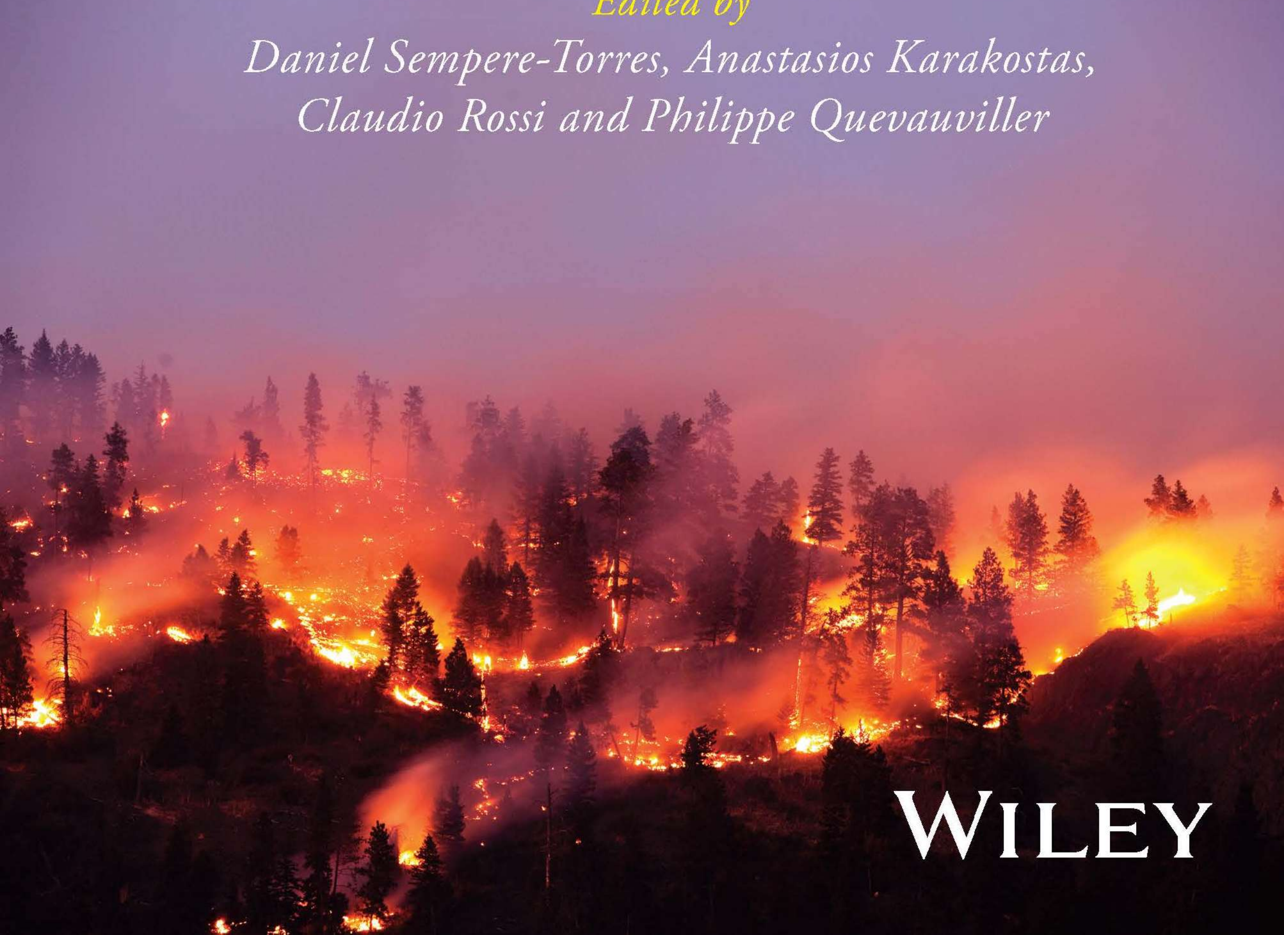
HYDROMETEOROLOGICAL EXTREME EVENTS

RESPONDING TO EXTREME WEATHER EVENTS

Edited by
Daniel Sempere-Torres, Anastasios Karakostas, Claudio Rossi and Philippe Quevauviller



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Series Preface

The increasing frequency and severity of hydrometeorological extreme events are reported in many studies and surveys, including the 5th IPCC Assessment Report. This report and other sources highlight the increasing probability that these events are partly driven by climate change, while other causes are linked to the increased exposure and vulnerability of societies in exposed areas (which are not only due to climate change but also to mismanagement of risks and 'lost memories' about them). Efforts are on-going to enhance today's forecasting, prediction and early warning capabilities in order to improve the assessment of vulnerability and risks and develop adequate prevention, mitigation and preparedness measures.

The Book Series on 'Hydrometeorological Extreme Events' has the ambition to gather available knowledge in this area, taking stock of research and policy developments at international level. While individual publications exist on specific hazards, the proposed series is the first of its kind to propose an enlarged coverage of various extreme events that are generally studied by different (not necessarily interconnected) research teams.

The Series encompasses several volumes dealing with various aspects of hydrometeorological extreme events, primarily discussing science-policy interfacing issues, and developing specific discussions about floods, coastal storms (including storm surges), droughts, resilience and adaptation, governance, and public health impacts. While the books are looking at the crisis management cycle as a whole, the focus of the discussions is generally oriented toward the knowledge base of the different events, prevention and preparedness, early warning and improved prediction systems.

The involvement of internationally renowned scientists (from different horizons and disciplines) behind the knowledge base of hydrometeorological events makes this series unique in this respect. The overall series will provide a multidisciplinary description of various scientific and policy features concerning hydrometeorological extreme events, as written by authors from different countries, making it a truly international book series.

The Series so far is made of five volumes, an introductory one on '*Hydrometeorological Hazards: Interfacing Science and Policy*' (2015, Ed. Ph. Quevauviller), a second volume dealing with '*Coastal storms: Processes and Impacts*' (2017, Ed. P. Ciavola and G. Coco), a third volume on '*Droughts: Science and Policy*' (2019, Ed. A. Iglesias, D. Assimacopoulos and H.A.J. Van Lanen), a fourth volume intitled '*Facing Hydrometeorological Extreme Events: A Governance issue*' (2020, Ed. I. La Jeunesse and C. Larrue), and a fifth one on '*Hydrometeorological Extreme Events and Public Health*' (2022, Ed. F. Matthies-Wiesler and Ph. Quevauviller). The volume '*Responding to Extreme Weather Events*' is the sixth book of this Series; it has been written by experts in the field, covering various horizons and (policy and scientific) views gather from three major international research projects funded by the European Union Horizon2020 Framework Programme. It offers the reader an overview of scientific knowledge about challenges related to responses to weather extreme events, in particular impact forecasting, use of artificial intelligence and cybertechnologies for extreme weather event's management, and communication and public warnings.

Ph. Quevauviller
Series Editor

1

The ANYWHERE Paradigm Shift in Responding to Weather and Climate Emergencies

Impact Forecasting, Dynamic Vulnerability and the Need for Citizen's Involvement

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1.1 Disaster Risk Management in Times of Climate Change: The Need of a Proactive Approach

The world has just seen the hottest decade on record during which the title for the hottest year was beaten eight times (WMO 2023). This tendency will continue for decades, even if global and European efforts to cut greenhouse gas emissions prove effective. We also know today that **'There is no definitive way to limit global temperature rise to 1.5°C above pre-industrial levels'** *(IPCC SR 1.5)*. Even a drastic temporary decrease in emissions (the 2008 financial crisis or during COVID-19 pandemic) has proved to have little effect on the overall trajectory of global warming. Therefore, and especially after the extreme events observed worldwide during 2021 and 2022, it is widely recognized that the effects of climate change (CC) are already happening today.

Responding to Extreme Weather Events, First Edition. Edited by Daniel Sempere-Torres, Anastasios Karakostas, Claudio Rossi, and Philippe Quevauviller.

Moreover, the analysis of the impacts of natural hazards in the last 50 years (see WMO 2021) shows that the **frequency and severity of these extreme climate and weather events are increasing and exacerbating climate-related economic and social losses.** And the urgency to react to their consequences is a social priority with significant political and economic implications, as proven by the climate emergency declaration of the *EU parliament (November* 2019),[1] and several other *national and regional parliaments*[2] and *leading cities*[3].

As stated by the EU Strategy on Adaptation to Climate Change (EC 2021a, b),[4] the EU and the global community are underprepared for the increasing intensity, frequency and pervasiveness of climate change impacts, especially as emissions continue to rise. We must rapidly build our resilience to CC by moving from raising public awareness and concern to mass action on adaptation. Accordingly, the **'Adaptation to CC, including Societal Transformation'**, has become one of the five Horizon Europe Missions to push this significant societal challenge[5].

In this regard, Early Warning Systems (**EWSs**) have become a crucial instrument for disaster risk management **(DRM)**. Now promoted by the United Nations (UN) through the 'Early Warnings for All initiative'[6], EWS can be especially critical during weather/climate emergencies. However, to be effective, they must be able to trigger the intended actions for damage reduction to be undertaken by authorities, first and second responders and citizens (i.e. the earliest responders in place, also seen as the zero-order responders, Briones et al. 2019).

Nonetheless, triggering the full chain of emergency management starting with the hazard forecasts up to the emergency management actions is not a simple objective, as the *catastrophic floods of July 2021 in Germany and Belgium*[7] exemplified (over 180 deaths in just a 200 mm daily rainfall event, see Table 1.2). Currently, the available scientific and technical advancements enabling us to anticipate extreme events are not well integrated into the real-life protocols of authorities and first responders. Hence it is critical to develop and implement EWSs adapted to the local needs of authorities, first responders and the population. And be able to connect them to local/community risk management plans able to ensure that the warnings can trigger the required local actions that can effectively reduce damages and loss.

This chapter, and some of the following ones, summarizes the **paradigm shift in responding to weather and climate emergencies based in the project results and lessons learnt during the ANYWHERE innovation action.**

1.2 Adapting Risk Management to the 'New Normality': The Case of Flood Risk Management

Before describing the details of the **ANYWHERE** proposed tools and results, it is important to illustrate the challenge of what it means to consider the effects induced by the CC through a particular well-known hazard, such as floods.

Floods are the most significant natural hazards in Europe in terms of the number of events, people affected and economic losses. But it is also, together with storms, the most relevant natural hazard worldwide (CRED 2020). Hydrological hazards (floods, and heavy-rain-induced disasters) are also the natural hazard that has most increased in frequency in the last 30 years (Kron et al. 2019).

Table 1.1 Differences between riverine and coastal floods compared with pluvial and flash floods under climate change effects.

	Riverine and coastal floods	Pluvial and flash floods
Time response	Long: days	Short: several 1/4 hours
Location	We know where: • Mapping of risk can be done • Defence and structural measures are possible • **PLANNING** is CRUCIAL	Can be ANYWHERE: • The probability increases with climate change (an increase in heavy rains) • The probability increases with an increase in wildfires • Structural measures are out of the question • **REAL-TIME MANAGEMENT** of the response is crucial
What to do	**We know** what to do • River restoration • Floodplain recuperation • EVACUATION is possible	**At present we DO NOT know** what to do: • Need of a NEW PARADIGM • **CITIZENS'** involvement is crucial • **SELF-PROTECTION** Flood Risk Management Plans • Subsidiarity principle

In this context and as seen in Table 1.1, it is important to recognize the differences between what are considered 'classical or typical floods' (e.g. riverine and coastal floods) and the 'new intensified floods', episodes that are not only increasing in their frequencies but also in their intensities and amount (and level) of seen socio-economic impacts due to CC (e.g. pluvial and flash floods).

On one hand, riverine and coastal flood events have long response times (that can go from several hours to several days) and thus the time between the event starts and the main consequences is of the order of several hours or days. However, pluvial and flash floods are directly related to heavy-rains and the associated torrential phenomena have extremely short response times (usually a few quarters of an hour). Consequently, these types of events trigger emergencies that develop too quick for a reactive response based on direct observations. Thus, the only appropriate emergency response must be based on the timely anticipation of the event (at least a few hours in advance, Alfieri et al. 2016). This implies that decision-making needs to rely into trusted, but uncertain, high-resolution forecasts instead of waiting to receive direct observations (only available when the impacts are already occurring), what it is by itself a significant operational challenge.

On the other hand, for the first category we can anticipate where these kinds of events will happen (around the river flood-prone areas, or in particular areas of the coastal line). Therefore, risk cartographies can be pre-established, making possible to plan defences and structural measures, as well as evacuation plans. Thus, planning is crucial to cope with these types of floods.

Contrarily, heavy-rainfall-induced floods can happen anywhere. Moreover, given the effects of CC on the increase of the frequency and severity of heavy rains, as well as on other factors amplifying the torrential character of flash floods (such as the increase of the number and severity of forest fires, which worsens the magnitude of flash floods due to the loss of vegetation; see Lavabre et al. 1993; Versini et al. 2013; Wine and Cadol, 2016; Wagenbrenner et al. 2021), pluvial and flash floods have multiplied by 3 in the last 30 years[8] and they are at present the climate-induced hazard that has increased the most. In this context, emergency management cannot only be based on planning, and the **real-time management of the response becomes crucial.**

Furthermore, whereas in riverine and coastal floods we have enough experience with effective measures to reduce and manage the associated risks (through river restoration works, floodplain recuperation actions and evacuation plans etc . . .), in the case of pluvial and flash floods, we need to recognize that essentially the current established knowledge in flood risk planning and management turns out to be useless (as in the case of July 2021 in Germany and Belgium).

In these floods, as in any other hazards where climate change is making knowledge based on past experience irrelevant, we need to acknowledge that a change of paradigm is required. Change of paradigm that implies accepting to **move from planning-based strategies towards real-time management strategies, essentially based on EWSs adapted to the local needs**, providing actionable information able to trigger the response, not just of the local authorities, but also of the citizens. This requires a disruptive societal transformation in emergency management through the implementation of flood risk management plans, which should include as a major component the concept of **self-preparedness and self-protection actions**, previously identified and adapted to the most vulnerable points and communities, a transformation that should be supported by advanced and adapted technological tools (Gräßler et al. 2020).

To understand the urgency of such a societal transformation, Table 1.2 shows the main characteristics of recent heavy-rainfall events recorded in Europe in 2020 and 2021. Whereas during the catastrophic floods in Germany in July 2021, the quantities recorded represented the equivalent of 2 months of accumulated rainfall registered in 24 hours, we can see that this event is not extraordinary in our 'new' CC times. Thus, we urgently need to start being prepared to face events delivering these 2-month accumulated rainfall in less than 24 hours or more, such as the event on the 4 October 2021 in Rossiglione, Liguria (IT), where the European rainfall-accumulated record in 12 hours has been beaten: 740 mm in 12 hours, representing **one year mean rainfall accumulated in 12 hours**.

These and the other events in Table 1.2 can help us to understand the magnitude of the new scenarios we need to be prepared to, and the urgency with which we need to start initiating the adaptation to the consequences of climate change.

1.3 Changing the Paradigm: Impact-Based Multi-Hazard Early Warning Systems to Move from Reactive to Pro-Active Emergency Response Strategies

In this context, adapted **DRM** will require an update of the tools and methodologies to evolve our present risk assessment capacities, crisis management and preparedness strategies for the natural hazards under CC. Thus, an enhanced DRM cycle will require tools using different types of information and forecasts that can enable the anticipation of disasters, providing **Early Warnings supporting the situational awareness and rapid deployment of responders in vulnerable areas**.

Table 1.2 Some examples of recent heavy rainfall events giving us what can characterize the 'new normality' under climate change times.

	Total accumulated rainfall	Maximal intensity	In terms of average monthly rainfall
14 July 2021 Germany	200 mm in 24 h	>40 mm in 1 h	2-month rainfall in 24 h
1 September 2021 @ Alcanar (ES)	220 mm in **3 h** 260 in 24 h	**77 mm in 30 minutes**	6-month rainfall in 24 h
8 September 2021 @ Agen (FR)	130 mm in **3 h**	80 mm in 1 h	2-month rainfall in 3 h
18 December 2020 @ Cerdanyola (ES)	**300 mm** in 24 h	>100 mm in 1 h	6-month rainfall in 24 h
4 October 2021 @ Rossiglione, Liguria (IT)	**900 mm** in 24 h **740 mm in 12 h**	**>180 mm in 1 h**	**12-month rainfall in 12 h**

To that end, impact-based EWS **(IEWS)** (WMO 2021) and particularly multi-hazard impact-based EWS (**MH-IEWS**) for weather emergencies have been *promoted by the WMO and the Sendai Framework (Target G),*[9] (Murray 2021) see Figure 1.1[10,11], as the next step to translate forecasts into information **supporting actionable decisions during emergencies** and triggering **site-specific actions based on early risk forecasts.**

Although many current initiatives are trying to develop the concept of IEWS for weather and climate-induced disasters, there are very few successful experiences in implementing and demonstrating MH-IEWS in an operational environment (Merz et al. 2020). The successful H2020 Innovation Action **ANYWHERE** (www.anywhere-h2020.eu), winner of the EC Security Innovation Resilience Award in 2022,[12] is one of them.

1.3.1 From Reactive to Proactive Emergency Response Strategies

This innovative pathway can be clarified by taking the example of the case of the floods in Germany in July 2021. For this event, a clear warning for the *river Ahr*[13] (one of the most affected areas) was available through the European Flood Awareness System (*EFAS,*[14] part of the Copernicus Emergency Management Services, *CEMS*[15]), was available **more than 24 hours in advance of the floods**, see Figure 1.2. Moreover, the *ANYWHERE A4EU system*[16] provided a high-resolution warning based on the *OPERA network radar data*[17] for the portion of the river most affected **5 hours in advance** (with enough time to take self-protection actions and reduce the number of fatalities). Consequently, the technology to activate actionable solutions through a risk management self-protection protocol was fully available and working correctly. However, the EU society has not yet the capacity to react effectively to these new climate-induced emergencies, even if we have already the technology to anticipate their occurrence and impacts,[18] as the declarations in front of the Commission of Inquiry about these floods in the Walloon Parliament have shown.[19] Thus, the main

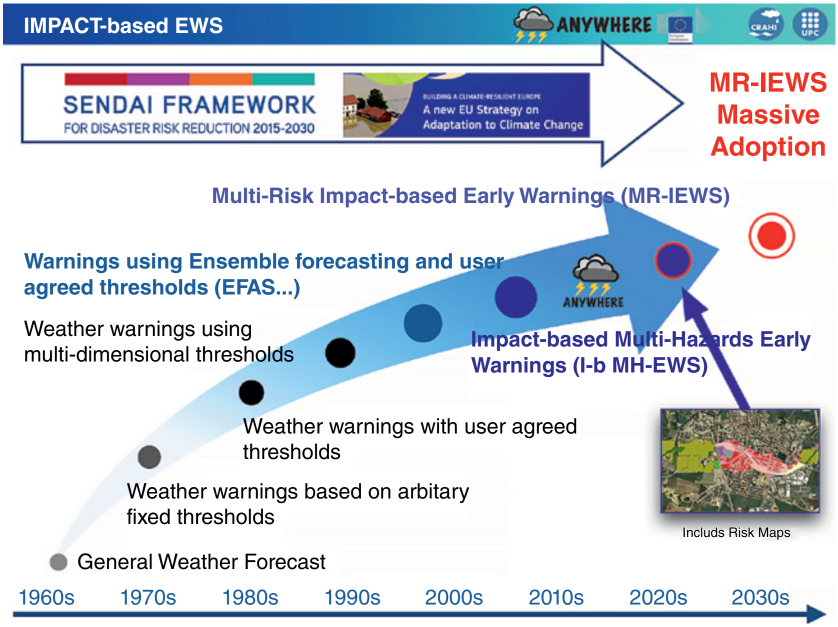

Figure 1.1 Evolution of the warning systems to support decision-making during weather and climate emergency. The initial general weather forecast has been transformed in different families of weather warnings issued by the National Meteorological Services. The advancements of the last years include the integration of probabilistic approaches using ensemble forecasting, as in the European Flood Awareness System (EFAS), or the impact-based multi-hazard early warning systems (MH-IEWS), among which *ANYWHERE* is one of the first real-time systems tested in operational environment in several Emergency Management Centres in Europe. In the next years, it is foreseen that these MH-IEWS could evolve towards new Multi-Risk Early Warning Services able to be massively adopted to support international initiatives such as the Sendai Framework for Disaster Risk Reduction, to promote the EWS4ALL initiative of the WMO as well as the international initiatives supporting climate change adaptation (CCA).

challenge is how to use this technology to empower Emergency Management Centres to transform advanced meteorological forecasts into high-resolution hazard and impact forecasting products providing information about the magnitude of the event and the expected consequences, allowing them to trigger the required actions to minimize damages and losses.

In this strategy, an important step is to understand that nowadays, the usual practices in most emergency management centres (EMCs) are still mainly reactive (first the emergency is detected, usually through 112 calls, then the reaction follows pre-established protocols, see Figure 1.3-above). There are very few exceptions of EMCs **able to act in proactive mode**, i.e. integrating forecasting capabilities or initiating the response based on the early detection of weak signals (before the emergency becomes evident). In the last years, several H2020 projects (**EMERGENT**, **ANYWHERE**, **I-REACT**, **BEAWARE**) have shown that technological developments can be of precious help for an anticipated response of first responders.

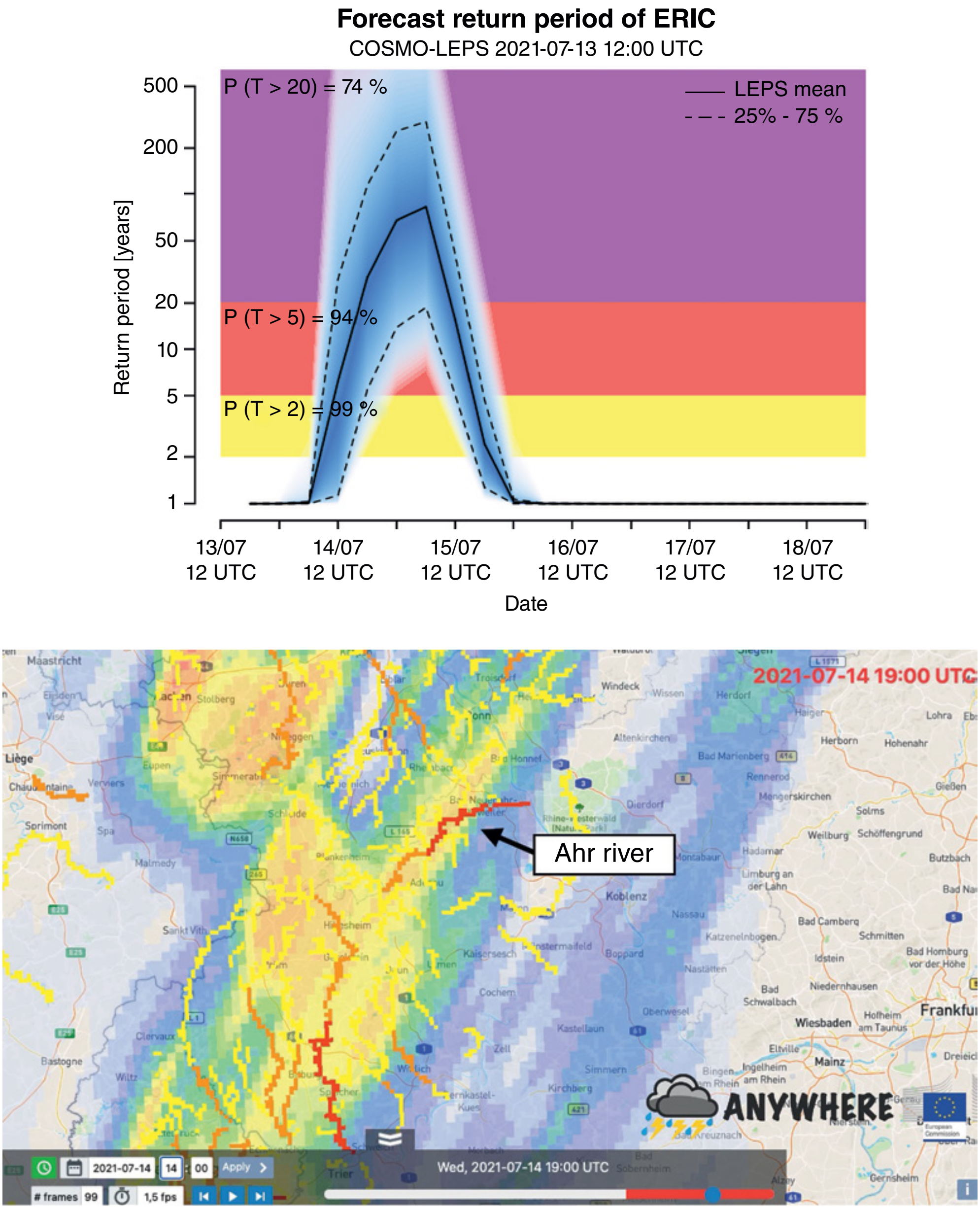

Figure 1.2 (Above) *ERIC flash flood indicator* announcing 74% probability of exceeding the highest warning level for the Ahr river (Germany) using the meteorological model forecast run on the 13 July at 12 : 00 UTC (>24 hours before the flood peak). *Source*: *EFAS*. (Below) Forecasted *ERICHA flash flood indicator* showing the maximum warning level on the Ahr river issued the 14 July at 14 hours UTC (5 hours in advance) using the rainfall nowcasts from the OPERA radars composites. *Source*: *ANYWHERE*.

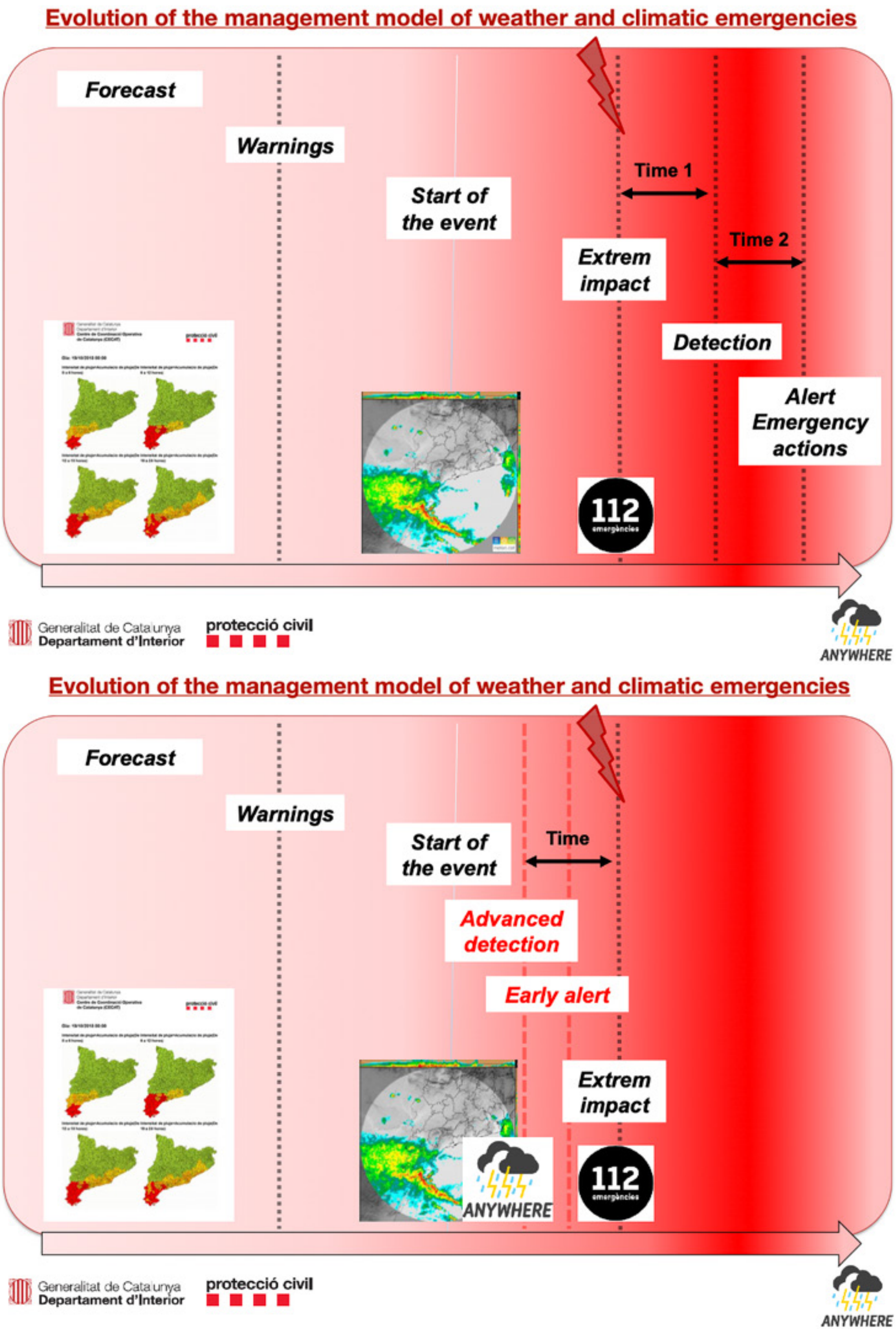

Figure 1.3 Change on the management model of weather-induced emergencies thanks to the *ANYWHERE* project developments: (above) Instead of detecting the impacts with delay time 1, and start the emergency actions with delay 2; (below) the ANYWHERE platform allow to anticipate the detection of the event and advance the response before the occurrence of the impact. *Source*: Courtesy of Sergio Delgado, Department of Civil Protection of the Generalitat de Catalunya.

In particular the *ANYWHERE* project has developed an operational **multi-hazard EWS** for extreme weather and climate events, able to translate the most advanced meteorological forecasts into *impact forecasting products* to support emergency management (Abily et al. 2020, see Section 1.3.2). The system was verified, tested and operationally demonstrated in **7 Emergency Management Centres covering the entire climatic range in the EU for 18 months,**[20] demonstrating in real time that the generalization of the proactive way of working in EMCs is now possible (see Figure 1.3-below).

These **ANYWHERE** innovations translate meteorological forecasts into anticipated impacts and **automatically connect them to critical points to trigger a set of pre-defined actions** (for instance, those of the self-protection plans), allowing civil protections and EMCs to start the response phase before the occurrence of the impacts, **reducing the damages through the concept of dynamic vulnerability** (Sempere-Torres 2019), see Section 1.4.

This capacity was tested operationally during the 50-year return period **Storm Gloria (19–23 January 2020)**, which severely affected the east coast of Spain, and in particular Catalonia in a severe way. During this event the Civil Protection of Catalonia triggered several response actions (including the management of the river Ter dams, and the confinement of tens of thousands of affected inhabitants of different cities) **based on impact forecasting early warnings for the first time in Europe**, before observations were available (saving over six hours for the operations).

1.3.2 The ANYWHERE MH-IEWS

The **impact forecasting concept** implemented by the ANYWHERE project consists of running state-of-the-art hazard-forecasting algorithms and models (driven by advanced meteorological forecasts) and combining them with the available exposure and vulnerability information to translate them into impact forecasts (see Figure 1.4).

In ANYWHERE, these algorithms and models are connected or encapsulated in a joint real-time MH-IEWS running in parallel to generate hazard forecasts for floods, flash floods, landslides and debris flows, storm surges, forest wildfires, droughts, heatwaves and weather-induced health impact, convective storms, severe winds and snowfall. The outputs of these algorithms were compiled in a catalogue of products describing the hydro-meteorological situation and forecasting the hazard level and expected impacts[21] that were served in real time by the ANYWHERE MH-IEWS to support emergency management and self-protection actions in the pilot sites of the project.

Given the differences in the characteristic scales of the different weather and climate hazards considered, the driving meteorological inputs are adapted to each hazard. These included the use of observations and radar-based precipitation nowcasts for the most local and fast-evolving hazards, such as convective storms or local flash floods and landslides (Palau 2021; Palau et al. 2020, 2023); limited-area Numerical Weather Prediction (NWP) models (driving the forecasting systems for floods, flash floods) and medium-range and seasonal forecasts (for the drought impact forecasting algorithms).

The ANYWHERE MH-IEWS is connected to the Continental-scale hazard and impact forecasts generated by the Copernicus Emergency Services (CEMS)[22]: mainly, the hydrological forecasts of the European Flood Awareness System (EFAS); the fire

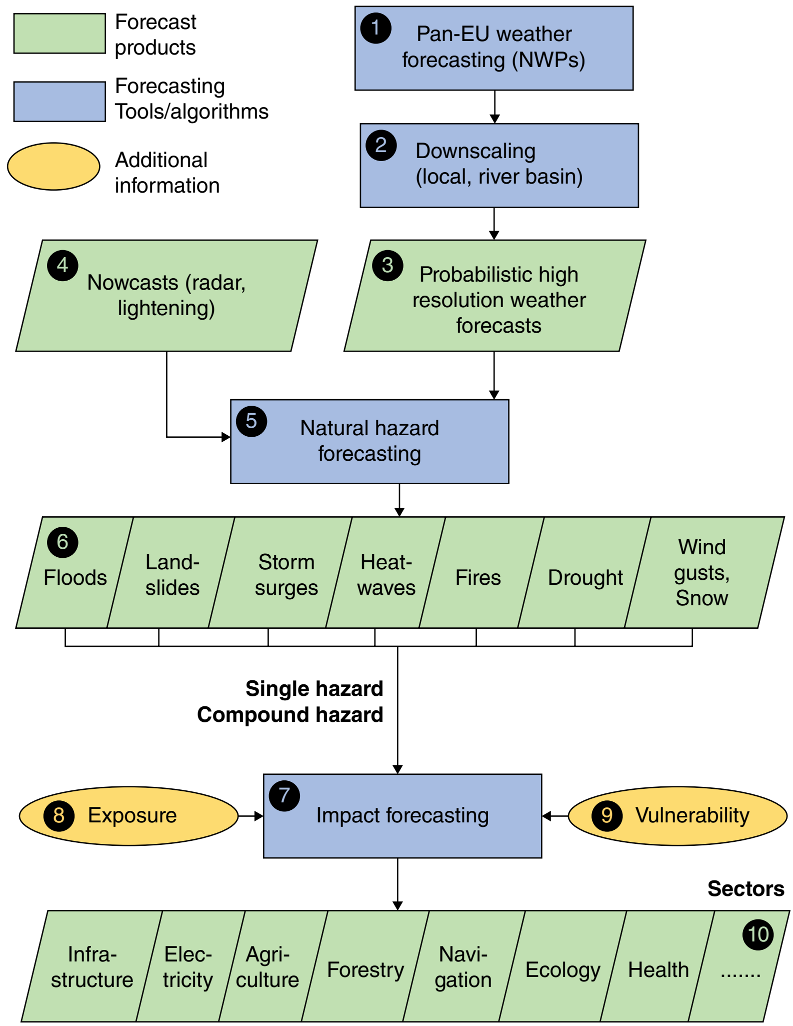

Figure 1.4 ANYWHERE multi-hazard IEWS forecasting platform: products and tools/algorithms to forecast weather-induced natural hazards and associated impacts.

of the European Forest Fire Information System (EFFIS) and the European Drought Observatory (EDO).

The EFAS flood products were complemented with flash flood hazard and impact nowcasts at Continental scale (Park et al. 2019; Ritter et al. 2021) and regional scale (Corral et al. 2019; Poletti et al. 2019; Ritter et al. 2020, 2022; Láng-Ritter et al. 2022), combining the hazard forecasts with the flood hazard and risk maps developed in the framework of the EU Floods Directive (2007); the vulnerability layers at the relevant scale to assess the expected losses and the expected impacts on population and critical points.