collected in TIM, could be used to improve correction algorithms of QPE and help in flooding nowcasting and response.

Similar accelerations of thunderstorm outflow as in MCS can be expected for downbursts impinging on and channeled through complex terrain. Downbursts are locally descending jets which can cause damaging winds when colliding with the surface and spreading out horizontally from the high-pressure region of the cold pool, and which give rise to toroidal vortex structures (e.g., Fujita, 1990; Canepa et al., 2023). Due to their small spatial and temporal scales, the dynamics of downbursts over complex terrain are not well understood and require further research with high-density observations and simulations ~~(e.g., Canepa et al., 2020)~~(e.g., Canepa et al., 2020; Burlando et al., 2024).

2.5 Storm impacts on infrastructure and society

Damages from severe convective storms with tornadoes, wind gusts, hail, ~~flash floods~~extreme rainfall, or lightning, including secondary impacts such as landslides ~~, can be immense~~are now dominating global insured loss from natural catastrophies (SwissRe, 2024). Developing a better understanding of these impacts is a prerequisite to developing adequate measures to mitigate losses. A subtopic that has received renewed attention in recent years is the mechanical or engineering perspective of severe convective hazards. Regarding tornadoes, which are still underestimated in many European countries (Antonescu et al., 2017), ESSL has recently proposed an international Fujita (IF) scale for tornado ratings based on wind damage indicators that can be used internationally, not just in the US where the enhanced Fujita scale is used based on US infrastructure (ESSL, 2023a). More data from tornado damage surveys will continue to improve the IF scale in the future. In contrast, flash flood damage in complex terrain is strongly linked to rainfall-runoff processes and hence, ~~by nature~~from the impact perspective, a hydrological problem ~~to which meteorological output can only~~ (e.g., Ravazzani et al., 2016; Marvi, 2020; Merz et al., 2020). However, accurately representing SCS in numerical models is crucial to provide background data ~~(e.g., Ravazzani et al., 2016; Marvi, 2020; Merz et al., 2020)~~ for hydrologic models (next section).

~~Hail is the dominating source of SCS damage.~~ The collection of large hailstones, 3D scanning and analysis of their internal layers, or study of impact kinetic energy on structures such as roof shingles is increasingly pursued by different groups such as the Insurance Institute for Business and Home Safety (IBHS) in the US (Brown and Giammanco, 2013), the North-

300 ern Hail project in Canada (Brimelow et al., 2023) and the Bureau of Meteorology in Australia (Soderholm and Kumjian, 2023). ~~However,~~ Impact studies can for example help establish building codes to prevent hail damage. Schmid et al. (2024) recently showed that the lack of accurate information on hail ~~stone~~ occurrence, size, and distribution is also hampering damage assessments and risk modeling efforts ~~. With sensitive structures such as solar panelsand wind turbines spreading quickly, such studies are especially~~ important for insurances. Economic growth (e.g., more cars, solar panels, greenhouses) is a major

305 driver of the increasing trend in SCS losses (SwissRe, 2024). Thus, it is important to quantify the damage and loss that can be expected from hail, wind, or their particularly damaging combination: wind-driven hail (Morgan and Towery, 1976), which is currently ~~still~~ difficult to predict. The comparison of ~~large datasets of the~~ 3D scanned and dissected hailstones as well as hail size distributions between different continents, elevations, or climatic regions could also provide valuable insights into hail growth ~~and microphysics within thunderstorm clouds and their relationship to the atmospheric background environment~~

310 (Soderholm and Kumjian, 2023).

~~Furthermore, the~~ The impact of severe weather on society is strongly ~~dependant on human behaviour~~ dependent on human behavior and risk perception (e.g., Ripberger et al., 2019). Unfortunately, education on severe convection storms is very limited throughout Europe, perhaps because of the relative rareness of such events and limited cross-border exchange. This may affect people's trust in severe weather forecasts and how they perceive a severe weather threat. For instance, appropriate

315 safety measures and behavior when encountering tornadoes, large hail, strong winds or lightning are typically not common knowledge. ESSL and the TIM partners share the goal to improve ~~these conditions through~~ this through internal exchange about better ~~warning practices~~ impact-based warning practices, exchange with national civil protection agencies, as well as ~~through~~ education and outreach at TIM measurement sites and in the media during the field campaign. Furthermore, the topic of severe convective storms is also somewhat underrepresented in university courses, especially compared to the U.S. where

320 most severe weather research groups are situated. TIM aims to engage students from European universities in the field campaign and thereby help to build the next generation of severe weather forecasters and researchers.

2.6 Improvements in NWP

Numerical weather prediction (NWP) models are an important basis for forecasts of severe weather. The following NWP strategies are particularly useful to capture the chaotic nature of SCS. Short-term NWP forecasts, i.e. for the next hours, can be

325 blended with information from nowcasting systems ~~,~~ that extrapolate observations collected in real-time (e.g., Bojinski et al., 2023)~~, or~~. Additionally, the models can be initialized very frequently, e.g. every hour or less, in so-called rapid update cycles (Benjamin et al., 2004) assimilating a range of observations available at that time (Miyoshi et al., 2016). Often an ensemble of multiple simulations is performed whereby the initial state or the evolution of the predictions is subtly perturbed. The uncertainty resulting from small differences in initial conditions, CI or storm interactions can thus be reflected (Durran and

330 Weyn, 2016; Bachmann et al., 2020; Bojinski et al., 2023).

Despite these advances in severe weather forecasting techniques, notable forecast errors can occur when NWP models ~~are not able to correctly simulate convective initiation or the correct~~ fail to predict CI or the type of convective system. Over complex terrain, such errors are frequent because crucial processes like moisture advection or terrain-induced flow systems are not

captured by the model (e.g., Panosetti et al., 2016). For example, on 19 July 2023 a series of record-breaking hailstorms occurred across North Italy as intense supercells initiated over the southern Alps and moved across the Plains. Operational NWP models either failed to produce the storms, or underestimated their intensity (Fig. 4). In this and other challenging cases (e.g., Mandement and Caumont, 2021), a big unknown was how storms will behave once they move out of the mountains and onto the plains: they may intensify or decay. This transition from mountains to plains seems neither well-understood from a storm-dynamics perspective, nor generally well-predicted by NWP models.

It is known that NWP models have shortcomings near mountainous terrain as their horizontal resolution is only sufficient to resolve the topography to a certain extent. The smoothing at the smallest resolved scales affects how well the interaction between the surface and the lowest layers can be represented (e.g., Rotach et al., 2022). Furthermore, the parameterizations for unresolved surface-atmosphere exchange processes were mostly developed for flat terrain and much coarser grids which introduce considerable errors across steep topography (Ceppi et al., 2013). Neglecting or simplifying subscale effects and using climatological fields in parameterizations are perhaps unfitting assumptions in NWP models. This includes challenges of numerical model "grey-zones", where resolved processes and parameterizations overlap (e.g., Chow et al., 2019; Kramer et al., 2020; Kirshbaum, 2020; Wei and Bai, 2024). Methods used for convective-scale data assimilation are not as advanced as for global models (Gustafsson et al., 2018). Improving these terrain-related processes in models is the subject of research within the TEAMx project (Rotach et al., 2022). Modeling experiments within TEAMx regarding CI (Serafin et al., 2024) can be built upon within TIM.

Furthermore, the exceptionally high spatial and temporal resolution of TIM-data is of particular interest given that the latest generation of (pre)operational regional NWP models realize grid spacings of 1 km and below (e.g., Meteoswiss' ICON-D1 and -D05), which is also planned for global models such as the Extremes Digital Twin by the EU Destination Earth programme (ECMWF, 2023). Field campaign
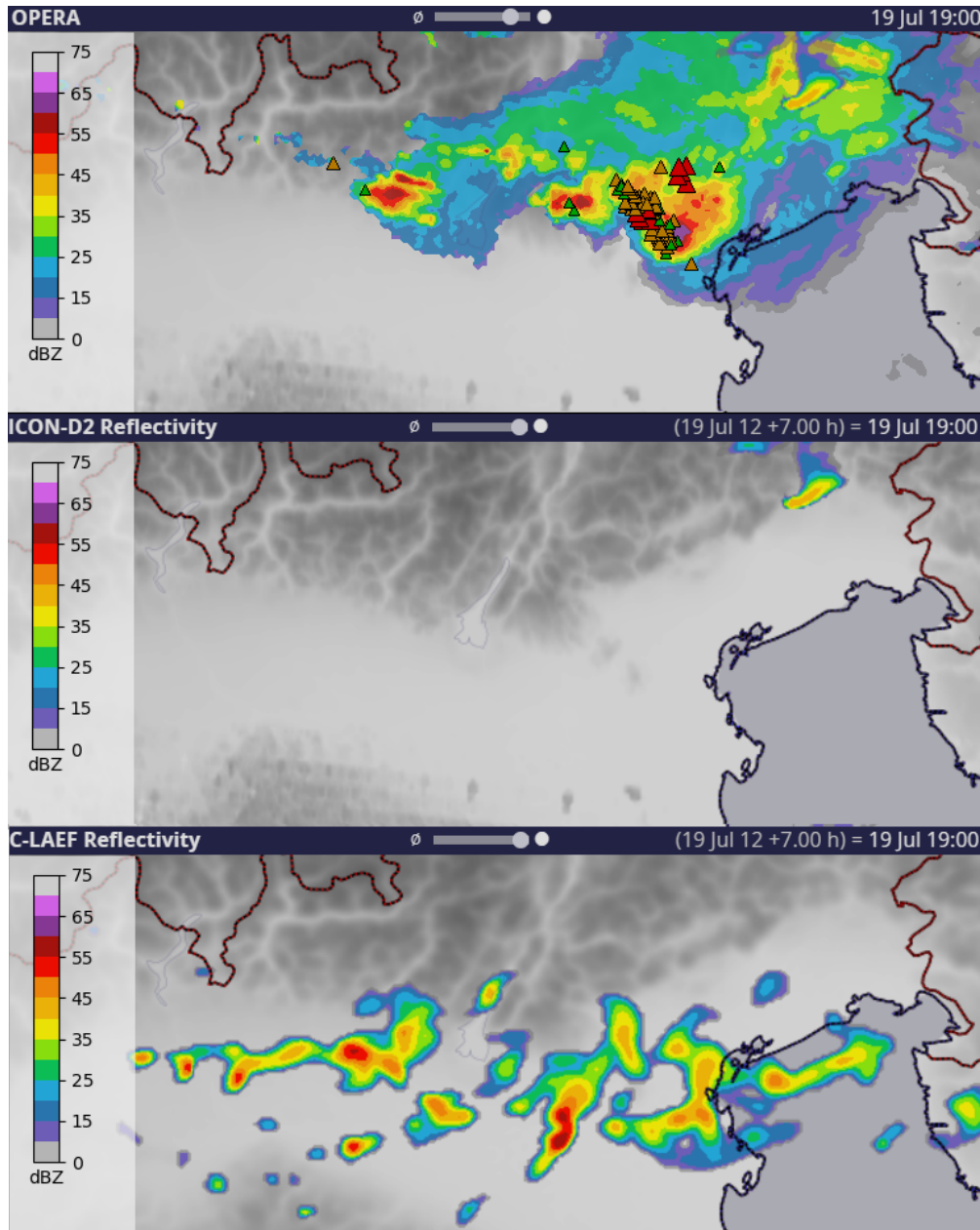
Figure 4. Composite radar reflectivity (OPERA) and ESWD hail reports over northern Italy on 19 July 2023 (green: hail diameter 2-5 cm; orange: hail diameter 5 - 9 cm; red: hail diameter > 10 cm), and +7 hours forecast reflectivity by two operational NWP models: ICON-D2 and C-LAEF. The supercell producing the extremely large hail between 18:00 and 19:00 UTC was missed by ICON-D2. C-LAEF forecasted convection, but with weaker maximum intensity.

data from drones, surface observations, Doppler wind lidars, or other sources ~~could be tested~~ are useful in model comparison and data assimilation studies ~~(e.g., Sgoff et al., 2022; Nomokonova et al., 2023; ?)~~ (e.g., Adam et al., 2016; Fourrié et al., 2021; Sgoff et al. . Since the presence of orography is still often neglected in current NWP postprocessing algorithms (e.g., Schwartz and Sobash, 2017), such observations would also allow the identification of physically-based predictors and targeted observations that could locally improve the calibration of ensemble prediction, nowcasting systems, and machine learning techniques for severe weather warnings in regions influenced by mountains (e.g., Dabernig et al., 2017).

Another potential area of NWP improvement is a better handling of microphysical processes within storms (Morrison et al., 2020). Many uncertainties remain regarding the actual concentration, properties and number of particles in the various hydrometeor classes (cloud water, rain, graupel, snow, hail) because of a lack of ~~measurement~~ data as research aircraft tend to avoid the most intense parts of those storms (e.g., Heymsfield et al., 2023). However, relatively recent innovations including drones, neutrally buoyant sondes, and vertically-pointing radars (Trömel et al., 2017; Sokol et al., 2018) offer new possibilities ~~to collect measurement data~~ in addition to polarimetric radars, disdrometers, or aircraft in-situ observations that are crucial for the improvement of parameterizations ~~by weather services and the academic community. The importance of these innovative observations and their potential use in TIM will be explored below. Furthermore, the effects of aerosol loading are relatively poorly understood and their improvement may benefit forecasts (Seifert et al., 2023; Barthlott et al., 2024), especially on days where the aerosol loading is high~~ (e.g., Taufour et al., 2018).

Overall, addressing the following areas within TIM is likely to lead to progress in NWP performance: (1) the characterization of the pre-convective environment across complex terrain by developing better data assimilation procedures (e.g., Gustafsson et al., 2018; B , (2) improving parameterizations for surface-air interactions (Ceppi et al., 2013; Goger et al., 2019; Rotach et al., 2022) and microphysics (e.g., Labriola et al., 2019; Malečić et al., 2022), (3) improving data assimilation of ongoing convection in satellite and radar and assimilating data from novel sources. As discussed further in section 2.8, the new generation of geostationary meteorological satellites (MTG, Meteosat Third Generation) enables more accurate atmospheric moisture determination and a Lightning Imager, which can be assimilated into NWP models and used in nowcasting (Leinonen et al., 2023).

2.7 Climatology and Climate Change

Pan-European severe convective storm climatologies have been produced based on different data, such as severe weather reports, lightning, satellite products, and reanalyses (Punge et al., 2017; Taszarek et al., 2019, 2020a; Manzato et al., 2022b; Lombardo and Bitting, 2024). These studies agree relatively well on a main convective season in summer over most of Europe, except over Mediterranean regions, where activity peaks in fall but with relatively low severity (with the exception of flood events). As discussed in the introduction, summertime hotspots for severe convective storms are found near mountain ranges, for example around the Alps, the Pyrenees, the Massif Central, the Black Forest, the Dinaric Alps, and the Carpathian Mountains. ~~Details of this severe storm clustering are still not fully understood, also because public reports of severe weather suffer from biases such as spatial heterogeneity. Continued growth~~ Continued improvement of report networks like ESWD~~for example by supporting~~, public user reports ~~across Europe but also comparison with diverse pan-European datasets such as~~

from satellites, radars via App, and SCS detections from satellite, radar, and lightning networks will provide further details on where severe storms typically initiate, become severe, and decay (e.g., Nisi et al., 2018; Manzato et al., 2022b).

New data gathered in TIM is limited in time and cannot directly assess these climatological features, long-term variability, and effects of climate change. Yet, results from a constrained field campaign can be of immense value for these research areas by improving process understanding or by probing "analog" storms that occur in conditions presumably representative of future climate conditions (e.g., Lasher-Trapp et al., 2023).

As one effect of global warming, the increase in average temperature throughout the troposphere and associated scaling in moisture content is generally expected to increase CAPE and hence thunderstorm severity (e.g., Romps, 2016; Agard and Emanuel, 2017; Martín et al., 2024). This upward trend is robust for Europe both for past and projected trends of CAPE or related thermodynamics parameters (Mohr and Kunz, 2013; Mohr et al., 2015; Púčik et al., 2017; Rädler et al., 2019; Battaglioli et al., 2023), as well as in severe weather reports. Stronger updrafts in high CAPE environments are one factor increasing the likelihood of flash floods, in addition to higher moisture content and slower storm motion (e.g., Kahraman et al., 2021). In its Sixth Assessment Report the Intergovernmental Panel on Climate Change (IPCC) states that climate models consistently and with high confidence project environmental changes that would likely lead to an increase in the frequency and intensity of severe thunderstorms, also involving tornadoes, hail, and winds (Calvin et al., 2023, Chapter 11). However, there is low confidence in the specifics of these projected increases.

Large uncertainties remain for the trend in hail, tornadoes, and convective winds because One reason is that many climate models have a bias in low-level moisture and CAPE (e.g., Gopalakrishnan et al., 2025). Another problem is that other impact factors than thermodynamics exist, which could counter-balance the positive trend in CAPE and which are not as well understood (e.g., Raupach et al., 2021). For one, convective inhibition and entrainment are likely to increase in a warmer climate which could lead to decreases in initiation frequency and storm coverage frequency and coverage of SCS (e.g., Trapp and Hoogewind, 2016; Chen et al., 2020; Peters et al., 2024). The area affected by hail is also likely to decrease because of an increase in the melting layer depth, although large hail is less affected and is expected to become more frequent due to the positive trend in CAPE (e.g., Gensini et al., 2024). Complicating this, Lin and Kumjian (2022) have indicated that increases in CAPE do not necessarily cause storms to produce larger hail, although such the extreme values of CAPE might be they considered are relatively rare in Europe (e.g., Taszarek et al., 2020b). Furthermore, the frequency and the typical thunderstorm organization could change in response to modifications in the larger-scale circulation and resulting weather patterns (e.g., Mohr et al., 2020; Ghasemifard et al., 2024). This is important because severe convective wind gusts and extreme precipitations are often associated with MCSs (Saharia et al., 2017; Gatzen et al., 2020; Pacey et al., 2021) while most large hail and strong tornadoes are produced by supercells, at least in the US (Blair et al., 2011; Smith et al., 2012; Blair et al., 2017). For Europe, this is likely similar but only researched in certain regions (Tuovinen et al., 2015; Wapler, 2017; Feldmann et al., 2023) (Tuovinen et al., 2015; Wapler, 2017; Feldmann et al., 2023; Wells et al., 2024).

It is unclear how accurately climate models capture these circulation changes. Another more general limitation of climate models for convective storm research is that most of them still depend on convection parameterization, although research with convection-permitting climate simulation is currently ongoing (e.g., Lenderink et al., 2024)(e.g., Kahraman et al., 2021, 2024; Lenderink e

. The accuracy of climate models across mountainous areas may also be impaired by systematic errors in modeling surface-atmosphere exchange processes across complex terrain (e.g., Rotach et al., 2022). The record-shattering reports in recent years ~~(e.g., ?)~~ give the impression that at least in some regions global warming ~~likely has a strong~~ has an influence on severe convec-

tive ~~storm frequency. Interestingly~~storms, although the influence of economic growth on vulnerability and exposure is likely more important (e.g., SwissRe, 2024). Unfortunately, other observations less sensitive to economic factors and with periods long enough for climate trend analysis ~~, such as from lightning data or hail pads, indicate no clear upward trend thus far (Manzato et al., 2022b, a; Augenstein et al., 2023),~~ are scarce. Augenstein et al. (2024) showed predominantly negative trends in lightning over central Europe, although it is somewhat unclear how representative ~~they are for severe storms in general~~lightning is for SCS. Hail pad networks indicate less small and more large hail, but these trends are for small regions and mostly not significant (Manzato et al., 2022b, a).

In short, more research beyond the trends of convective parameters such as CAPE seems required to gain more robust knowledge on trends in severe weather. This is where even a relatively short-term field campaign can help because a better fundamental understanding of the storm dynamics, microphysics, CI, and the production mechanisms of severe convective hazards is needed to know what signals to look for in climate projections and to anticipate how these processes may change in a warmer climate.

2.8 Innovative observations and their use

Advances in severe storm research and forecasting have ~~always~~ often been linked to development and ~~improvements~~improvement of new observational techniques such as radar or satellite (e.g., Brooks et al., 2019). Many new methods and instruments are currently being developed or implemented which could likewise improve our understanding of severe convective storms. As discussed further in this section, this includes new polarimetric radar algorithms, drone-based observations, swarmsondes, microwave links, and new instruments on ~~the Meteosat Third Generation (MTG) geostationary and later on the Metop Second Generation (Metop-SG)~~ geostationary and polar-orbiting satellites. A field campaign on convective storms in the following years would be ideal to test these new platforms ~~,~~ and to validate their performance ~~by comparing different observationsof the same cases, and gather new insights. By conducting such a field campaign, technologies, and instruments will again be improved and refined in return as well.~~ against other observations.

For one, the evolution of storm-top features as seen from satellite imagery has been shown to be strongly linked to storm severity. These features include above anvil cirrus-plumes, warm wake areas, overshooting top properties, or storm-top divergence (e.g., Homeyer et al., 2017; Bedka et al., 2018; Murillo and Homeyer, 2019; O'Neill et al., 2021; Murillo and Homeyer, 2022; Scarino et al., 2023). Questions remain how these characteristics ~~compare in imagery from GOES and the MTG satellites~~ translate to the Meteosat Third Generation (MTG) satellite imagery and how indicative these features are in rapidly changing conditions near complex terrain. Novel and more precise information on cloud top properties, cloud-ice content, precipitation and aerosol properties will be provided by the METimage, Ice Cloud Imager (ICI) and the Multi-Viewing Multi-Channel Multi-Polarisation Imaging (3MI) instruments on the polar-orbiting Metop-SG satellites as of 2026.

470   Lightning is another type of dataset that can be detected remotely with a variety of methods and provides valuable information about the microphysics and severity of a thunderstorm. The new satellite-based MTG ~~lightning imager~~ Lightning Imager (LI) ~~will require~~ is similar to the Geostationary Operational Environmental Satellite (GOES) Geostationary Lightning Mapper (GLM) over the Americas (Rudlosky et al., 2020), but requires validation with ground-based lightning sensors before it can be used in research or assimilated in forecast models. In addition to the LI and 2D lightning detections, Lightning Mapping Ar-

475 rays (LMAs) can be deployed to study the 3D electrification and polarity in thunderstorms, as was done during RELAMPAGO (Medina et al., 2021). Many mechanisms have been proposed (e.g., Pruppacher and Klett, 2010) and it has been shown that even slight differences in the environment can have profound effects on cloud electrification, which is an active field of research (Carey et al., 2003; Carey and Buffalo, 2007; Fuchs et al., 2015; Schultz et al., 2015; Chmielewski et al., 2018; Ringhausen et al., 2024). Examples to be investigated in TIM are changes in the lightning activity, polarity or flash size (e.g., Figueras i

480 Ventura et al., 2019; Erdmann and Poelman, 2024) of the storms that traverse complex terrain and undergo rapid changes in response to environmental characteristics such as CAPE, vertical wind shear, cloud base height, or warm cloud depth. These could be linked to microphysics of the storm assessed through polarimetric radar (e.g., Kumjian and Ryzhkov, 2008), hail collection, and in-situ observations within clouds. A better understanding of these processes would allow for the development of parameterizations and better lightning prediction in NWP models (e.g., Cummings et al., 2024).

485   Furthermore, vertical profiles of the atmosphere are invaluable for severe storm forecasting and research, because they allow for quantification of the ingredients for severe ~~storm~~ storms (e.g., Doswell, 1987; Doswell et al., 1996). As touched on in sections 2.1 and 2.3, the distribution of moisture both vertically and horizontally plays an important role for convective storms. The new 0.9 micron channel of the MTG Flexible Combined Imager (FCI) instrument for the first time allows for the quasi-continuous monitoring of total column moisture content including in the lowest few hundred metres of the troposphere,

490 with sampling rates over Europe of 10 minutes (available now) down to 2.5 minutes (by around 2027). Such data could help forecast ~~new cell formation and thereby flooding by~~ CI, back-building convection, as well as local boundaries ~~which are known to influence CI and storm severity. Hence, such horizontally homogeneous moisture data is highly desirable, but verification of the MTG retrieval algorithms with in-situ data at high spatio-temporal resolution is necessary, especially near complex terrain. Similarly, the~~ . The FCI as well as the new geostationary infrared sounder (IRS) on board of the MTG-S1, which

495 can also provide vertical profiles of temperature and moisture, ~~requires comparison with high-frequency classical~~ require comparison with in-situ soundings and ground-based radiometer soundings near orography and in proximity to SCS. The potential value of IRS as a complement to standard soundings has been ~~evaluated~~ demonstrated at the ESSL Testbed in the quasi-operational setting (Groenemeijer, 2019). Although there are limitations to detect low-level moisture near the ground with this data, availability of infrared soundings from geostationary orbit at 30-min resolution over Europe will add significant

500 value and overcome the current limitations on temporal resolution of such data from polar-orbiting instruments such as IASI on Metop. Despite this disadvantage of polar-orbiting satellites, EarthCARE is promising for profiling cloud microphysical properties and aerosols with an overpass time around 13:30 UTC over Europe, a typical mature convective storm period.

    Recent alternative profiling methods are commercial microwave links (CMLs) and uncrewed aircraft systems (UAS or *meteodrones*). As an opportunistic remote-sensing tool, CMLs typically used in cell towers are rapidly evolving and E-Band

505 CMLs are increasingly installed in several countries to enable 5G. E-band CMLs can provide information on water vapor variability (e.g., Fencl et al., 2021). Research is needed to fully exploit the fast-developing K-, E-, and W-band commercial microwave link (CML) networks for use in precipitation and water vapor monitoring in terms of retrievals and direct data assimilation at different frequencies. Regarding UAS, in-situ aerial measurements with Meteodrones of the lower troposphere were tested as high up as 6 km above ground (Guay et al., 2023), compared against radiosonde and remote-sensing instruments

510 (Hervo et al., 2023) and found to meet WMO requirements (WMO, 2024). ~~Meteodrones are of interest for vertical profiles of temperature, humidity, wind speed and wind direction and can operate in horizontal wind speeds of up to 25 m s^{-1}.~~ Despite the limitations of drones due to strict airspace regulations and maximum operable wind speeds, they could offer a low-cost way to collect high-resolution 3D data that are difficult to attain with conventional point measurements.

Other drone applications are photographic documentation purposes. Cloud, dust, rain- and hail-shaft development can be

515 observed in time-lapse mode without the limitations imposed by buildings or vegetation being obstacles to the ground-based observers. Photographic post-event analysis of ~~wind damage, rain~~ rain damage, hail damage, and ~~hail damage~~ wind damage (ESSL, 2023b) as well as analysis of hail size distribution are feasible based on images taken from drones (Soderholm et al., 2020; Lainer et al., 2024). ~~The importance of aerial imagery including aeroplanes and drones was also stressed in damage survey guidance (Holzer et al., 2023).~~ High-resolution satellite imagery can be used in a similar way for some applications

520 (Shikhov and Chernokulsky, 2018; Gallo et al., 2019; Kunkel et al., 2023).

The global advent of dual-polarization radar data ~~in recent decades~~ has enabled the identification of ~~specific~~ polarimetric signatures linked to the dynamic and microphysical processes ~~at the heart of severe thunderstorms (e.g., Kumjian and Ryzhkov, 2008; Kumjian~~ ~~. Thanks to these observations, novel algorithms have been developed to enhance the estimation of storm severity , like the automated detection and appropriate assimilation of columns of enhanced~~ in storms (e.g., Kumjian and Ryzhkov, 2008; Kumjian, 2013; Da

525 . Because the severity is intrinsically related to the presence of updrafts and size-sorting signatures, many applications of polarimetric variables are known. For example, differential reflectivity (Z_{DR}) ~~(Snyder et al., 2015; Schmidt, 2020; Trömel et al., 2023) . However,~~ and co-polar cross correlation coefficient can be used to assess hail and lightning (Snyder et al., 2015; Schmidt, 2020; Trömel et , the discrimination between tornadic and nontornadic supercells (Loeffler et al., 2020), and the early prediction of tornadoes (French and Kingfield, 2021). Another application is the spectral analysis of the polarimetric variables which can explain

530 microphysical processes of hydrometeors detected at different radar beam heights (Lakshmi et al., 2024). However, operational radar data quality is often limited near complex terrain (Feldmann et al., 2021; Germann et al., 2022). For many radar diagnostics related to storm severity like Probability of Hail (POH, Delobbe and Holleman, 2006), Vertical Integrated Liquid (VIL, Greene and Clark, 1972), Maximum Estimated Size of Hail (MESH, Witt et al., 1998), or Z_{DR} columns, a high vertical resolution is needed, and beam shielding by mountains is problematic. Another challenge is the lack of low-level data~~.~~

535 ~~A lot of the~~, which limits the use of Dual-Doppler wind retrievals (Brook et al., 2021) and radar storm signatures ~~,~~ such as hook echoes or the Z_{DR} inflow arc (Fujita, 1958; Kumjian and Ryzhkov, 2009)~~, are at very low levels and generally not observed in mountains. Similarly~~. Furthermore, QPE in mountains can lead to errors in flood assessments due to strong reflectivity gradients below the melting level (e.g., Chen et al., 2023). ~~In a field campaign, the deployment of mobile radars could target the observational gaps that currently exist to quantify errors in operational networks. Such an approach was tested in~~

540 ~~France and Switzerland and can systematically deliver highly resolved thunderstorm data (e.g., Grazioli et al., 2019). Similar gap-filling data gathered in TIM can open pathways for improved estimation of storm severity diagnostics. This includes the polarimetric variables introduced above but also 2D and~~ The usage of mobile research X-band radars in TIM can complement and address limitations and gaps of operational radars. For instance, 3D wind fields ~~within storms, which are known to have a strong influence on~~ can be retrieved from dual-Doppler analysis in areas that are scanned by more than one radar.

545 Such retrieval is beneficial for updraft detection and validation (Evaristo et al., 2021) as well as for hail and tornado ~~potential (Dennis and Kumjian, 2017; Sessa and Trapp, 2020, e.g.,).~~ research (Sessa and Trapp, 2020; Pounds et al., 2024, e.g.,). Mobile radars can also allow for an improved classification of hydrometeor classes (Besic et al., 2016) and tracking of convective cells (Kollias et al., 2024).

Lastly, *swarmsondes* (Markowski et al., 2018) are balloon-borne probes that act as a pseudo-Lagrangian drifter and that

550 are drawn through the storm. Swarmsondes can be released in dozens ~~or potentially even hundreds~~ per thunderstorm and were found to fill the lack of reliable, aboveground, thermodynamic observations near and in convective storms. Swarmsondes in Europe were first used in the Swabian MOSES campaign in 2021 (Kunz et al., 2022). A slightly adapted version called *Hailsonde* ~~is currently being used as part of the LIFT campaign in Europe and the Northern Hail Project in Canada to~~ can mimic and analyze the trajectory and growth of falling hailstones within thunderstorm updrafts ~~(Brimelow et al., 2023; Kunz et al., 2024; Soderholm, 202~~

555 (Soderholm, 2024). Lack of such data from within thunderstorms is perhaps one of the biggest limitations in the field of convective storms. Much of our knowledge and model parameterizations of microphysical properties, such as hydrometeor concentrations within storm clouds, is based on storm-penetrating flights of the T-28 aircraft, which was retired around 20 years ago ~~(e.g., Allen et al., 2020)~~(e.g., Allen et al., 2020; Heymsfield et al., 2023). Hence, gathering such data with aircrafts or sondes in a field campaign could allow for big leaps in our understanding and forecast capability.

560 ## 3 Conclusions

3.1 Summary

As reviewed in section 2 and based on our White Paper survey, a wide variety of research topics (RT) exists regarding severe convective storms near mountains. Fig. 5 ~~summarizes these subjects and highlights their synergies. The importance of this research is emphasized by the observed increase in severe storm losses in recent years as well as the projected increase in~~

565 ~~severe storm activity because of climate change. ESSL is therefore coordinating the TIM field campaign as a first-of-its-kind Pan-European campaign on severe convective storms with a focus on mountain-related processes. To be highlighted as main research questions for the TIM campaign are~~ provides an overview of these topics and highlights the methodologies and data sources involved. The key research questions can be summarized as follows.

(1) Why do severe weather reports cluster near mountain ranges? To answer this, the terrain-induced perturbations of
570   environmental parameters like CAPE and wind shear will need to be weighed against storm-scale processes and CI in different regions and scenarios. (RT 1,2,3,4)
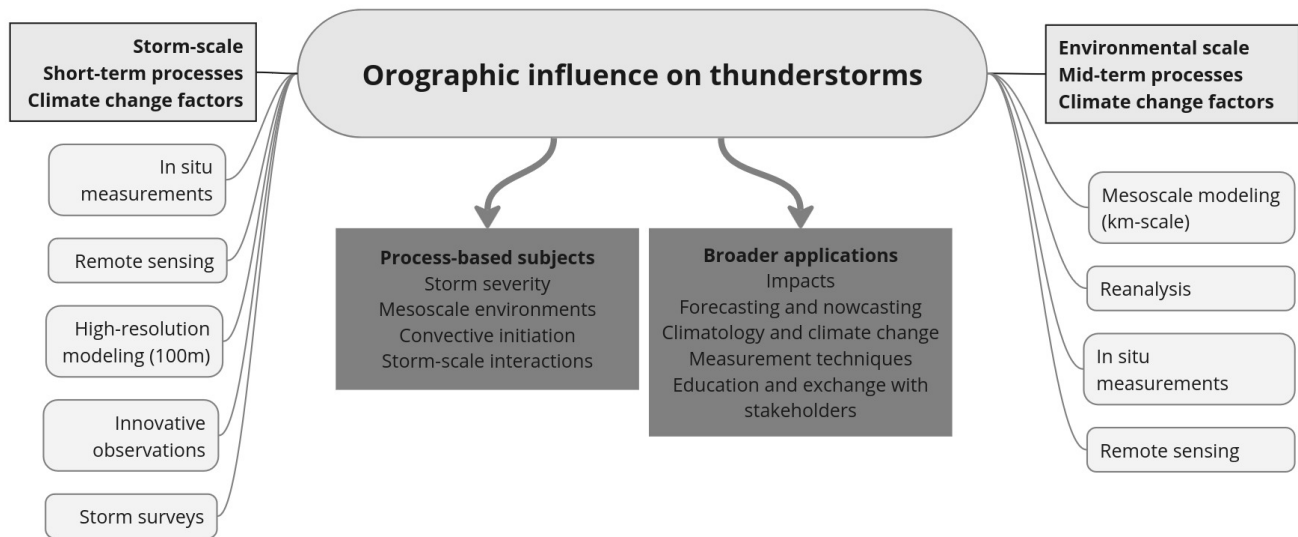
Figure 5. Overview of the ~~research topics in TIM~~ scopes and ~~their synergies across methods and scales~~scale of TIM research subjects, as well as the corresponding methodologies

(2) What are gaps in our understanding of the storm-internal processes leading to large hail, strong winds, lightning, tornadoes, and extreme precipitation and how are these processes modulated by the orography? Such basic understanding is also essential to better anticipate the impact of global warming on severe storms. (RT 1,4,5,7,8)

575   (3) What are the strengths and limits of new observation techniques from satellites, radars, or drones? TIM will provide the unique opportunity to compare these datasets to high-resolution sampling of individual storms and of heterogeneous environments near complex terrain. (RT 2,4,6,8)

(4) What observations are most important to improve numerical weather prediction models and nowcasting? ~~High-resolution datasets~~ Higher-resolution datasets (than currently operational) of the pre-storm environment and thunderstorm prop-

580   erties in TIM can be used in model studies to help answer this question and also to improve data assimilation and parameterizations of orographic or microphysical processes. (RT 1,4,6)

~~Detailed~~ The importance of these research topics is emphasized by the observed increase in related losses in recent years and the projected increase in severe storm activity because of climate change. ESSL is therefore coordinating plans for the TIM field campaign as a first-of-its-kind Pan-European campaign on severe convective storms. These plans are currently being

585   worked out in regular meetings with all partners. This White Paper may serve as scientific basis for further planning of the campaign and ~~specific strategies targeting these and other research questions will continue over the next years. Here, we only provide a first impression of the general campaign concept. Table ?? and Figure 6 provide an exemplary~~ the writing of funding proposals. Since the ultimate scope of TIM will depend on the success of these proposals and further planning, a detailed
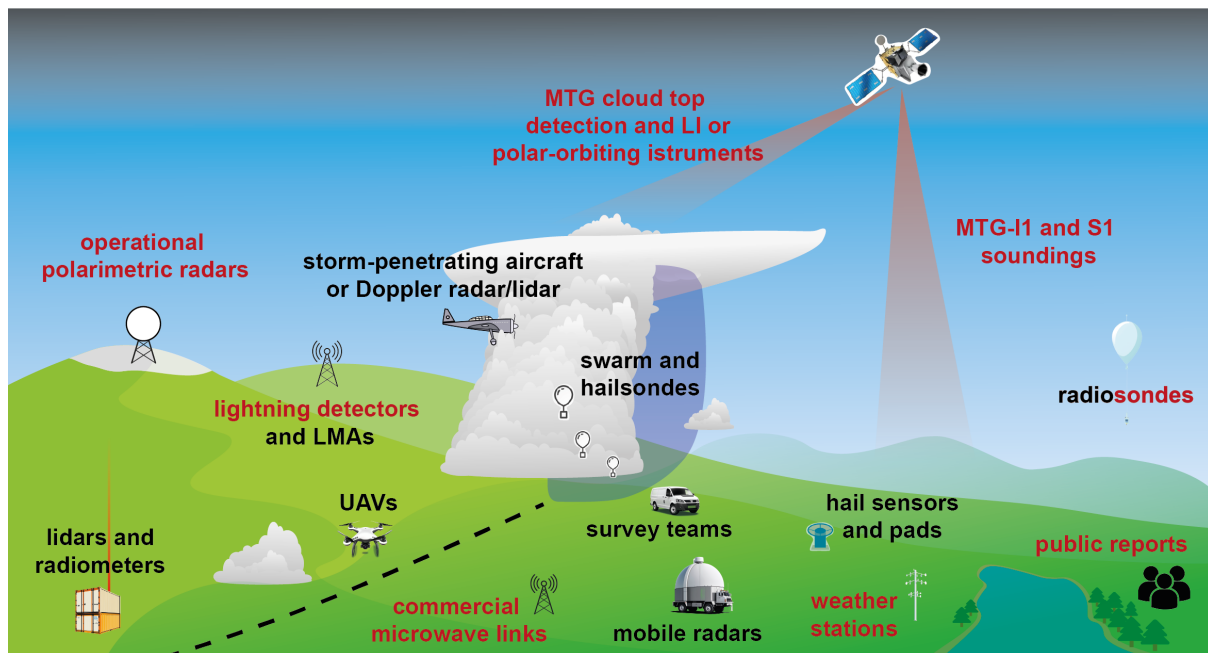
Figure 6. Overview of the observations planned in TIM. Since the campaign is still in an early phase, this can be seen as an ~~exemplary~~ ideal or example setup. Red colored text denotes ~~already or soon-to-be~~ at least partially operational data while black text would be part of TIM operations.

campaign plan cannot be presented here. However, to give a reader an impression of how we envision TIM, the rest of this section briefly discusses the planned concept.

3.2 Preliminary TIM campaign rationale

Figure 6 provides an example overview of the ~~planned~~ data collection. The TIM campaign can profit from the wealth of already operational observations across Europe (red text in Fig. 6). This includes meteorological stations with ground data, regular vertical soundings, radars, satellites, lightning sensors, and public reports. Some of these datasets are currently not openly available to researchers. One example is the European radar network, which is globally unique in its density and coverage and provides excellent opportunities for analysis over a large region but is often only analyzed for each country separately. Data sharing in TIM could therefore accelerate the development of new radar-based algorithms for severe weather prediction, for instance based on machine learning (Leinonen et al., 2023; Forcadell et al., 2024). ~~The open-data approach of TIM provides a pathway to make datasets available to participating researchers and to include early feedback into what data structures are most useful, for example for machine learning scientists~~To this end, part of the funding will be allocated to create a central data hub for systematic data collection, exchange, and long-term archiving. Ideally, TIM will be a first step towards permanent sharing of ~~such datasets~~ operational datasets for SCS research in the future.

However, additional data from the TIM campaign is needed, especially in and around thunderstorms and at higher spatial and temporal resolution than currently provided by operational networks (black text in Fig. 6). This includes mobile radars, swarmsondes, drones, high-resolution soundings, and survey teams. Such observations are often difficult to obtain due to the fast-evolving and small-scale nature of convective storms. Thus, to sample a high number of cases it is necessary to be mobile. On the other hand, some of the research objectives described herein require specific measurements which can only be supplied by fixed instruments, such as lidars, hail sensorsdisdrometers, LMAs, or high-density station networks, which cannot be re-located on a daily basis (e.g., Emeis et al., 2018).

A field campaign with both mobile and fixed-site measurement strategies offers the unique opportunity to address this dilemma.

To sample individual storms and their hazards, TIM will deploy several mobile teams that can travel to a region where high-impact storms are expected on a given day. Most severe weather events cluster in time and space, so mobile teams can collect data in the same region over multiple days or by traveling from west to east within a conditionally unstable airmass. At the same time, multiple permanent TIM focus sites will be set up over the convective season to continuously monitor the same region, supplemented by the mobile teams when severe storm activity is expected in the same location. A similar strategy has been successfully used in several campaigns focused on convective storms in target regions (e.g., PERILS, RELAMPAGO). A unique aspect of the current plans for TIM is that focus sites will be maintained by participating institutions based on their individual funding and therefore tailored to the specific research interest in these regionsresearch focus. In parallel, core funding of TIM will support mobile teams to collect additional high-resolution where they have the highest research usedata. This flexible approach allows the effective use of funds and overlap of different research topics (Fig. 5).

Figure 7 highlights potential regions of interest (ROI), where ROI are identified through clustering analyses of ESWD severe hail reportsin the TIM domain. While storm reports can be subject to reporting biases, ESWD report densities show good agreement with existing climatologies and using the large ESWD database allows to identify regions of high activity where interest and potential impacts are most relevant. Primary hotspots with very high report densities delineated by kernel-density estimation (KDE) are apparent along the central northern and central-to-eastern flanks of the European Alpsincluding the Jura and Swabian Juraas well as to the North of the Carpathian Mountains. Relatively fewer but yet distinct clusters grouped by density-based spatial clustering of applications with noise (DBSCAN) become apparent in the vicinity of medium mountain ranges such as the Massif Central, the Bohemian Massif and the Dinaric Alps. This is one way to objectively define ROI and is used as an example here to highlight the most important ROI: the Po valley and the border region between Austria and Slovenia south of the Alps; the valleys near the Swiss Jura, Black Forest, Swabian Jura, and Southern Bavaria north of the Alps; and regions around the Pyrenees, Massif Central, Dinaric Alps, Bohemian Massif, and Carpathian mountains. Many secondary ROI are also visible in Fig. 7. It is important that ESWD reports can be subject to reporting biases, so some of these secondary
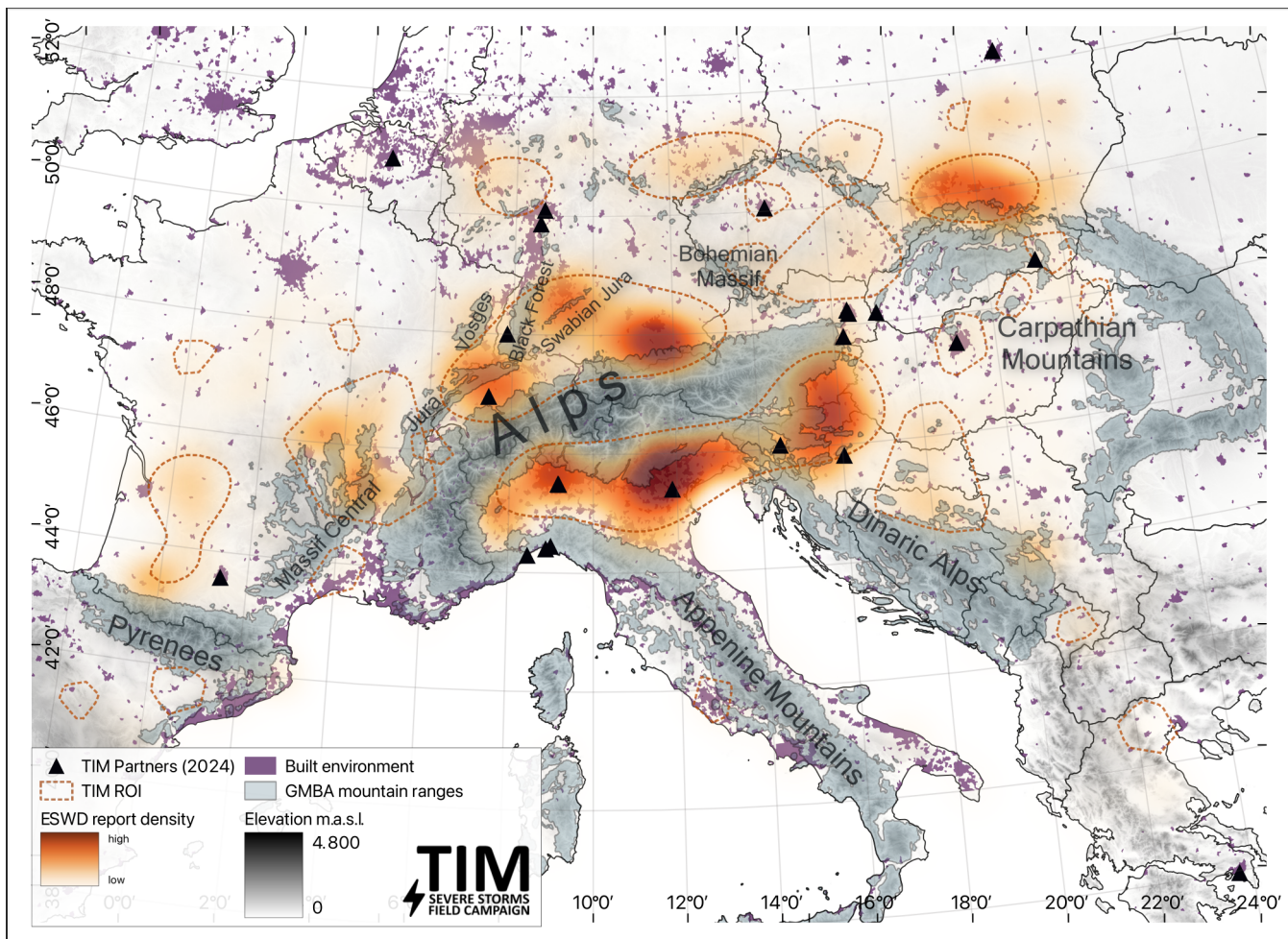
Figure 7. Map of the TIM domain with regions of interest (ROI). ROI were identified based on in-domain ESWD severe hail reports (c.f. Fig. 1). Red shading indicates primary hotspots with high report densities from kernel-density estimation (KDE). To represent secondary clusters, reports grouped by density-based spatial clustering of applications (DBSCAN) are indicated with lighter shading. Also shown are mountain ranges of the GMBA mountain inventory (Snethlage et al., 2022b, a) and built-up surfaces (Pesaresi and Politis, 2023). Black triangles show official TIM partner institutions headquarter locations as of May 2024 (see list below).

ROI in less-populated regions such as around the Carpathian mountains are likely more impacted by SCS than depicted here (Šinger and Púčik, 2020). Nevertheless, the reports show good agreement with existing radar-based climatologies in Europe (e.g., Punge and Kunz, 2016; Fluck et al., 2021) and allow to identify regions of high impact. Which focus sites can ultimately be investigated in depth with TIM will depend on the priorities and funding of individual partner institutions.

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Besides geographical and climatological differences among the regions, also the densities, lengths and types of operational observations vary substantially. ~~TIM aims at addressing these regional differences both in the planning and interpretation of the results.~~

645 The collaboration between many institutes brings together the necessary expertise to handle these diverse data needs, which no single institution can cover on its own. TIM already has a long list of partner institutions officially engaged who also contributed to this article (see ~~next section~~ below and Fig. 7). ~~ESSL is leading these efforts~~ A core investigative team lead by ESSL will be established to lead these efforts and to ensure that possible conflicting interests over ~~the wide spectrum of~~ many institutions can be coordinated. ~~Because of this spectrum of interests~~ Working groups on individual subtopics, such as

650 Climatology, Radar, air-borne data, and idealized cloud modeling, are currently being established and will be expanded to specify the plans for TIM. Because of the spectrum of topics and because of the high spatio-temporal variability of convective storms (e.g., Taszarek et al., 2020a) the campaign is planned for three consecutive convective storm seasons, currently from ~~2026 to 2028.~~ 2027 to 2029. This is followed by two years of data analysis to ensure the effective and coordinated use of the observations. This observational data will be supplemented by numerical modeling experiments tailored to the respective

655 research questions and focus regions.

Furthermore, ESSL testbeds during and after the campaign provide ample opportunities to foster exchange with European severe weather forecasters.

High-quality forecasts focused on severe convective storms are also essential for the coordination of the campaign. Like in previous severe storm campaigns, a forecast team will be responsible for briefing the research groups on an active campaign

660 day. The forecasts can benefit from the bundled resources of partner institutions and experience of projects like the European Storm Forecast Experiment (ESTOFEX), Previsione Temporali (PRETEMP), as well as local forecast offices who know the characteristic meteorology of a certain mountain range.

Thanks to the globally-connected severe storms community, TIM can also profit from the experience of international researchers. ~~Exchange at the recent European hail workshop has already opened fruitful discussions and opportunities for~~

665 ~~international collaboration. Specifically~~ For example, TIM researchers could coordinate with, and learn from the ~~planned~~ ICECHIP and TEAMx campaigns (Adams-Selin et al., 2022; Rotach et al., 2022). Their research foci (hailstorms in the US Great Plains and terrain effects on the atmosphere) ~~could~~ can be complemented and linked by TIM's focus on severe convection near mountains. ~~Further coordination~~ Exchanges with the Northern Hail and Tornado Projects (e.g., Brimelow et al., 2023), the LIFT campaign (Kunz et al., 2024), and observational efforts of the Australian Bureau of Meteorology (e.g., Soderholm,

670 2024) are ~~planned~~ already ongoing. TIM has the ambition to foster ~~international collaboration~~ collaboration with international researchers as well as stakeholders and policy makers, educate through public and media outreach, and introduce students to the field of convective storms, which will ultimately help to meet the challenges that the increasing risk of ~~these phenomena~~ SCS pose to European society.

~~Preliminary list of potential TIM observations during the active field campaign. The list is non-exclusive and not necessarily~~

675 ~~to be realized at all locations.~~ **Data Details** ~~Radiosondes or Meteodrones Vertical profiles of temperature, moisture, and wind with a temporal resolution <1 hour and comparing different terrain-relative locations Satellite-based soundings Test temperature~~

and moisture profiling and detection of horizontal heterogeneities against in-situ measurements Operational (polarimetric) radars Nowcasting and analysis of storms, including internal microphysical and dynamical processes Mobile Doppler radars Higher-resolution data for the above for in-depth dynamics or gap filling analyses Drone surveys Detection of hail spectra, hail swaths, and damage surveys from hail, tornadoes, and straight-line winds Manual survey temas Hail collection and manual damage surveys. Launching of Swarmsondes. Public reports Collection of widespread severe weather reports as ground truth Hail pads or sensors Same as above for hail with higher accuracy and detailed spectrum information Swarmsondes Gathering within-storm data such as updraft and downdraft velocity, moisture content, internal boundaries, and hail trajectoriesSatellite cloud top detection Analysis of cloud top features and their link to severe weather Satellite lightning mapper Same as above for lightning Lightning sensor network See above Lightning Mapping Arrays Analysis of 3D lightning activity and polarization regions Airborne Doppler lidar and radar Measurements of 3D winds Storm-penetrating aircraft Gathering within-storm data such as water content, CCN and INP concentrations Ground-based and airborne lidars High-resolution vertical profiles of wind shear and boundary layer processes Meteorological station network High-resolution data near the surface Isotopic water vapor and aerosol collectors Source analysis of water vapor composition and aerosols

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Table 1. Glossary of abbreviations that are repeatedly used

CAPE	Convective Available Potential Energy
CCN	Cloud Condensation Nuclei
CI	Convection Initiation
CIN	Convective Inhibition
CML	Commercial Microwave Link
ESSL	European Severe Storms Laboratory
IF	International Fujita (Scale)
INP	Ice Nucleating Particle
LMA	Lightning Mapping Array
MCS	Mesoscale Convective System
MESH	Maximum Estimated Size of Hail
POH	Probability of Hail
QPE	Quantitative Precipitation Estimation
ROI	Region of Intereerest
RT	Research Topic
SCS	Severe Convective Storms
VIL	Vertical Integrated Liquid

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