Received: 27 December 2021 | Revised: 29 November 2022 | Accepted: 17 March 2023

DOI: 10.1002/met.2124

REVIEW

Meteorological Applications Science and Technology for Weather and Climate Open Access RMetS

Towards nowcasting in Europe in 2030

Stephan Bojinski[1] | Dick Blaauboer[2,3] | Xavier Calbet[4,5] | Estelle de Coning[6] | Frans Debie[3] | Thibaut Montmerle[7] | Vesa Nietosvaara[1] | Katie Norman[8] | Luis Bañón Peregrín[4] | Franziska Schmid[2,9] | Nataša Strelec Mahović[1] | Kathrin Wapler[10]

[1]European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT), Darmstadt, Germany

[2]Network of European Meteorological Services (EUMETNET), Brussels, Belgium

[3]Royal Netherlands Meteorological Institute (KNMI), de Bilt, The Netherlands

[4]State Meteorological Agency (AEMET), Madrid, Spain

[5]European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT) Satellite Application Facility in Support of Nowcasting and Very Short Range Forecasting (NWCSAF), Madrid, Spain

[6]World Meteorological Organization (WMO), Geneva, Switzerland

[7]Météo-France, Toulouse, France

[8]UK Met Office, Exeter, UK

[9]Geosphere Austria, Vienna, Austria

[10]German Weather Service (DWD), Offenbach, Germany

Correspondence
Stephan Bojinski, European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT), Darmstadt, Germany.
Email: stephan.bojinski@eumetsat.int

Abstract

The increasing impact of severe weather over Europe on lives and weather-sensitive economies can be mitigated by accurate 0–6 h forecasts (nowcasts), supporting a vital 'last line of defence' for civil protection and many other applications. Recognizing lack of skill in some complex situations, often at convective and local sub-kilometre scales and associated with rare events, we identify seven recommendations with the aim to improve nowcasting in Europe by the national meteorological and hydrological services (NMHSs) by 2030. These recommendations are based on a review of user needs, the state of the observing system, techniques based on observations and high-resolution numerical weather models, as well as tools, data and infrastructure supporting the nowcasting community in Europe. Denser and more accurate observations are necessary particularly in the boundary layer to better characterize the ingredients of severe storms. A key driver for improvement is next-generation European satellite data becoming available as of 2023. Seamless ensemble prediction methods to produce enhanced weather forecasts with 0–24 h lead times and probabilistic products require further development. Such products need to be understood and interpreted by skilled forecasters operating in an evolving forecasting context. We argue that stronger co-development and collaboration between providers and users of nowcasting-relevant data and information are key ingredients for progress. We recommend establishing pan-European nowcasting consortia, better exchange of data, common development platforms and common verification approaches as key elements for progressing nowcasting in Europe in this decade.

KEYWORDS

collaboration and co-development, European Weather Cloud, high-resolution NWP, Meteosat Third Generation, nowcasting, observing systems, probabilistic forecasts, seamless prediction

1 | PURPOSE AND SCOPE—THE IMPERATIVE FOR BETTER NOWCASTING

Severe weather impacts on economies in Europe have significantly increased over the past decade compared with earlier decades, as shown in loss statistics by the reinsurance sector (MunichRe, 2021). Severe storms have been shown to become more frequent and more devastating over Europe in a changing climate (Hoegh-Guldberg et al., 2019; Pucik et al., 2019), and this is expected to continue in the coming decades (Seneviratne et al., 2021). The probability of severe convection environments and heavy rainfall events is set to increase across most of Europe (Kendon et al., 2014; Pucik et al., 2017).

Nowcasts, that is, weather forecasts with lead times of 0–6 h, are supporting a vital 'last line of defence' for protecting lives and weather-sensitive economies against the worst impacts of severe weather, complementing more long-term forecasts (Sugier, 2019). Nowcasting is the part of weather forecasting that is directly connected with the observed weather. Therefore, historically, two main branches of nowcasting can be distinguished: nowcasting techniques based on extrapolation of observations, and nowcasting based on numerical weather prediction (NWP). Many descriptions of nowcasting have been formulated, such as 'the description of the current state of the weather in detail and the prediction of changes that can be expected on a timescale of a few hours' (Browning, 1981).

Nowcasts are relevant first and foremost for the protection of life and livelihoods, civil protection and for a growing number of economic sectors, for example, aviation, shipping, road and railway operations. These all require precise forecasts at very short range of fog, thunderstorms, high winds including tornadoes, wind gusts, severe precipitation, freezing conditions and hail. Low cloud and fog, aerosol and dust load, and winter weather conditions (ice and snow) have a strong impact on transportation. Likewise, agricultural activities, energy sector, construction sector, tourism and recreational activities have increasing demands for tailored very short-range forecast products. Nowcasts are also generally useful for the public to support, for example, planning or recreational activities. Increasingly, nowcasts are combined with longer range forecasts as part of a seamless Earth system prediction chain (Ruti et al., 2020). The economic value of weather forecasts in Europe is estimated between 0.025% and 0.25% of GDP (Hallegatte, 2012; WMO, 2015a, 2015b), that is, between 3.5 and 35 b€/year for EU-27 2019 figures.

Although nowcasts are generally useful, in many complex situations, at convective, sub-kilometre scale and for rare events, the skill of nowcasts issued by NMHSs in Europe is often insufficient to meet the societal demand for accurate, relevant information on severe or disruptive weather (e.g., Sulik, 2022).

Given these high stakes, the institutions with official warning authority in Europe, the NMHSs, need to take concerted action to improve nowcasts and derived warnings and advisories. Key drivers in this area include:

- Classical nowcasting techniques, mainly based on observations, and blended techniques, are improving by exploiting more, as well as non-traditional data sources, applying ensemble methods and taking advantage of new approaches including machine learning (ML) (Agrawal et al., 2019; Sønderby et al., 2020);
- NWP-based forecast skill is improving towards shorter lead times as a function of rapid model update cycles (RUCs), more powerful processing technology, availability of model ensembles, better physical process understanding and advances in data assimilation;
- ML can help parameterize processes that are not adequately represented in models or observations (Han et al., 2020), for example, at sub-kilometre scales;
- Next-generation satellite systems to enhance nowcasting and very short-range forecasting are on the horizon, with the first Meteosat Third Generation (MTG) satellite launched in late 2022 and operational data available about a year later.

The purpose of this paper is to make recommendations that should help NMHS improve the skill of nowcasting and, as a result, better support the protection of lives and weather-sensitive economies in Europe. We come up with seven main recommendations described in Section 4, which we believe are achievable by 2030. They are based on our analysis of: emerging demands for nowcasting by society and meteorological forecasters (Section 2), the state of the observing system (Section 3.1), nowcasting tools and techniques (Section 3.2), infrastructure supporting data access and tools for the nowcasting community in Europe (Section 3.3), and the state of forecast verification and quality control (Section 3.4). We have used existing review literature and guidance in the field (e.g., EUMETNET, 2020a; Schmid et al., 2019; Wapler et al., 2019; WMO, 2014; WMO, 2017; WMO, 2020).

2 | EMERGING DEMANDS FOR NOWCASTING BY SOCIETY AND METEOROLOGICAL FORECASTERS

2.1 | An evolving context

Value of nowcasting to help mitigate high-impact weather effects is mostly realized at local scales. This explains why

Meteorological Applications Open Access RMetS
Science and Technology for Weather and Climate

requirements for nowcasting information (e.g., accuracy of a wind forecast) and derived applications (e.g., operating a renewable energy farm) may be highly dependent on local conditions, such as topography, resilience or vulnerability of population and infrastructure. Some meteorological services have recognized that the skill of their nowcasts is not always fully meeting needs (see Figures 1 and 2).

By 2030, users will expect information faster, that is, with higher timeliness and better ease of access; they will demand information highly tailored to their context. Impact-based forecasts are becoming an established practice, based on an assessment of hazard, vulnerability and probable risk (METEOALARM, 2021). Specialized users want tailored forecasts that utilize the latest scientific developments, and are interested in forecast verification results, whereas other user communities are less demanding. Delivery and communication of probabilistic forecasts and their interpretation is an area of active development and should be improved. Nowcasting services need to be better tuned to specific audiences, for example, for professional end users, or for the media and public (HIWeather, 2021). Reducing losses to lives, property and the economy depends not only on a good forecast of severe weather but also on translating that forecast into actionable information for the 'last mile', that is, the vulnerable population, infrastructure or economic asset that need to be protected.

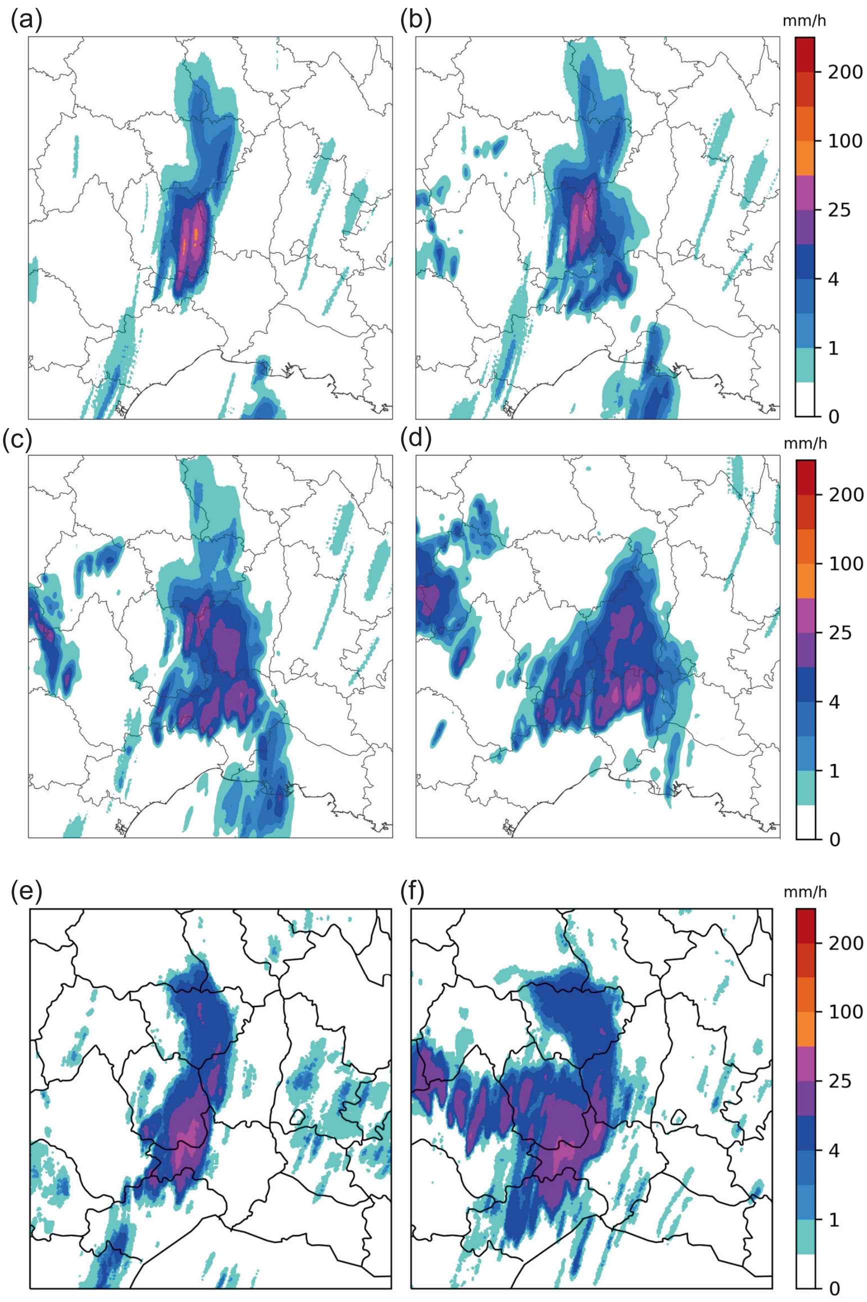

FIGURE 1 Example for nowcast/very short-range forecasting using a combined observation and NWP-based method, demonstrating the challenge of predicting convective-scale system evolution in complex terrain. Depicted here is 1 h cumulated rainfall predicted by the Météo-France PIAF (blending of extrapolated 5 min quantitative precipitation estimates (QPE) from radar observations and from the AROME-PI NWP model), 19 Sep 2020 at 8 UTC, valid at (a) 9 UTC, (b) 9 h30 UTC, (c) 10 UTC and (d) 11 UTC, zoomed over the Cévennes area in the South of France. Panels (e) and (f) display the observed values deduced from radar and rain gauges valid respectively at 9 h30 UTC and 11 UTC. For this stationary MCS strongly driven by orographic forcing, the extrapolation firstly fails in keeping the main cell at the right place because of the medium- to large-scale synoptic forcing towards the NE. The localization of convective cells at the southern flank of the system, and of the stratiform anvil in the north is then quite well captured by AROME-PI until the end of the 3 h forecast, although the total rain rates were finally underestimated compared with the observations.

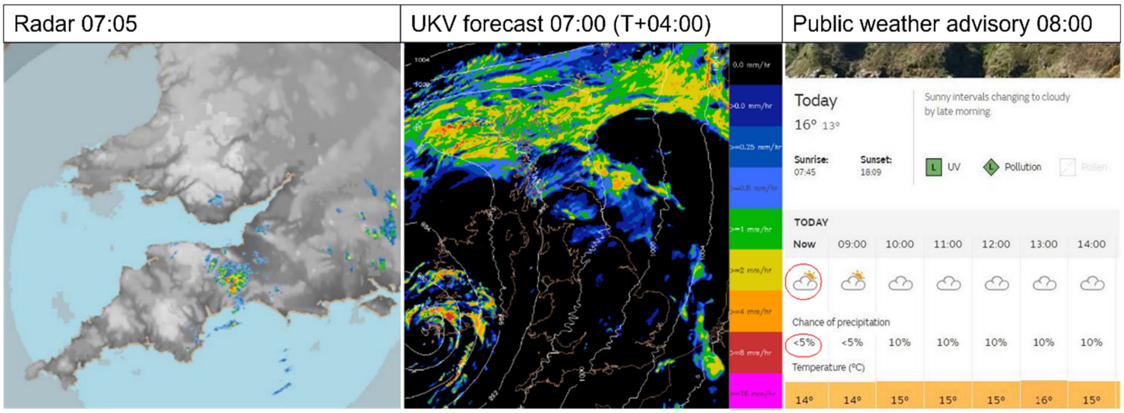

FIGURE 2 While radar imagery showed precipitation over Devon, SW England, on 20 October 2020 at 07:05 UTC and local rain gauges measured up to 15 mm/h for about 20 min, the MetOffice UKV regional model 4 h forecast showed no rainfall, probably due to an underestimation of potential temperature and moisture in the boundary layer; this led to a public weather advisory, which underestimated the probability of rainfall.

Climatic conditions and societal vulnerability vary considerably across Europe, hence impacts are highly context dependent (e.g., comparing the impact of a 5-cm snowfall event in northern latitudes vs. in the Mediterranean). In addition to increased intensity of some severe weather due to climate change, some weather patterns are shifting as shown, for example, in recent occurrences of Medicanes (see, e.g., Miglietta et al., 2020) or heavy rainfall events in wintertime in northern Europe (e.g., Whan et al., 2020). Such trends need to be considered in the evolution of nowcasting products, for example, in terms of thresholds and probability representation. Interaction with users in developing such products should be done through training and testbeds, such as those organized by the European Severe Storms Laboratory (ESSL).

Nowcast developments are driven on the one hand by the availability of new data and models, and on the other hand by science to transform data into information that is delivered to users (HIWeather, 2021). Through crowdsourced data and mass-deployed passive sensors (e.g., in cars and mobile phones), we expect much faster feedback loops between the providers of nowcast information and users on the one hand, and feedback on the accuracy and reach of forecasts on the other (Barras et al., 2019). We also expect that data quality control and integration methods should advance rapidly, for example, by using ML techniques. Such experiences should be exchanged among the users and providers of nowcasting information. These exchanges would benefit from the experience of actors such as the EU Emergency Response Coordination Centre, which uses impact-based forecasts and warnings to coordinate disaster relief worldwide (ERCC, 2021), and private companies that develop and run their own models for nowcasting and forecasting (Agrawal et al., 2019; IBM, 2021; Sønderby et al., 2020).

2.2 | Surveying operational services and their end users

In 2020, two EUMETNET surveys focused on the needs for improving nowcasting products and services. One survey was distributed among the NMHS participating in EUMETNET Nowcasting Programme (E-NWC; EUMETNET, 2022), and the other among their end users. Of 27 invited NMHS, 14 responded to the NMHS survey. Concerning the user survey, responses from 232 users from 18 countries were collected (Sivle et al., 2022). The share of end user categories providing responses is shown in Figure 3: it varied significantly from country to country. Sectoral users included local government, energy, tourism, water, construction, and oil and gas.

The survey provides evidence that not all the needs and requirements of end users are being met. Therefore, NMHS were asked to list ongoing developments and new products. As ongoing developments, they stated higher quality (improvements) of user products, more frequent and quicker access to data, as well as higher resolution of data in time and space. As new products, they mentioned a possible renewal of the radar and lightning network, the development of seamless and probabilistic forecasting systems, the importance of impact-based forecasting, and the development of a common web platform. Both surveys revealed four priority areas where NMHS require action to improve nowcasting products and services:

i. High-density observations of key phenomena and their significance for end users
ii. Improving end user understanding of forecast uncertainty and communication of probabilistic information
iii. Training sessions for end users
iv. Development and application of seamless prediction systems

2.2.1 | High-density observations of key phenomena and their significance for end users

Observations of higher density are needed to provide more spatial detail, for observation-based nowcasts as well as to inform higher resolution models and their verification. For newer observation systems, several NMHS find drone measurements and disdrometer data very important. Crowdsourced data are of high interest as well. Many NMHS require a higher density of automatic weather station observations. This indicates that the primary outputs of nowcasting systems are still surface fields (2 m temperature, precipitation, 10 m wind), as nowcasting requires a high-quality analysis. However, the distribution and evolution of surface fields in the nowcasting range also depend on the upper-air fields that define phenomena such as fronts and cyclones. Still, many of the nowcasting systems currently used are primarily 2D systems.

Based on the end users' responses, it seems that observing and predicting weather features such as tornadoes, turbulence, icing, hail, lightning/thunderstorm as well as fog and clouds will gain importance in the future, as shown by their ability to 'trigger action' (Figure 4). Strong wind and gusts result in the most action taken by end users, followed by heavy rain and thunderstorms. Concerning the lead time needed for taking preparatory measures, end users need 1 h in advance to disseminate information, and for personnel and non-personnel preparatory measures, more time is required (at least 6 h).

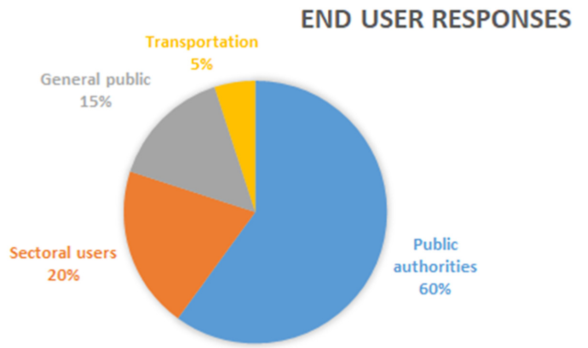

FIGURE 3 Distribution of responses by end user groups to EUMETNET E-NWC 2020 survey on nowcasting products and services.

2.2.2 | Improving end user understanding of forecast uncertainty, and communication of probabilistic information

Lack of communication between the NMHS and end users can be one of the reasons for insufficient understanding and utilization of probabilistic nowcasts/forecasts by end users, thus slow uptake of such products. When dealing with weather warnings, end users can encounter several problems. According to the survey, more than 30% of the end users think that the issuing of too many warnings has a 'dulling effect', more than 30% of the end users have difficulties when dealing with uncertainties in weather forecasts and warnings, and again more than 30% of the end users must deal with inappropriate warnings. It is important that the end users are aware of the benefits and limits of the forecasts (and resulting warnings) and that they have access to an objective evaluation of products. However, 40% of NMHS do not provide verification results of nowcasting products and probabilistic forecasts to their end users, partly due to the difficulty of presenting them in an easily understandable way (see also Section 3.4).

Nevertheless, nearly 40% think that probabilistic information provides more representative and useful information in time and space compared with a standard single-value weather forecast. Although they state that a single value may facilitate the decision-making procedure

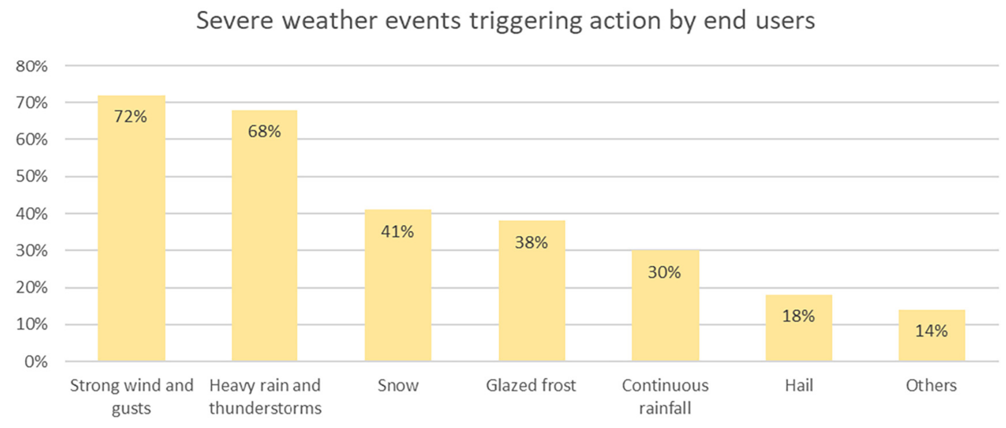

FIGURE 4 Types of severe weather events causing 'action' by end users, according to EUMETNET E-NWC 2020 survey on nowcasting products and services.

compared with a range of values that can make decision-making harder, they recognize that a single value give you less or no information about the uncertainty of forecasts. Forty percent of the end users are convinced that nowcasts presented in probabilistic form help them to take faster, better and easier decisions. The preferred forms of probabilistic products are maps, for example, a coloured map showing the different probabilities between 0% and 100% in a region and surroundings (64% of responses by end users). This is followed by graphs (e.g., chance of rain showers, probability of rain; 51%) and percentages (e.g., there is a 10% chance of the temperature exceeding 36°C; 42%). Knowing the uncertainty of a forecast supports decision-makers in responding to end users' requirements.

Forecast uncertainty is communicated to end users mostly by regular consultation. Often end users are not familiar with forecast uncertainty and have little background in forecasting. There is a high risk that they may not interpret the forecasts properly, which can be compounded by the fact that the outputs are not self-explanatory enough (especially probabilistic forecast maps are more difficult to understand than deterministic forecast maps). Direct consultation is often necessary but the question arises to what extent it could be complemented or replaced by more efficient self-explanatory tools and training material.

2.2.3 | Training sessions for end users

Due to a lack of resources, training sessions for end users on nowcasting products cannot be organized on a regular basis. The use of common platforms and training materials on various meteorological products and situations could be beneficial. Only 45% of NMHS answered that they use the Eumetcal (the European Virtual Organisation for Meteorological Training) portal for training purposes, mostly for satellite and radar information. Only 15% of end users regularly attend training sessions with their meteorological institute, and 32% of end users occasionally attend such training sessions. However, 30% of end users say that they do not attend specialized trainings/workshops/post-event reviews with their meteorological service or consultation. When asking end users if they need more training, 52% of end users answered 'yes', while 44% answered 'no'. Many of them expressed training needs in the areas of: learning how to use the different products that are available for different operations and devices, understanding of different weather phenomena and processes, reading weather maps, operational use of probability forecasts, weather systems, interpret probability forecasts and communication. These topics should be increasingly included in future training sessions.

2.2.4 | Development and application of seamless prediction systems

Seamless prediction systems allow for physically consistent forecasts across several forecasting systems with lead times from minutes to several days and beyond. Such systems are therefore an active area of development at many NMHS. From the survey, only eight NMHS out of 27 have developed or are planning to develop a seamless prediction system. Six of them are developing a seamless prediction system, but most of these systems are not yet operational. It is not entirely clear why many NMHS are not developing a seamless prediction system. Reasons could be lack of manpower and know-how, development effort or low expected benefit. It would be helpful to investigate these barriers in more detail and find ways how to support NMHS in the development of seamless prediction systems (see Section 3.2.3).

2.3 | Forecasters in NMHS

Over the coming decade, the forecasters' role will change because of improving models and technology, but how exactly is a topic of active discussion. Here, we are offering some possibilities: many forecasters may use highly integrated and (semi-)automated systems to issue forecasts that will allow them to reorient much of their tasks: away from manual forecast production towards quality-controlling the operational system, and to contribute to model evaluation and verification. With automated systems taking over routine forecasts and warnings of less critical nature, forecasters will spend more time on monitoring complex situations and on formulating critical warnings. For these purposes, they will have more ensembles and higher frequency and higher resolution outputs at hand. Further, communication with and advising decision-makers especially in critical high-impact events will become an increasingly important task of forecasters. In a world of information overflow, forecasters must become excellent communicators so that customers and end users can evaluate the full range of options and make the right decisions based on best quality warnings and advisories (Persson, 2013). Tools that integrate multiple information sources and detect the key signals for forecasters will become increasingly the norm (e.g., Cintineo et al., 2014; Nisi et al., 2013).

In 2020, the EUMETNET Eumetcal programme conducted a Training Needs Assessment to update the inventory of the current full scope of training needs at NMHS from observing techniques and forecasting needs to climatological skills. The assessment showed that key training needs of forecaster are the interpretation of observational data, nowcasts and NWP ensemble data during high-impact weather events, especially on the very short-range forecasting time scales. Eumetcal is putting forth these training needs with the providers of training in cooperating with the larger training providers like EUMETSAT, ECMWF, WMO Global Campus and several larger NMHSs.

Following the current trend, most of the end user requirements will be satisfied with products that feed into their downstream applications, demanding forecaster advisories mostly in unusual, high-impact weather situations (Persson, 2013). To meet this goal, nowcasters must dedicate time to continually improve their training in these areas. They must have the adequate technical and human resources to maintain situational awareness, and must regularly interact with end users to understand and satisfy their needs.

Operational forecasters will benefit from an operational training testbed programme on the use of next-generation satellite products in severe convective storm forecasting. Funded by EUMETSAT and led by the ESSL during the period 2022–2025, the testbeds are set to introduce new EUMETSAT satellite data from the MTG and polar-orbiting EPS Second Generation programmes to about 10%–15% of the operational meteorological workforce of European NMHS. EUMETSAT is planning similar training activities specifically for aviation forecasting, and for fire monitoring and mitigation.

Although the meteorological training of forecasters will benefit from advances in knowledge of the atmosphere and the use of tools with greater skills, they will be required to have training in non-meteorological fields such as statistics, cognitive biases and techniques for communicating with end users. Generating actionable information is critical to support the 'last mile', that is, vulnerable populations, infrastructure or economic assets that need to be protected.

Towards 2030

We recommend to establish and maintain close, regular feedback loops among providers of nowcasting information, forecasters and end users between now and 2030, with the goal to continuously improve nowcasting tools and services, for example, in national and European-level nowcasting fora.

3 | EVOLUTION OF COMPONENTS FOR NOWCASTING IN EUROPE TOWARDS 2030

3.1 | Observations

This chapter focuses on key surface and space-based observational capabilities over the European domain and their expected improvement over the coming years. The evolution of global Earth observation capabilities over the next 10–20 years globally (WMO, 2019) will underpin advances in global and regional NWP, and in many other weather and environmental applications, including nowcasting.

3.1.1 | Surface-based networks overview

Compared with other regions, Europe is relatively well covered by surface-based observation networks supporting nowcasting and other meteorological applications. However, there are gaps and, in particular, the localized nature of severe and high-impact weather events demands additional observations for forecasting and verification (Marsigli et al., 2021). To identify shortcomings in their observation networks, in 2019, European NMHS requested the Observations Programme of EUMETNET to carry out a gap analysis for the region of Europe (the EUMETNET Composite Observing System (EUCOS); Sugier, 2019; Figure 5). The analysis highlighted wide-ranging deficiencies compared with requirements defined by WMO (WMO, 2021a). EUMETNET adopted a user-oriented approach to analyse the highest priority gaps, sensitive to affordability constraints (EUMETNET, 2020a, 2020b).

The main challenge identified in the EUMETNET analysis that needs to be addressed with better observations, particularly but not limited to the boundary layer, is the forecasting and real-time monitoring of convection and associated hazards (thunderstorm, strong wind/wind gusts, tornadoes, high rainfall rate and hailstorms). These manifest at all forecasting timescales, that is, from the challenge to forecast the sudden deepening and heavy precipitation associated with convection around extra-tropical storms reaching Europe, to a challenge to provide customized impact-oriented warnings of hazards associated with convective events.

The four other most common challenges to be mitigated by better observations of temperature, humidity, precipitation and cloud base height are (i) localized fog formation depth and dispersion (particularly important for the transport sector); (ii) winter and polar-region weather (e.g., polar low, freezing precipitation, snowfall, snow depth, ice and avalanche forecasts in mountainous

Layer	Application Area	Land Domain										Ocean Domain									
		Accuracy		Horizontal spacing		Vertical resolution		Observation cycle		Timeliness		Accuracy		Horizontal spacing		Vertical resolution		Observation cycle		Timeliness	
Planetary boundary layer	Nowcasting / VSRF	T	w	T	w	T	w	T	w	T	w	T	w	T	w	T	w	T	w	T	w
		q	iwv	q	iwv	q		q	iwv	q	iwv	q		q		q		q		q	
	Aeronautical Meteorology	T	w	T	w	T	w	T	w	T	w	T	w	T	w	T	w	T	w	T	w
		q		q		q		q		q		q		q		q		q		q	
Near-surface	Nowcasting / VSRF	T	w			T	w	T	w	T	w	T	w			T	w	T	w	T	w
	Aeronautical Meteorology		w						w		w		w						w		w
			P						P		P		P						P		P

FIGURE 5 Summary of the EUCOS gap analysis for basic atmospheric variables (Temperature T, wind w, humidity q, pressure P, and integrated water vapour iwv) for nowcasting/very short-range forecasting and aeronautical meteorology applications over land and ocean areas. The colour of each cell indicates the achievement on average over 2018 of the: (yellow) minimum requirement; (green) breakthrough requirement; and (blue) goal requirement as set in the WMO OSCAR database. The (grey) cells represent gaps in the EUCOS observing networks; the (blank) cells represent areas where there is no registered requirement.

areas); (iii) weather events in complex terrain, including locally forced precipitation and high-impact winds; and (iv) precipitation types in the boundary layer (e.g., freezing precipitation, hail and snow) as well as the amount reaching the surface for hydrological applications and transport services.

3.1.2 | Non-traditional sources including internet-of-things-based and crowdsourced data

While basic networks operated by NMHS according to WMO standards (WMO, 2022) continue to provide the backbone of high-quality observations for weather, climate and related environmental applications, data from non-traditional observing sources are expected to increasingly contribute and complement basic meteorological networks, provided that the data are adequately processed, quality-controlled and exchanged in near real time. Hintz et al. (2019) provide a summary on the use of non-traditional data by European NMHS.

To be useful for nowcasting and NWP, crowdsourced data collection and pre-processing need to be a collaborative effort between weather centres, combined with industry and the private sector to improve and unify standards and best practices coordinated by EUMETNET, and at global level by WMO. However, for some applications, flexible quality standards should be applied to data from non-traditional sources if they are filling observational gaps, for example, in support of nowcasting and very short-range forecasting at local scale (de Vos et al., 2019; Met.no, 2020). Hence, there is significant growth potential in the smart use of internet-of-things (IoT)-based and crowdsourced data in nowcasting applications, both in the forecast, post-processing and in verification (see Section 3.4).

EUMETNET recently started a scoping study on a Supplementary Observations dataHub (E-SOH) intended to encourage and facilitate the near real-time exchange of hourly and sub-hourly observations from surface stations including those not currently routinely exchanged such as rain gauge data, solar radiation, snow depth and wind gust data. At the same time, a database will be developed to collect and quality control new data types like crowdsourced data and other data sources. These datasets should enhance the availability of observational data that are important for nowcasting. The European Weather Cloud (EWC) is one of the hosting options (see Section 3.3).

Towards 2030

1. In line with the EUMETNET analysis, we recommend closing the following observation gaps, as a matter of priority:
   a. The provision of profile observations of humidity, wind and temperature, in terms of horizontal and temporal resolution, with a focus on the boundary layer. This could be achieved by improving the coverage of aircraft-based observations (e.g., expansion of MODE-S aircraft surveillance radar data), research into emerging technologies such as differential absorption lidar (DIAL), Raman lidar, Doppler wind LIDAR, ground-based microwave radiometers, and observations from unmanned aerial vehicles (UAV).
   b. The provision of near-surface observations everywhere, but of highest priority over the seas, complex terrains, North Africa, including all the basic meteorological variables as well as snow, hail, soil moisture and visibility. One should explore the complementary value of high-volume, lower quality observations (e.g., data from personal weather

stations, mobile phones, car sensors and webcams) to NMHS core networks.

c. Reinforced efforts to extract more value out of existing capabilities: improving the quality of the OPERA radar Quantitative Precipitation Estimations (QPEs) composite and radial wind products as well as expanding their coverage (see also Section 3.1.3); exploring the value of additional products from the Global Navigation Satellite System (GNSS) networks as well as expanding this network towards Eastern Europe and North Africa; developing aerosol products from the Automatic Laser Ceilometer (ALC) network.

2. Design and run experiment(s) to study the relative impact of observed atmospheric profile data on Limited Area Modelling and nowcasting tools. These studies should compare state-of-the-art methods, verification metrics and focus on a representative set of areas of interest (e.g., airport for fog forecasting, coastal zone with high frequency of high-impact weather, urban areas and venue of major sporting events such as the Paris Olympic Games). The following should further be considered in these experiments:

- The impact of timeliness and frequency of observations: for example, frequencies as high as 10 s are achieved for observations of temperature, humidity and winds at Schiphol airport in support of aviation forecasting.
- Additional observing parameters that are most required for better constraining of observations and modelling of the lower layer, for example, soil moisture, evapotranspiration and soil composition.

3.1.3 | Surface-based radar networks

Ground-based meteorological radar measurements are one of the most useful data sources for nowcasting applications, as they are used for QPE (Reyniers, 2008), for object-based or gridded-based quantitative precipitation forecasts (QPF) using extrapolation techniques (cf. Section 3.2.1), for data assimilation in convective-scale NWP systems (cf. Section 3.2.2). Such data are equally useful in warning systems and in seamless prediction algorithms that blend extrapolated radar imagery and their counterpart simulated by NWP models (Section 3.2.3). Where available, ground-based radar is clearly the primary observation system for producing warnings of weather hazards linked to strong convection, as it scans a large area in 3D with an update rate of a few minutes. Some limitations need to be recognized, such as inhomogeneous coverage in complex topography with uncertainties arising from beam blockage, progressive degradation of QPE quality with increasing height from the radar (Kitchen & Jackson, 1993), beam broadening with range leading to lower resolution data at longer range, and removal of non-meteorological targets.

In addition to reflectivities, which are directly linked to the number and the size of targets in the sampled volume, the Doppler winds are also used in operational NWP systems through data assimilation and for the detection of gust fronts or meso-cyclones in real time. With the further addition of dual polarization (DPOL), precipitating hydrometeor types can be differentiated, which is particularly useful for hail or snow detection (Kumjian, 2013; Witt et al., 1998). Such capability helps in non-meteorological target removal and in the correction of the signal attenuation along the beam, which improves QPE (Ryzhkov et al., 2005). In addition, reflectivity data can also be used to generate 3D mosaics of reflectivity (Bousquet & Tabary, 2014; Smith et al., 2016). Diagnostics derived from 3D mosaics, for example the vertically integrated ice (e.g., Mosier et al., 2011), provide additional information on severe weather. Finally, studies such as Fabry (2004) have shown the possibility of using refractivity derived from an apparent fluctuation in the range of fixed ground targets close to the radar for estimating the moisture field near the ground, with potential for detecting convection initiation.

At the European level, one of the main challenges is to collect radar data from different countries, which often use different scanning strategies or different algorithms for echo identification and clutter removal. This is the main goal of the EUMETNET OPERA project (https://www.eumetnet.eu/activities/observations-programme/current-activities/opera/, Figure 6).

Towards 2030

By 2030:

- The radar network should become denser, especially over urban areas. DPOL variables should be more widely used for target identification and attenuation correction. Doppler winds should also be increasingly used for automatic gust front and mesocyclone detection. These approaches will be explored in the RDP2024 project (Masson et al., 2020), for which 2 X-Band radars will be combined with a C-Band over the Paris area in order to produce high-resolution QPE (100 m) for nowcasting during the 2024 Olympic games. New-generation radars such as phased array could be of great interest because of their very high temporal resolution made possible by the electronic scans. This technology is however still very expensive and the addition of DPOL capability technically complex.

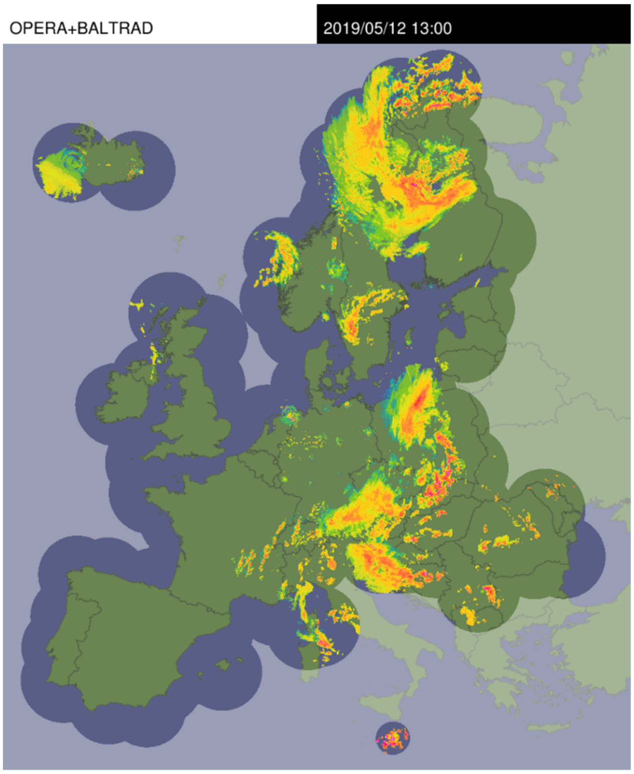

FIGURE 6 Example for radar echo composite generated within the EUMETNET OPERA program (source: Janne Kotro, FMI).

- Establish routine pan-European exchange of radar data, to allow for the generation of consistent pan-European products such as QPE or volumetric scans for NWP, and to improve forecasts for areas with overlapping radar coverage across national borders.

3.1.4 | Lightning detection

The most active parts of potentially damaging thunderstorms are difficult to be precisely identified and tracked even using radar and/or satellite data. In such cases, lightning data provide an essential information source for nowcasting and issuing of thunderstorm warnings. Measurements of lightning strokes and the real-time display of lightning stroke frequency, lightning types and the height of intra-cloud strokes help tracking thunderstorm development. This is useful for determining the severity of a thunderstorm and assessing its potential impact: for example, a sudden increase in flash rate ('lightning jump') often serves as a proxy for an intensifying thunderstorm. Surface-based lightning data also constitute one of the most cost-effective data sources for remotely sensing weather.

For NMHS, energy suppliers, emergency management and other weather dependent industries, the fast and reliable supply of accurate lightning information forms an integral part of weather information. Highly precise lighting data are among the most important meteorological data in modern aviation, allowing air traffic controllers to better assess weather conditions, enabling fine-tuning of flight routes as well as reducing the length of ground handling stops at airports. Other end users are the traffic and shipping industries as well as railway operators, wind farms, operators of pipelines or high voltage power lines and organizers of open air and outdoor activities.

Currently, lightning measurements are performed by a large number of ground-based lightning networks, both NMHS-owned and commercial, with sensors spread worldwide and, since the launch of the Geostationary Lightning Mapper (GLM) on the NOAA GOES-R geostationary meteorological satellite series and the Lightning Mapping Imager (LMI) on the Chinese FY-4 satellite series. A comparable space-based capability will become available over Europe and Africa and over the surrounding seas with the Lightning Imager (LI) on MTG.

Sudden increases in the total lightning flash rate (intra-cloud + cloud-to-ground lightning) called 'lightning jump' have been found to precede the occurrence of severe weather such as large hail, severe wind gusts associated to thunderstorms and/or tornadoes (e.g., Wapler (2018) and Figure 7). It is estimated that the precise detection of lightning jumps can give forecasters up to 20 min of additional lead time for warning (Kris White, U.S. NWS Alabama, pers. comm.).

Despite all these benefits from lightning detection, to fully exploit these data, some challenges still need to be solved. While the lightning jump, which can double or triple the number of lightning strokes in a particular storm cell, is good at indicating which thunderstorms are building, it is not good as a tool for forecasting specific weather events. The strongest correlation has been found between lightning jump and hail occurrence. Some heavy rainfall events induced by less well-developed thunderstorms do not produce significant amounts of lightning (Farnell & Rigo, 2020). An added problem is the splitting and merging of the cells, so the automation of lightning jump detection is a challenging task.

Ground-based lightning detection networks provide useful and detailed information about convective storm characteristic and development; however, these networks are limited to some continents. The extensive spatial coverage of space-based lightning mapping from geostationary orbit enables the tracking of violent storms and severe weather even in remote regions and over the oceans. In addition to benefitting nowcasting over Europe, significant benefit to forecasting severe thunderstorms is expected over the African region where most of the lightning hotspots worldwide can be found (Albrecht

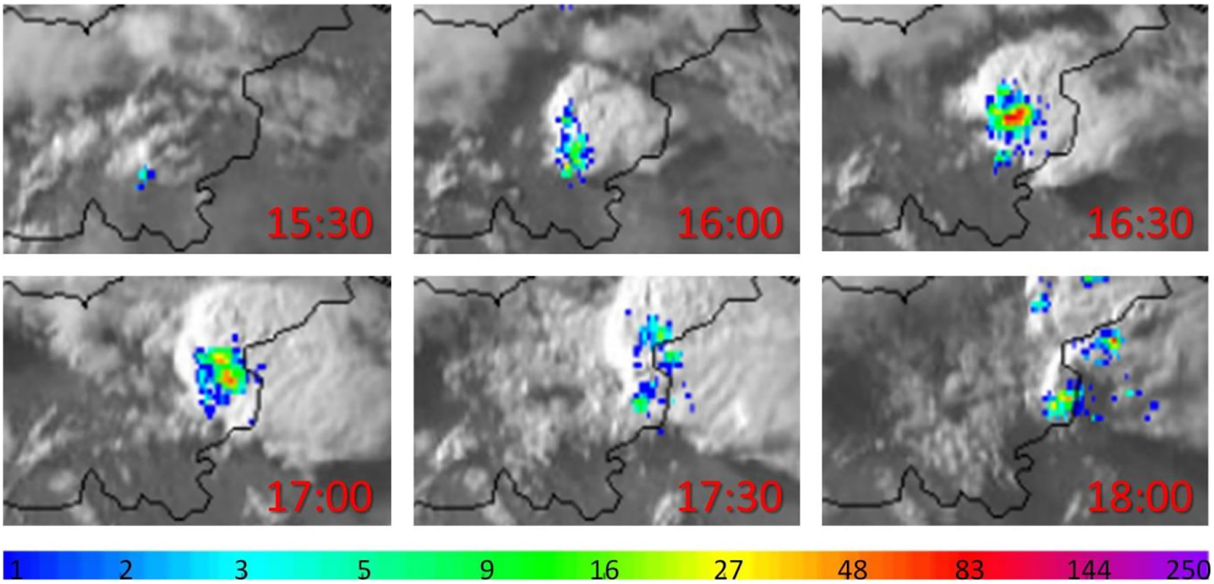

FIGURE 7 Hailstorm in Slovenia on 5 July 2018. Meteosat-10 SEVIRI HRV (grey), 5-min lightning density (logarithmic colour bar) with 3*3 km^2 horizontal resolution, derived from the surface-based LIghtning localization NETwork (LINET). (from Wapler (2018) © ESSL, EUMETSAT, DWD).

et al., 2016). Since 2017, forecasters in the U.S. National Weather Service have been gaining experience in using space-based GLM data in operations (Rudlosky et al., 2020; Stano et al., 2018). More recently, KNMI Netherlands and Meteo-France have been experimenting with GLM products in forecasts for the Caribbean territories under their responsibility. The EUMETSAT Satellite Facility in Support of Nowcasting and Very Short-Range Forecasting (NWCSAF) plans to integrate products from the MTG LI into their software. To jump-start the use of upcoming lightning mapping data enabled by the MTG mission (see section below), European forecasters should fully tap into the knowledge and experience gained by their colleagues, and training programmes should be designed accordingly.

Towards 2030

The performance and limitations of lightning data detected from ground and space have to be investigated in detail. Furthermore, the potential of merging these two data sources needs to be explored in more detail, and more research on the differences and similarities of both detection methods is required. Based on 4 years of experience with data from the GOES-16 and −17 GLM, studies correlating both measurements have shown that the detection efficiency from space is affected by the opacity of clouds in the wavelengths used by these sensors (Murphy & Said, 2020). Furthermore, the significance of basic products (flashes, groups) and products accumulated over time/space in the forecasting process needs to be better understood. One focus here should be further investigation of the skill that the lightning jump can bring to nowcasting hail and other severe storm hazards.

3.1.5 | Meteorological satellites

Since 1981 and, following significant improvements in 2003 with Meteosat Second Generation, EUMETSAT meteorological satellite data have been providing critical information over Europe and Africa for nowcasting severe weather (Siewert et al., 2010) and for many other applications. Satellite-derived information on winds, clouds, humidity and other key parameters has been made available to forecasters as a basis for situational awareness, nowcasting and NWP. The need for better representation of the boundary layer and surface conditions in satellite data for nowcasting and short-range NWP has been identified (EUMETSAT, 2015).

As of 2023, and with planned operations until the early 2040s, the next generation of EUMETSAT satellites will provide users with a suite of products for better describing the atmospheric dynamical state, convective initiation and the convective life cycle: the MTG programme (Holmlund et al., 2021) delivers three observation missions with substantial expected benefits for nowcasting:

- A spectral imaging mission enabled by the Flexible Combined Imager (FCI), continuing the nearly 20-year heritage by Meteosat Second Generation SEVIRI with enhanced spatial, temporal and radiometric resolution, new spectral channels sensitive to low-level moisture and thin cirrus clouds, and more sensitive fire detection capability (Figure 8a). The imager provides data every 2.5 min over Europe, and every 10 min over the full Earth disc. Combining channel-based information

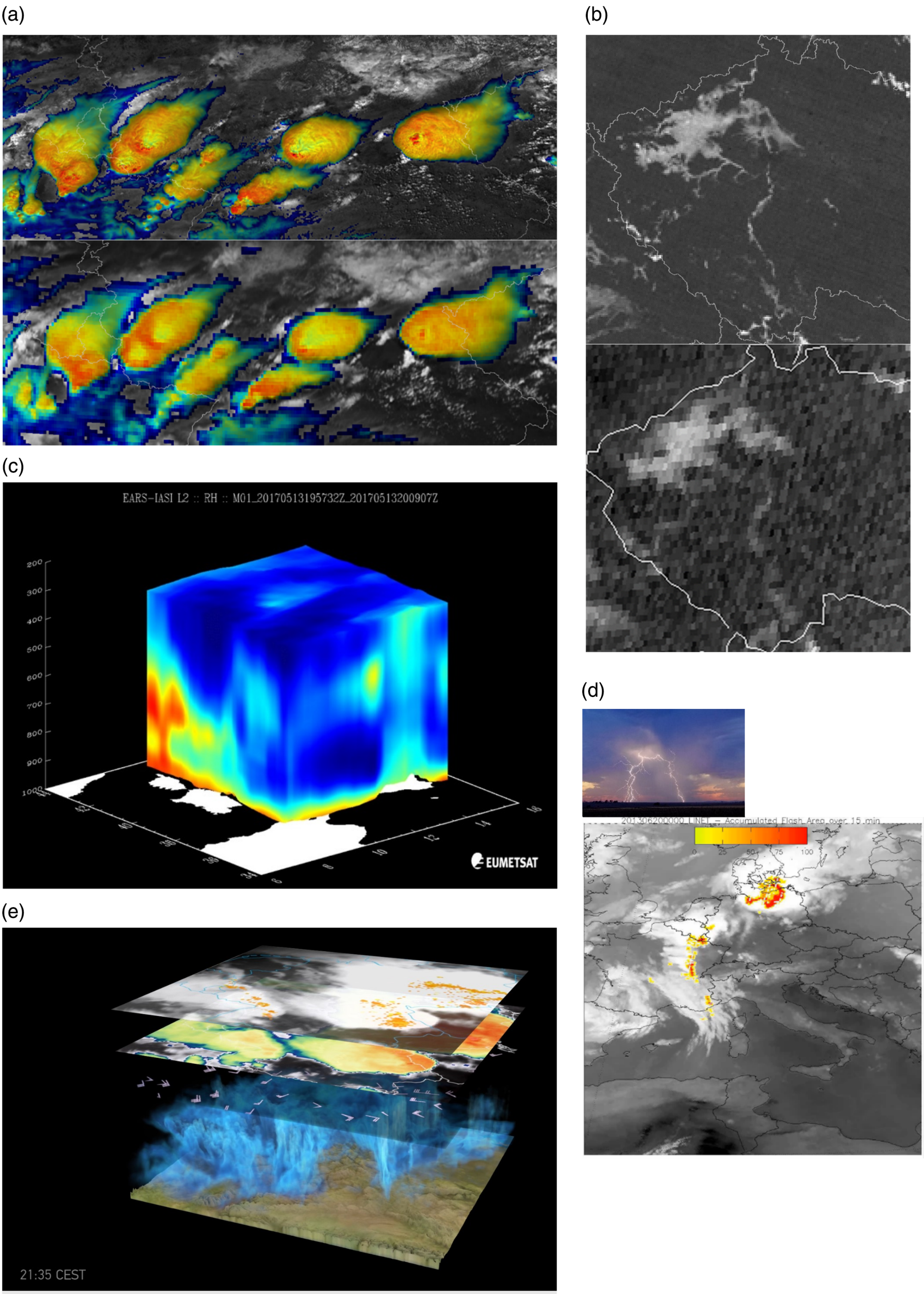

FIGURE 8 Legend on next page.

in red-green-blue (RGB) image composites provides forecasters with information on cloud type, phase, air-mass and convection.

- A lightning imaging mission enabled by the LI, providing continuous monitoring of time, position and intensity of optical pulses generated by lightning activity, over Europe and most of Africa. These are converted into geophysical flashes and accumulated products (Figure 8d). The space-based LI is sensitive to total lightning and can measure the extent and duration of flashes, thus complementing ground-based lightning detection networks (see section above).
- A hyperspectral infrared sounding mission enabled by the infrared sounder (IRS), providing atmospheric soundings of temperature, humidity and other trace gases, in cloud-free conditions, for the first time every 30 min over Europe. This repeat cycle and the 4 km spatial sampling (at nadir) of such data allow for tracking vertically resolved atmospheric motion in 3D/4D (Figure 8c). IRS fills a spatial and temporal gap in characterizing the atmospheric profile.

The next-generation polar-orbiting missions on the EUMETSAT Metop Second Generation (Metop-SG) satellites as of 2025 will see enhanced data and improved coverage particularly of higher latitude regions (roughly >60° N) to benefit nowcasting applications. Data from Metop-SG are planned to contribute to the international polar system jointly operated by NOAA and EUMETSAT. Due to viewing angle and parallax effects, imagery acquired from geostationary orbit is sometimes less useful in these regions. Figure 9 shows an example of a rapidly developing convective storm over Scandinavia, aptly captured by brightness temperature imagery from the Advanced Very High Resolution Radiometer (AVHRR) instrument onboard the three Metop satellites operating until late 2021. The most relevant missions on Metop-SG for nowcasting, planned to operate until the early 2040s, will be:

- The spectral imaging mission enabled by the METimage instrument on Metop-SG, providing improved spatial, spectral and radiometric resolution imagery as a basis for cloud products, polar atmospheric motion vectors and total precipitable water over land and ocean.
- The hyperspectral infrared sounding missions enabled by the new-generation InfraRed Atmospheric Sounder Interferometer (IASI-NG), allowing for atmospheric temperature and water vapour profiles and thus inference on instability.
- The microwave imaging mission realized by the Microwave Imager (MWI), continuing the 20-year heritage of such sensors operated by the United States and Japan, for all-weather detection of hydrometeors and estimation of precipitation parameters.

To improve nowcasting and very short-range NWP over high latitudes and the Arctic region, a prototype for a constellation of microwave sounders is planned as part of the Arctic Weather Satellite (AWS) programme. These will allow high-frequency all-weather monitoring of liquid and solid hydrometeors.

Data from the international constellation of polar-orbiting spectral imaging missions operated by the United States and China will further contribute to nowcasting in Europe if users have access to the data in near real time (EUMETSAT, 2021a). EUMETSAT and its

FIGURE 8 (a) Next-generation Meteosat (MTG) geostationary satellite capabilities: (a) + (b) Higher spatial resolution MTG imagery compared with MSG for cloud-top temperatures during Central Europe storm event; early-morning fog detection over Czech Republic. (c) temperature and water vapour profiles in 3D derived from IR soundings every 30 min over Europe. (d) continuous detection of lightning flashes accumulated over space and time. (e) collocation and combination of MTG products into a '4D weather cube' in support of operational forecasting, research and training. (a) Convective storm clouds over Central Europe ('Hessen storm'), as seen from Meteosat Second Generation SEVIRI imagery (lower panel) and with imagery from the VIIRS instrument on the NOAA Suomi-NPP satellite which is used to simulate the higher resolution MTG imaging mission enabled by the Flexible Combined Imager (FCI, upper panel) as of 2023. Higher spatial and temporal resolution will enable a better view on cloud-top details and, thus, more accurate assessments of storm intensity. Source: M. Setvak; 11 June 2018, 11.37 UTC; combining 0.865 μm imagery (background) and 11.45 μm (convective storms) to a 'sandwich' product. (b) Source: M. Setvak, J. Kerkmann; 16 Nov 2018, 01.37 UTC. Lower panel: MSG SEVIRI imagery at 5 km horizontal resolution (3 km at nadir), upper panel: simulated FCI imagery at ~2 km horizontal resolution (1 km at nadir), based on NOAA Suomi-NPP VIIRS data. The pictures show brightness temperature differences (VIIRS I4 (3.7 μm)–I5 (10.8 μm); SEVIRI 3.9–10.8 μm). (c) Variability of relative humidity in 3D over the central Mediterranean, derived from IR soundings of the Metop IASI instrument (Source: T. August, EARS IASI L2 product), mimicking next-generation MTG IRS-based products on atmospheric thermodynamics. (d) Illustration of an accumulated flash area product derived from the surface-based LINET lightning detection network. (e) Collocation of MTG data resulting in a '4D weather cube': four layers of information describing convective storms over Germany on 20 June 2013: at bottom, relative humidity in light to dark blue in a range 50%–100%, derived from a DWD high-resolution model; above that, Meteosat-based 2D wind field and a combined infrared-visible 'sandwich' product showing cool convective storm tops in red-orange hues. The top layer shows lightning flash density based on ground-based detection. The northern Alps are visible at the bottom front edge.

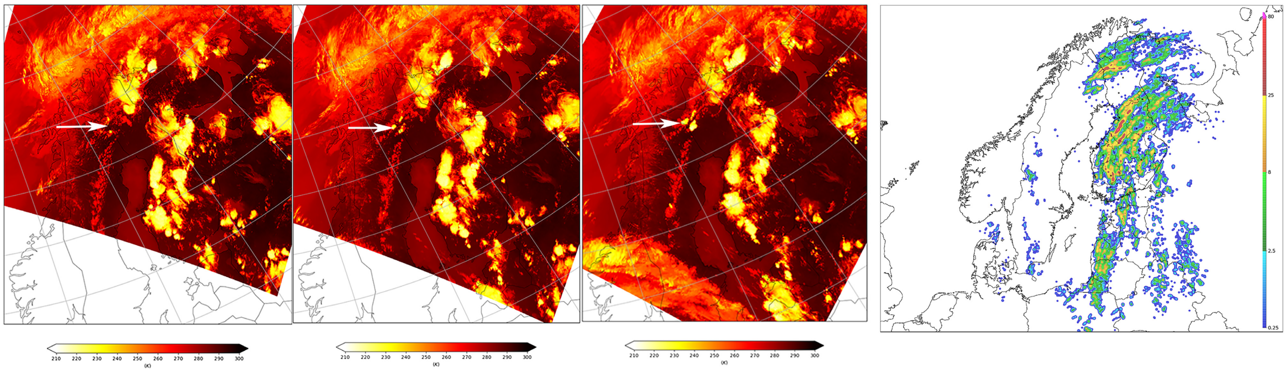

FIGURE 9 Nowcasting a severe thunderstorm in high latitudes over Scandinavia on 8 June 2019, using a sequence of brightness temperature measurements in Kelvin from three AVHRR instrument onboard Metop-A, -B, and –C: while at 16:35 UTC (left panel, Metop-A), there is only a small indication of the possibility of a convection initiation, after about 30 minutes, at around 17:16 UTC (middle panel), the Metop-C overpass indicates the development of multiple convective cells in the area of interest, which is confirmed by the passage of Metop-B at around 17:49 UTC (right panel). This would give local forecaster close to 30 min lead time to issue warnings on the thunderstorm, in areas without radar coverage. The inset shows cloud-to-ground lightning flash density observed by ground-based networks (flashes per 100 km^2 per day), 8 June 2019 00:00–23:55 UTC. Credit: FMI.

Satellite Application Facilities (SAF) are committed to produce a range of geophysical products, such as winds, clouds, instability indices, to support forecasting of severe weather and many other weather, climate and related environment applications. The NWCSAF (EUMETSAT, 2021b) provides software to generate a variety of nowcasting-related satellite products in near real time, such as satellite-derived winds, instability indices and humidity, convective cell characterization and tracking, convection initiation detection, turbulence determination, precipitation rate and image extrapolation (Table 1).

To exploit the enhancements in EUMETSAT's next-generation missions for nowcasting, NWCSAF products will be updated and new products developed using the LI and the infrared sounding mission. Table 1 provides a high-level overview of NWCSAF software packages and products planned in the 2022–2027 timeframe, in addition to maintaining the currently operational packages.

Towards 2030

Looking towards 2030, the integration of satellite-derived products into the nowcasting value chain needs to be further simplified and made more effective. This requires working with users in forecasting centres and by providing them with training, tools, and technical/scientific guidance. The wealth of new data and products—next-generation MTG-produced data rates are at least 50 times higher than those from current Meteosat—need to be analysed, understood and incorporated into nowcasting tools (see next section). Specialized entities such as NWCSAF, the ESSL (ESSL, 2021), and expert groups such as the Convection Working Group (EUMETSAT, 2021c) should share their knowledge, experience and tools with the broader European nowcasting community. Lessons learned by communities using data from the U.S. GOES, Japan Himawari and other satellites should be taken on board. Strong engagement by the weather research community is necessary to investigate and exploit the value for nowcasting of novel mission data such as from the infrared sounder and the LI on MTG.

3.2 | Methods and tools

Many severe high-impact weather events in scope of this paper are well described by observation-centric nowcasting methods in the forecast process, as they have superior skill to other methods (Section 3.2.1). Thanks to very frequent update and fast computational time, observation-based methods can quickly pick up phenomena with rapid development (typically within 5 min). In unstable conditions or in areas with orographic forcing, the forecast accuracy of, for example, rainfall can however drop quite rapidly, typically after 30–60 min (Germann et al., 2006). The skill provided by high-resolution (HR) NWP models is needed to extend the forecast range up to 6 h and beyond, especially when convection due to orographic forcing occurs (see Section 3.2.2). Blended techniques take the best of both worlds (Section 3.2.3). Wapler et al. (2019) provide an overview of the various techniques, of which a few are highlighted here, with an outlook to 2030.

3.2.1 | Observation-based methods

Observation-based nowcasting methods (cf. Wapler et al., 2019 for a recent overview) often use extrapolation

TABLE 1 High-level overview of major software releases by the EUMETSAT satellite application facility in support of nowcasting and very short-range forecasting (NWCSAF) in its 2022–2027 fourth phase of development and operations.

Supported orbit	New NWCSAF software package	Supported satellite sensors	Product categories
Geostationary	GEO-I NGI	MTG-I FCI, LI MTG-S IRS MSG SEVIRI Himawari AHI GOES-R ABI, GLM	Image interpretation and interpolation Clouds Precipitation Winds Instability indices Convective initiation Tropopause folding Gravity waves Thunderstorms Lightning
	GEO-S NGS	MTG-S IRS MTG-I FCI	Temperature Humidity Instability indices
Polar	PPS NGI	EPS-SG A METOP A, B, C NOAA (prior to NOAA-20) NOAA-20 S-NPP JPSS (all operational) EOS (Terra and Aqua) FY-3D (and all operational >D) Sentinel 3 A and B	Clouds Winds
	PPS-MW MW	EPS-SG B/MWI, ICI EPS-SG A/MWS AWS	Ice Water Path Liquid Water Path Precipitation

techniques applied to radar echoes or satellite-based cloud observations (see Section 3.1). This extrapolation interprets the apparent motion from the analysis of previous radar or satellite images. Optical flow or cross-correlation techniques are typically used to derive the motion. Applying such advection-based approaches for nowcasting relies on the assumption that the spatial extent, the internal structure as well as the intensity of the current cloud/precipitation field does not change over time. This will obviously lead to errors in the context of rapidly developing weather situations such as the development of deep convection. Thus, some approaches try to account for temporal changes in the cloud or precipitation structure and provide uncertainty estimates. It currently takes about 1–2 min to run an observation-based algorithm.

Feature detection and tracking methods are also widely used. Such nowcasting methods rely on the identification of specific weather systems as 'features' or 'objects', and fixed or adaptive reflectivity thresholds are applied to identify convective storms in radar data. Identifying such objects in successive measurements allows for tracking of objects over time including splitting and merging. Lightning data from ground- and space-based systems add information to convection nowcasting and for classifying the severity of thunderstorms (see Section 3.1).

In addition to the aforementioned techniques, sophisticated methods are emerging which combine and merge various data sources. For example, consistent, blended QPE products derived from radar, satellite (e.g., the NWCSAF precipitation products) and rain gauges can be beneficial for areas with limited radar coverage, or where terrain or other effects limit the value of radar-based QPE. However, the understanding of the physical differences among these measurements remains a limitation.

Empirical artificial intelligence (AI) and ML-based methods can be powerful to combine different data sources and reduce information overload for forecasters (Cintineo et al., 2014; James et al., 2018; Leinonen et al., 2022) as well as have the potential to be less computationally expensive and so very applicable to nowcasting timeframes. The COALITION (Nisi et al., 2013) and ProbSevere (Cintineo et al., 2018) tools calculate probabilities of severe storm occurrence, and Leinonen et al. (2022) propose an ML technique for nowcasting thunderstorm hazards. ML-based techniques have been applied to storm detection and tracking (Lee et al., 2021) and precipitation advection (Agrawal et al., 2019; Ayzel et al., 2020; Ravuri et al., 2021; Sønderby et al., 2020).

Furthermore, probabilistic products and nowcast ensembles are becoming more popular (Schmid et al., 2019) in quantifying the inherent uncertainty in well-established deterministic approaches. These require enough processing power to be calculated within strict timeliness limits. Calbet et al. (2018) showed that due to the intrinsic unpredictability at scales <6 km, nowcasting most likely will have to be mainly based on observations or on NWP-ensemble-based probabilistic fields.

Towards 2030

To advance observation-based nowcasting methods, it will be very important to foster the understanding of existing and new observations, for example, of crowd-sourced data or satellite-derived cloud, instability, moisture and lightning products (EUMETSAT, 2020a, 2020b), including uncertainty. These datasets should not only be analysed in a statistical way to optimize specific nowcasting verification metrics but should also be investigated to further build our understanding of meteorological processes and the variety of meteorological phenomena relevant in the nowcasting range, for example, via applied research projects at NMHS and with the research community. Development of algorithms should embrace probabilistic approaches, use advances in computing and the development of new approaches adopted from other fields, for example, from ML (e.g., Ayzel et al., 2020; Ravuri et al., 2021).

3.2.2 | NWP-model-based methods

As stated in the previous section, HR NWP models are needed to extend the forecast range up to 6 h for most cases, especially when convection and orographic forcing occur. For those cases, simulated observations usually show better performance than observation extrapolations. Frequent computation of initial states using data assimilation schemes (DA hereafter) with recent observations of various types is very important in this context. Furthermore, and as discussed in the next section, combining observation-based methods and NWP aims to produce the best solution between these two approaches.

HR NWP models

HR NWP models are run at km or sub-kilometre scale with a non-hydrostatic dynamical core, to explicitly represent processes linked to cloud and convection. Due to their high computational cost, such models are currently run over limited areas and their lateral boundary conditions are usually provided by global NWP models. Whether their initial state is deduced from dynamical adaptation of models at larger scales or after a DA process, such HR NWP models are prone to spin-up effects during the first integration steps due to imbalances in their initial fields. In addition, the computation of model outputs takes time. As a consequence, observation extrapolation methods which are available within a few minutes (see Section 3.2.1), are predominant typically up to ≥1 h lead time.

For longer forecast ranges and as NWP becomes more skilful for convective situations, NWP models play nowadays a crucial role in forecasting features such as short-lived storms or hazards (Sun et al., 2014). Short-term forecasts of other parameters of interest can be exploited in applications such as renewable energy production. Furthermore, NWP provides knowledge of their km-scale uncertainty that may not be in the initial state but is favoured by orography or large-scale conditions. One field of investigation is the accurate probabilistic representation of convective initiation (Majumdar et al., 2020).

As reviewed by Gustafsson et al. (2018), many meteorological centres operate HR NWP models to produce weather forecasts typically up to 2 days over their domain of interest several times a day. The AROME model, initially developed by Météo-France, is for instance used by many European countries that belong to the ALADIN/HIRLAM (now the ACCORD) modelling consortia. We can also cite among others COSMO (used by DWD, MeteoSwiss, Italy, Greece, Romania, Poland, Russia and Israel), ICON (DWD), UKV (Met Office), HRRR (NOAA) or LFM (JMA).

Data assimilation

All those NWP systems make use of assimilation of observed data to update a previous forecast in order to create a new initial state. The way information from observations is used in this state depends on the a priori knowledge of forecast and observation errors. Various methods are possible, from variational (3D or 4D-Var), sequential (EnKF and derivatives), to ensemble-variational (Bannister, 2017). As it is schematized in Figure 10, there will always be an incompressible gap between the real time and the time of availability of the NWP forecast. This is mainly due to the need for the observations to be received and to the computational time that is needed by both DA and model integration.

For nowcasting applications, the challenge is to find a compromise between the length of this gap and the quality of the initial state. RUC (typically hourly) that can be obtained by performing cycled assimilation/forecast steps such as in NOAA's HRRR (Benjamin et al., 2016) is also of great importance. The requested tight deadline for forecast outputs implies short cut-off times (typically 15 min), which makes it difficult to account for observations with later availability such as, for example, most

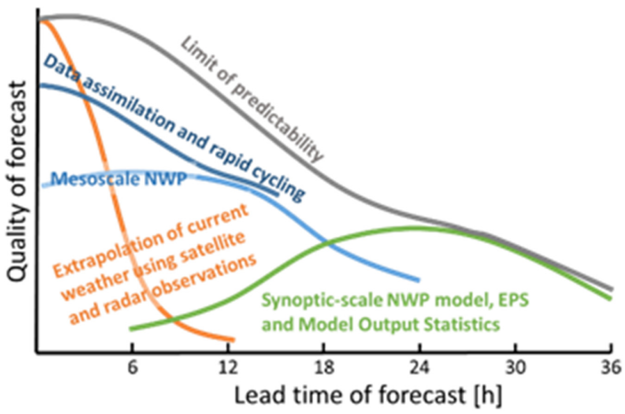

FIGURE 10 The quality of weather forecasts defined as a function of lead time for different forecasting methods. The figure is highly schematic and the quality of forecast is not-to-scale qualitative accuracy of the different performances. This figure is based on Browning (1980).

satellite-based radiances. For this reason, data from ground-based sensor, aircraft and Doppler radar are mainly used.

Pragmatic choices can be made in order to provide as fast as possible the different elements, such as background or lateral boundary conditions, respectively needed for the DA and for the forecast steps (Auger et al., 2016). Non-variational DA techniques can also be used additionally to nudge information such as cloud cover using, for instance, a combination of ceilometers and cloud-top pressure deduced from IR radiances in HRRR, or radar data through latent-heating methods (in HRRR again and in the UKV).

Towards 2030

Improvements in the representation of many physical processes used in HR NWP models, especially those that impact the boundary layer and the representation of cloudy or precipitating systems, can directly benefit nowcasting. The use of sub-kilometric resolutions seems particularly important for urban applications and for complex terrains. Projects such as the WMO Research Demonstration Project on the Paris Olympic Games in 2024 (RDP2024, Masson et al., 2020), will help in defining optimal configurations over small domains with such resolutions, especially for nowcasting applications.

As pointed out by Gustafsson et al. (2018), improvements in DA algorithms for HR NWP still are needed, for instance, to reduce displacement errors of, for example, forecasted precipitating patterns. In particular, (i) forecast errors need to be more flow dependent, (ii) hydrometeors should be included in the control variable (Zhang et al., 2013) and (iii) non-linearities in the model and in the operators that are used to simulate observations must be better taken into account. The ongoing NOAA Warn-on-Forecast project for ensembles (NEWSe, Weathley et al., 2015) is part of that context.

For nowcasting, fast data supply and rapid observation processing are key challenges. The quality of the retrieved analysis is directly linked to the type of the assimilated data, to their resolutions (temporal and spatial), to their overall quality and to their timeliness. In addition, denser observations are needed to better constrain small-scale features, such as low-level humidity, wind and temperature, which can play a crucial role for convective initiation. Radiances from imagers onboard geostationary satellites such as FCI on MTG will play a key role here.

Those developments will really be beneficial for nowcasting if the overall computation times drop quite drastically at all stages. ML could clearly help on this aspect to speed up different algorithms such as those used for observation simulation and DA, or automated quality control of observations (Husnoo et al., 2021). As computation costs directly rely on the number of grid points, the use of ensembles to produce probabilistic forecasts in real time is still challenging because of time constraints. Ensemble of forecasts should however be seriously considered, as amplitude and displacement errors linked to the phenomena that are classically considered in nowcasting quickly increase. Benefits of ensemble for short-term QPF for past situations have been shown by Lawson (2018). Providing probabilistic information would also be highly beneficial to forecasters and other end users (see Section 2.2).

3.2.3 | Combined methods for seamless prediction

Although nowcasting systems have traditionally been distinguished as mainly observation-based or on NWP-based, they are increasingly combining both sources of information.

The term 'seamless prediction' is used in general to cover timescales from minutes to months, but also considers all components of the Earth System—including hydrology and atmospheric composition, as well as links to users, applications and the social sciences (Ruti et al., 2020).

Here, the focus of seamless prediction is on the blending and integration of several elements including observation-based nowcasting and NWP to provide smooth, consistent forecasts. These are aimed at presenting outputs with consistency in quality, skill and content, regardless of the underlying method, with lead times from minutes up to few hours ahead (Schmid et al., 2019). Most of the current nowcasting tools solve blending by assigning different weights to each method during the first hours of prediction, with the observation-based nowcasting having more weight during the first hours and gradually yielding to the NWP-based prediction (Figure 10). In some methods, weights vary depending on the orography or the weather observed or forecast. Table 2 provides a summary of the main characteristics of observation-based and model-based approaches.

The intrinsic uncertainty of nowcasting, as well as the stochastic nature of atmospheric phenomena, especially convection, demand a probabilistic approach to prediction. If the probabilities accurately represent the uncertainty of the observation-based nowcast and that of the NWP, then they can be combined to produce skilful probability forecast over a wide range of lead times. Combination techniques for these probabilistic systems are under development, based on variational techniques or Kalman filters (Atencia et al., 2020), or by blending of probabilities (Moseley et al., 2022).

New techniques such as AI and ML are proving useful in reducing computation time and are showing great potential in the automatic adjustment of parameters or providing extra information (de Coning et al., 2020). Perception of probabilistic products can be difficult from a user's point of view and there have been rather sparse projects and surveys concerning this problem (Kox et al., 2015; Sivle et al., 2022; Wastl et al., 2018). There is an ongoing discussion among meteorologists on how to correctly apply these products in case of forecasting extreme events. Thus, the wider uptake of probabilistic nowcasts and applications will also require development of explanatory products, interpretation guidance and advanced visualization, in close cooperation with forecasters and end users.

There are several NMHSs that have implemented deterministic seamless prediction systems in the very short term such as SWIRLS-2 (Li & Lai, 2004), Nowc-Radiation (Martinez & Pallarès, 2019), SESORA (Urbich et al., 2020) or INCA (Haiden et al., 2011). Currently, as in deterministic, most of the probabilistic seamless products address the QPF and put together different nowcasting based on observation, mainly radar, with the EPS of NWP models, such as STEPS (Bowler et al., 2007). Several NMHS are undertaking comprehensive seamless prediction projects such as ULJAS at FMI, IMPROVER at Met Office, SINFONY at DWD (Blahak et al., 2018) or SAPHIR at ZAMG (Dabernig et al., 2020).

The next few years are expected to witness the expansion of seamless systems for predictions in the very short range, giving more value to the needs of users for continuous and consistent information regardless of the source.

Seamless systems for very short-range forecasts will increasingly use probabilistic approaches, simultaneously encompassing the treatment of objects and fields, and harvesting advances in ensembles at very short range. Members of analysis ensembles and members of observation-

TABLE 2 Main differences between nowcasting techniques based on observation and those based on NWP models.

Characteristic	Observation-based approach	Model-based approach
Starts from	Quasi-truth	Analysis
Spatial resolution	O (km)–O (100 m) or less	O (10 km)–O (100 m)
Temporal resolution of output	Minutes	Tens of minutes
Availability after last observation	A few minutes	Several tens of minutes
Update frequency	5 min or less	Every hour or few hours
Information on the short-range evolution of systems	Limited	Extensive
Combination of fields and objects	Challenging	Embedded
Treatment of uncertainty	Neighbourhoods, fuzzy logic, post-processes, EPS etc.	EPS; expansion with neighbourhoods or lagging; post-processes etc.
Skill (see Figure 10)	Advantages in the first hours of forecast	Advantages from a few hours of forecast
Towards 2030	• Data from new sources integrated synergistically. • Deeper understanding of meteorological processes. • More automation of prediction. • Use of ML/AI techniques to filter, process, post-process. • More extensive use of EPS, etc.	• More physical processes included in NWP, particularly in boundary layer. • Flow dependency of forecast error in DA. • Best retrieved analysis (MW radiation, hydrometeors ...). • Greater use of ML in the different steps of the NWP system. • Higher spatial resolution (urban applications).

based nowcasting will be prepared and calibrated correctly, reflecting the temporal and spatial statistical properties of the phenomena to be predicted (Atencia et al., 2020). Important progress will be made to integrate convection-permitting ensemble prediction systems (EPSs) in nowcasting ensembles, and to improve the combination techniques of the ensembles of both systems (e.g., Nerini et al., 2019). EPS will be calibrated from probabilities to scenarios and from low to high resolutions in space and time.

Undoubtedly, seamless probabilistic forecasts in the very short range will add significant value to forecasting; however, guidance will be needed for educating both forecasters and key end users in applying these predictions (cf. Section 2.2).

Towards 2030

To improve the various nowcasting and seamless methods and tools described in Sections 3.2.1–3.2.3 towards 2030, we propose a joint undertaking of nowcasting tool developers, to be launched and coordinated within the existing EUMETNET E-NWC programme and the anticipated WMO World Weather Research Programme (WWRP) Research Demonstration Project (RDP) SHOW-HOW. Their objectives should be to improve our understanding of the meteorological processes relevant for the nowcasting/seamless problem, to advance methods of data integration and combination including probabilistic approaches, and to improve the skill of nowcasting tools as well as seamless prediction through pan-European benchmarking and verification. The undertaking should foster the further development of algorithms, using advances in computational approaches and the development of new approaches adopted from other fields, for example, from ML. The EWC could serve as a common platform for these developments.

3.3 | Data and infrastructure

With the advent of new-generation satellites and ground-based measurements, observation data rates will increase by orders of magnitude, for example, MTG will generate at least 50 times more data than MSG. To advance nowcasting, it will be important to integrate and synthesize this wealth of data into a few parameters which can be quickly interpreted (see Section 3.2), requiring (i) standardized data formats such as NetCDF/CF or BUFR, (iii) metadata standards that allow for a description of each measurement and its physical interpretation, (iv) reduced data dissemination rates by using standardized compression methods and (v) nowcasting tools and near real-time data feeds available on centralized clouds, thus bringing users to the data as an alternative to disseminating data to users.

3.3.1 | High-availability data services and emergence of the European Weather Cloud

A highly reliable operational data flow is a precondition of safety-critical applications such as using nowcasting techniques for severe weather prediction. With exploding data rates from both the observing system and the model sphere, clear priorities are required in the data services realm to remain affordable and operationally viable. From the space-based observations side in Europe, EUMETSAT will continue to build on EUMETCast Satellite Rebroadcasting System for the delivery of safety-critical application data, in particular MTG data relevant for nowcasting. At the same time it is diversifying its data services portfolio to offer a mix of pull and push data services that complement EUMETCast Satellite for less stringent requirements, for example for applications in research and development, and as exploratory and fall-back solutions. A potential game changer in this regard is the EWC project, jointly developed by ECMWF and EUMETSAT, offering data processing resources close to the meteorological input data.

As such, the EWC aims to become the cloud-based platform for meteorological application development and operations in Europe and seeks to enable the digital transformation of the European Meteorological Infrastructure. It is dedicated to support the NMHS of the Member States of both ECMWF and EUMETSAT in fulfilling their official duties to protect life and property from impending meteorological hazards (Figure 11). Offering processing and storage capacity for the initiating organizations and their respective Member and Cooperating States, EWC is foreseen to further host activities such as research projects, training and prototyping new products. There will be near-real-time feeds of operational data from EUMETSAT and ECMWF, as well as climate data records, allowing users to 'bring' their software into a dedicated environment close to the data, rather than having to rely on dissemination and local capacity.

In a pilot phase until 2022, it is planned to host the NWCSAF software and the ESSL Displayer on the EWC. Developers of nowcasting tools should take advantage of the opportunities provided with the Cloud, as a platform to seed the formation of user communities around the development of 'merged' advanced products in support of forecasting, and use of common tools. In the coming years, the EUMETNET Federated Data Coordination Mechanism will be further developed, building on the EWC and enabling standardized access to data, including hourly and sub-hourly observations from surface stations including those not currently routinely exchanged such as rain gauge data, solar radiation, snow depth and wind.

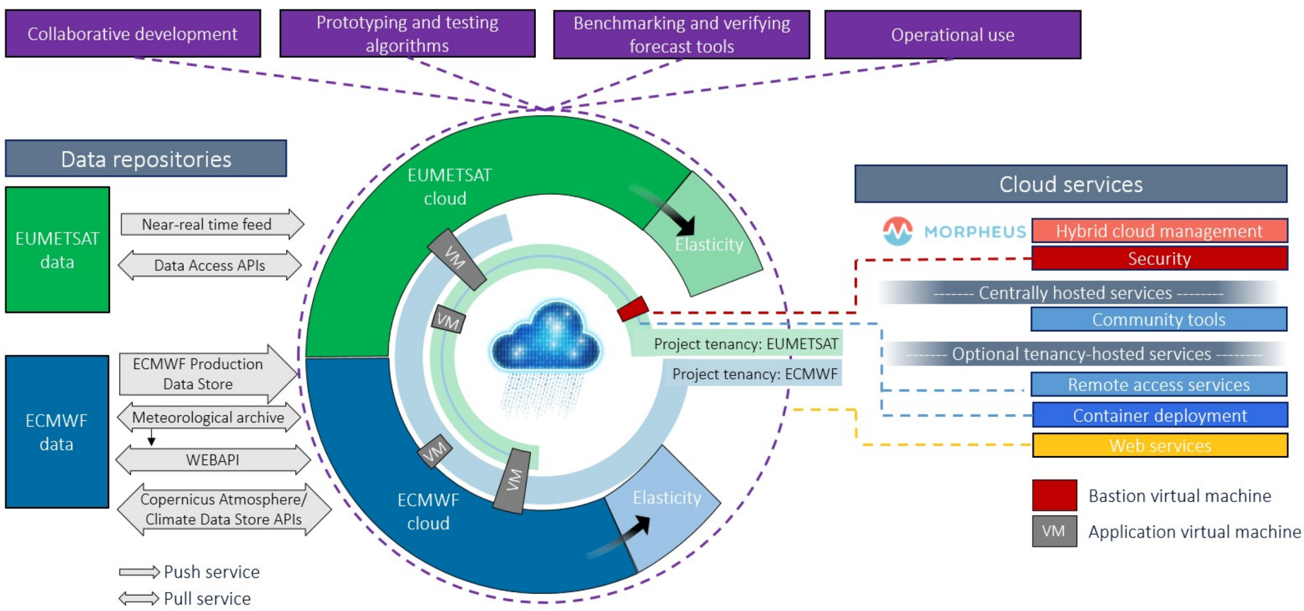

FIGURE 11 The European Weather Cloud, a joint undertaking by EUMETSAT and ECMWF providing centralized processing and storage capacity, for the benefit of collaborative activities by meteorological services, including development and benchmarking of nowcasting tools (schematic view of the system in its pilot phase).

Other cloud-based platforms are under development by among European NMHS to foster collaboration, cooperation and sharing of operational responsibility (e.g., met.group, United Weather Centres).

3.3.2 | Code sharing and co-development

To share development costs, groups of NMHS and researchers should co-develop nowcasting tools, ideally run on a cloud-based host infrastructure (e.g., the EWC). This will allow all countries to contribute, including those with small development teams. Open licences such as BSD or MIT should be used for these developments, to ensure sense of ownership and common access. Collaborative software development projects in the nowcasting area, such as pytroll (2021) and pySteps (2021), GeoWeb, and ADAGUC (KNMI, 2021), should be nurtured. Software such as Com-SWIRLS (Wong et al., 2016) and the EUMETSAT Nowcasting SAF software packages (EUMETSAT, 2021b) should be available as openly as possible. As an example, NOAA within the Unified Forecasting System (UFS) framework openly releases pre-operational code and tools for nowcasting and short-term weather prediction applications, as part of its engagement with the weather community (NOAA, 2021). By 2030, nowcasting tools and supporting packages should be available on common, standardized repositories such as github, and deployed as appropriate on the EWC.

3.3.3 | Visualization and display systems

Towards 2030, display systems and techniques will have to evolve with an increasing level of sophistication and diversity of nowcasting datasets (objects, fields and probabilistic information), and the needs of nowcasting research. Such systems shall render the results of nowcasting tools (objects, fields and probabilistic information) understandable for forecasters and end users. Several lines of development are important: comprehensive, but at the same time simple, plotting of 4D data cubes combining model and observational data could be a development line, and so is effective display of object-based, EPS and probabilistic forecasts. Powerful web-based meteorological data display systems will plot all data together in a common geographical projection, using next-generation Web Mapping, Feature and Coverage Services. Engaging meteorological display system and tool developers, such as through the European Working Group on Operational Meteorological Workstations (EGOWS), will be critical, as well as building upon research-oriented visualization tools such as Met.3D (Rautenhaus et al., 2015).

Towards 2030

- The EWC has become a core piece of meteorological infrastructure for accessing and sharing data, collaborative development of products and tools, and for development and operations.
- As identified in Sections 3.2.1–3.2.3, we recommend a joint undertaking among European NMHS around

nowcasting, for the (co-) development of nowcasting tools, based on common verification methods, code sharing and use of the EWC as a common cloud infrastructure.

3.3.4 | Forecast verification and quality control

Forecast verification has been developed in the last decades (WMO, 2021b). However, many approaches typically used for NWP forecast verification cannot easily be adopted to nowcasting. Verifying nowcasts is mostly relevant in case of high-impact weather events. These are usually rare, localized events, for which there is often a lack of reference data (and sometimes a lack of definition of what is a good warning.)

Validation and verification approaches applied in the nowcasting framework are very diverse. A typical approach to assess the quality of nowcasting a particular severe weather event is a subjective analysis based on available pieces of information and data to make a complete as possible picture. Although very useful, this approach is not applicable for a larger number of events and does not enable the calculation of statistics.

Thorough verification of nowcasts is hampered by the limited availability of observations that could serve as ground truth. While lightning detection networks can be used for the verification of the occurrence of thunderstorms, and radar networks provide useful measurements for the verification of precipitation, there is a lack of observations suitable for the verification of phenomena such as icing, freezing rain, wind gusts, hail, tornadoes, localized heavy precipitation and low clouds.

Databases of severe events such as the European Severe Weather Database (ESWD, Dotzek et al., 2009) provide a basis for verifying nowcasts; however, they are often non-publicly maintained by NMHS, often lack references to pertinent observations, and tend to be incomplete in coverage.

If no independent ground truth is available, a typical approach is to compare the nowcast with the analysis of the same nowcasting tool, for example, comparing the detected object with the +1 h-nowcast for this object calculated an hour before. While valuable for assessing the quality of tracking, location and intensity forecast, this approach does not answer the question of whether the algorithm really detected the phenomena of interest (e.g., a thunderstorm, fog, etc.).

Although desirable, comparative verification of various nowcasting methods across national borders is not easily accomplishable, due to issues mentioned in Section 3.1 as well as specific choices of threshold. Some forecast demonstration projects run during Olympic games also included nowcasting systems, which were then applied to the same area using the same input datasets.

Towards 2030

Standardized verification methods would enable benchmarking of nowcasting tools and thus provide a measure of quality to their authors and to users. This helps underpin the credibility of NMHS as the authority for issuing severe weather warnings, especially when compared with private sector offerings (Agrawal et al., 2019).

Nowcasting system development in Europe would greatly benefit from additional efforts in nowcasting (and weather warning) verification. New ideas must be developed to tackle the aforementioned existing limitations in nowcasting verification, including the verification of probabilistic forecasts. Marsigli et al. (2021) provide ideas focusing on verifying thunderstorm and fog forecasts. Alternative reference data sources might become useful, such as crowdsourced or socio-economic data (e.g., insurance reports, emergency calls, fire brigade operations data, mobile weather app data); however, these will require substantive efforts in quality control data curation and training of citizen scientists (e.g., Barras et al., 2019; Gaia et al., 2017; WMO, 2021b).

In addition to parameter-based verification (e.g., anemometer for wind gusts), impact-based verification (fallen trees as indicator for wind gusts) should be investigated further. These will require 'models' to 'translate' impacts to physical parameters which may depend on various external factors (e.g., in the case of fallen trees, the condition of the soil, season, leaf coverage, etc.). First experiences have been gathered using data from fire brigade operations.

Recommendations towards 2030 related to verification and quality control are embedded in the overall set of recommendations provided in Section 4.

4 | CONCLUSIONS—KEY LINES OF DEVELOPMENT TOWARDS 2030

We have taken a tour d'horizon along key elements of the value chain of nowcasting high-impact weather with our focus on Europe, now and towards 2030. We looked at evolving user needs and identified key developments, such as new observations, NWP-based and ensemble prediction methods, that hold promise to improve nowcasting products and services by European NMHS over this decade. We also identified gaps and recommended actions to address them.

Nowcasting algorithms and tools are tuned mostly to local or national conditions and input data types. Observing networks vary from country to country in many aspects (e.g., radar configuration, network density and measuring strategy). Some data needed for nowcasting are not a priori exchanged internationally. Recent surveys on nowcasting applications and user aspects (e.g., Gundersen & Simon, 2018; Strauss & Wang, 2013) showed big differences among European countries in using nowcasting tools and applications. While certain NMHS have widespread activities, many deal with lack of manpower and sufficient resources for their nowcasting-related activities. Due to the aforementioned limitations, the situation in nowcasting is different from NWP where the development is planned, continuous and coordinated in the frame of various consortia. NWP models can be adapted to various regions relatively easily. This enables effective cross-border transfer of knowledge and methodologies and their fast introduction into operational use for all members. Combining resources in NWP consortia also reflects the generally larger effort required for developing and maintaining NWP code than for a classical nowcasting tool. One goal of a joint undertaking by European NMHS around nowcasting should be in adjusting for these differences.

Better pan-European nowcasting skill is important for forecasting and mitigating hazards related to large-scale severe weather events, for example, derechos (Johns & Hirt, 1987; Gatzen et al., 2020) or rapidly developing cyclones (Fink et al., 2009). Concerning such events, communication (both operational and in terms of data/knowledge exchange) across borders generally needs improving. Detailed, large-scale views about the distribution of certain important parameters are often missing (e.g., wind gusts), either not exchanged or only with insufficient density or frequency. Real-time communication and information exchange would be important to obtain a bigger picture and to understand/forecast the genesis and intensity of the above-mentioned phenomena.

Currently, the main information source on European severe weather is the METEOALARM portal (METEOALARM, 2021), as well as individual portals maintained by the NHMS. However, across borders, there are large inconsistencies in defining the warning levels, because of differences in criteria, requirements, forecasting capabilities, availability of observations or experience. There have been several activities in the past to fill these gaps and to create unified nowcasting products for large domains, for example, INCA-CE (Wang et al., 2017) or OPERA (Saltikoff et al., 2019). Despite being successful, it was also shown that merging information from several, qualitatively different observational sources or NWP/nowcasting products is a difficult task. To provide common nowcasting information at sufficiently high resolution will above all require high-quality observational databases consisting of a large number of frequently-updated inputs (on the order of minutes).

It is possible that the role of NWP models in nowcasting will increase with wider use of RUC and further increases in resolution (approaching the scale of large turbulent eddies). Nevertheless, the problem of bridging the most recent observation-based nowcast with very short-range NWP forecasts remains. Despite higher forecast accuracy, advances in IT, visualization tools and so forth, it remains a challenge to tailor information to end user needs. This can lead to misunderstanding or even the refusal of nowcasting products in extreme cases.

One of the more recent trends in severe weather forecasting and nowcasting supported by WMO is impact-based forecasting (WMO, 2015a, 2015b). Relationships between severe weather events and their potential impact are still not well understood and their variability across Europe can be very high. Further investigation and access to socio-economic data will need intensive cooperation of NMHS with several institutions (e.g., insurance companies, civil protection agencies and forestry). Building nowcasting capacity with civil protection agencies has been the subject of research projects such as the H2020 ANYWHERE (http://anywhere-h2020.eu/).

Pan-European methodologies should be developed, which will again require deep interdisciplinary cooperation (e.g., with wind engineers, civil protection, electricity companies, etc.). One of the most challenging tasks is forecasting the impact of rare events, because the lack of previous experience can cause an underestimation of possible consequences by both forecasters and disaster management authorities. These are typically situations with local extreme events such as tornadoes, winter precipitation types (freezing rain), and multi-hazard impacts, for example, heavy rainfall leading to landslides. Sometimes, relatively common meteorological phenomena (e.g., thunderstorms and lightnings) represent a threat in certain conditions involving crowds (e.g., Horváth et al., 2007) or in a weather-exposed terrain (sea, lakes, mountains, etc.). Warning apps and message push broadcasts using mobile phones could help mitigate such dangerous situations, in addition to traditional warning channels (TV, radio and sirens). Moreover, a European journal should be established that offers a platform for the nowcasting, forecasters and end user communities, equivalent to the AMS Journal Weather, Climate and Society,

Based on the above discussion and the gaps and recommendations identified in earlier sections, we recommend the following to be accomplished to advance nowcasting in Europe by 2030:

- Foster and maintain close, regular feedback loops among providers of nowcasting information, forecasters and end users to enable continuous improvement of nowcasting tools and services, for example, in a European-level nowcasting forum
- Address observational gaps identified in the EUMETNET EUCOS analysis, and improve availability and access to higher density observational data, particularly in the boundary layer, to support forecasting of high-impact weather, and verification
- Establish routine, automated pan-European exchange of radar data based on common quality control and data management, to allow for the generation of consistent pan-European products such as QPE or volumetric scans for NWP, and to improve forecasts for areas with overlapping radar coverage across national borders
- Design and run experiment(s) to improve the understanding and to study the relative impact of observed surface and satellite-based data on Limited Area Modelling and nowcasting tools. The experiment(s) should take advantage of novel observations such as space-based lightning and crowdsourced data, and ML/AI techniques. For example, weather research projects in target areas such as the 2024 Paris Olympic Games should bring new insights.
- Establish more seamless and probabilistic nowcasting methods across Europe, and make their results better understandable to forecasters and key end user communities, supported by guidance and best practices (e.g., through the EUMETNET E-NWC programme and the WMO WWRP Forecasting Demonstration Project SHOW-HOW).
- Create a joint undertaking among European NMHS around nowcasting, for the (co-) development of nowcasting tools, based on common verification methods, code sharing and use of common cloud infrastructure such as the EWC. By 2030, the EWC should become a core piece of meteorological infrastructure for accessing and sharing data, collaborative development of products and tools, and for development and operations.
- Establish a European journal that offers a platform for the nowcasting, forecasters and end user communities, equivalent to the AMS Journal Weather, Climate and Society

AUTHOR CONTRIBUTIONS

Stephan Bojinski: Conceptualization (lead); supervision (lead); writing – original draft (equal); writing – review and editing (lead). **Dick Blaauboer:** Conceptualization (equal); writing – original draft (equal); writing – review and editing (equal). **Xavier Calbet:** Conceptualization (equal); writing – original draft (equal). **Estelle de Coning:** Conceptualization (equal); writing – original draft (equal). **Frans Debie:** Conceptualization (equal); writing – original draft (equal). **Thibaut Montmerle:** Conceptualization (equal); visualization (equal); writing – original draft (equal); writing – review and editing (equal). **Vesa Nietosvaara:** Conceptualization (equal); writing – original draft (equal). **Katie Norman:** Conceptualization (equal); visualization (equal); writing – original draft (equal). **Luis Bañón Peregrín:** Conceptualization (equal); writing – original draft (equal). **Franziska Schmid:** Conceptualization (equal); writing – original draft (equal); writing – review and editing (equal). **Nataša Strelec Mahović:** Conceptualization (equal); writing – original draft (equal). **Kathrin Wapler:** Conceptualization (equal); visualization (equal); writing – original draft (equal).

ACKNOWLEDGEMENTS

The authors would like to acknowledge contributions and comments from the following individuals: Mateusz Barczyk, Claire Bartholomew, Evelyn Cusack, Paul Davies, Eoghan Harney, Simon Keogh, Thomas Kratzsch, Ingo Meirold-Mautner, Paolo Ruti, Joachim Saalmüller, Lothar Schüller, André Simon, Jacqueline Sugier, Roope Tervo, Sreerekha Thonipparambil and two anonymous reviewers.

CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

ORCID

Stephan Bojinski https://orcid.org/0000-0002-8684-6562

REFERENCES

Agrawal, S., Barrington, L., Bromberg, C., Burge, J., Gazen, C. & Hickey, J. (2019) Machine learning for precipitation nowcasting from radar images. arXiv preprint arXiv:1912.12132. Available from: https://arxiv.org/abs/1912.12132

Albrecht, R.I., Goodman, S.J., Buechler, D.E., Blakeslee, R.J. & Christian, H.J. (2016) Where are the lightning hotspots on Earth? *BAMS*, 97, 2051–2068. Available from: https://doi.org/10.1175/BAMS-D-14-00193.1

Atencia, A., Wang, Y., Kann, A. & Meier, F. (2020) Localization and flow-dependency on blending techniques. *Meteorologische Zeitschrift (Contributions to Atmospheric Sciences)*, 29(3), 231–246. Available from: https://doi.org/10.1127/metz/2019/0987

Auger, L., Dupont, O., Hagelin, S., Brousseau, P. & Brovelli, P. (2016) AROME–NWC: a new nowcasting tool based on an operational mesoscale forecasting system. *Quarterly Journal of the Royal Meteorological Society*, 141, 1603–1611. Available from: https://doi.org/10.1002/qj.2463

Ayzel, G., Scheffer, T. & Heistermann, M. (2020) RainNet v1.0: a convolutional neural network for radar-based precipitation nowcasting. *Geoscientific Model Development*, 13, 2631–2644. Available from: https://doi.org/10.5194/gmd-13-2631-2020

Bannister, R.N. (2017) A review of operational methods of variational and ensemble-variational data assimilation. *Quarterly Journal of the Royal Meteorological Society*, 143, 607–633. Available from: https://doi.org/10.1002/qj.2982

Barras, H., Hering, A., Martynov, A., Noti, P.-A., Germann, U. & Martius, O. (2019) Experiences with >50,000 crowdsourced hail reports in Switzerland. *BAMS*, 100, 1429–1440. Available from: https://doi.org/10.1175/BAMS-D-18-0090.1

Benjamin, S.G., Weygandt, S.S., Brown, J.M., Hu, M., Alexander, C. R., Smirnova, T.G. et al. (2016) A north American hourly assimilation and model forecast cycle: the rapid refresh. *Monthly Weather Review*, 144, 1669–1694. Available from: https://doi.org/10.1175/MWR-D-15-0242.1

Blahak, U., Wapler, K., Paulat, M., Potthast, R., Seifert, A., Bach, L. et al. (2018) Development of a new seamless prediction system for very short range convective-scale forecasting at Deutscher Wetterdienst. 20th EGU General Assembly, EGU2 018, Proceedings from the Conference Held 4–13 April, 2018 in Vienna, Austria, p.9642.

Bousquet, O. & Tabary, P. (2014) Development of a nationwide real-time 3-D wind and reflectivity radar compositein France. *Quarterly Journal of the Royal Meteorological Society*, 140, 611–625.

Bowler, N.E., Pierce, C.E. & Seed, A.W. (2007) STEPS: a probabilistic precipitation forecasting scheme which merges extrapolation nowcast with downscaled NWP. *Quarterly Journal of the Royal Meteorological Society*, 132(620), 2127–2155.

Browning, K.A. (1980) Review lecture: Local weather forecasting. *Proceedings of the Royal Society of London A*, 371, 179–211. Available from: https://doi.org/10.1098/rspa.1980.0076

Browning, K.A. (1981) Nowcasting: Mesoscale observations and short-range prediction. In: Battrick, B. & Mort, J. (Eds.) *Proceedings of an International Symposium Hamburg, Germany, 25–28 August. European Space Agency SP-16*, http://refhub.elsevier.com/B978-0-12-409548-9.11777-4/rf0025

Calbet, X., Peinando-Galan, N., DeSouza-Machado, S., Kursinski, E. R., Oria, P., Ward, D. et al. (2018) Can turbulence within the field of view cause significant biases in radiative transfer modeling at the 183 GHz band? *Atmospheric Measurement Techniques*, 11, 6409–6417. Available from: https://doi.org/10.5194/amt-11-6409-201

Cintineo, J., Pavolonis, M.J., Sieglaff, J.M. & Lindsey, D.T. (2014) An empirical model for assessing the severe weather potential of developing convection. *AMS Weather and Forecasting*, 29, 639–653. Available from: https://doi.org/10.1175/WAF-D-13-00113.1

Cintineo, J., Pavolonis, M.J., Sieglaff, J.M., Lindsey, D.T., Cronce, L., Gerth, J. et al. (2018) The NOAA/CIMSS probSevere model: incorporation of total lightning and validation. *AMS Weather and Forecasting*, 33, 331–345. Available from: https://doi.org/10.1175/WAF-D-17-0099.1

Dabernig, M., Schicker, I., Kann, A., Wang, Y. & Lang, M.N. (2020) Statistical post-processing with standardized anomalies based on a 1 km gridded analysis. *Meteorologische Zeitschrift (Contributions to Atmospheric Sciences)*, 29(4), 265–275. Available from: https://doi.org/10.1127/metz/2020/1022

de Coning, E., Schmid, F., Haimberger, L., Lehmann, V., Steinle, P. & Wang, Y. (2020) Special issue on development and application of seamless prediction systems. *MetZ*, 29(3), 179–181. Available from: https://doi.org/10.1127/metz/2020/1048

De Vos, L., Leijnse, H., Overeem, A. & Uijlenhoet, R. (2019) Quality control for crowdsourced personal weather stations to enable operational rainfall monitoring. *GRL*, 46, 8820–8829. Available from: https://doi.org/10.1029/2019GL083731

Dotzek, N., Groenemeijer, P., Feuerstein, B. & Holzer, A.M. (2009) Overview of ESSL's severe convective storms research using the European Severe Weather Database ESWD. *Atmospheric Research*, 93(1–3), 575–586. Available from: https://doi.org/10.1016/j.atmosres.2008.10.020

ERCC. (2021) EU emergency response coordination Centre. Available from: https://erccportal.jrc.ec.europa.eu/ [Accessed 23rd December 2021]

ESSL. (2021) The European Severe Storms Laboratory. Available from: www.essl.org [Accessed 23rd December 2021]

EUMETNET. (2020a) Observations R&D plan and statements of guidance for the EUCOS region for nowcasting and very short-range forecasting, aeronautical meteorology, and short-range NWP. Available from: http://www.eumetnet.eu/wp-content/uploads/2020/08/EMN_StatementofGuidance_EUCOSregion_NowcastingandVeryShortRangeForecasting.pdf [Accessed 23rd December 2021]

EUMETNET. (2020b) Statement of guidance EUCOS region aviation meteorology. Available from: https://www.eumetnet.eu/wp-content/uploads/2020/08/EMN_StatementofGuidance_EUCOSregion_AviationMeteorology.pdf [Accessed 23rd December 2021]

EUMETNET. (2022) EUMETNET nowcasting programme. Available from: https://www.eumetnet.eu/activities/forecasting-programme/current-activities-fc/e-nwc/

EUMETSAT. (2015) Findings and recommendations from a panel discussion on the "use of satellite information in nowcasting and short-range NWP", EUMETSAT meteorological satellite conference, 21–25 September 2015, Toulouse, France.

EUMETSAT. (2020a) Detection and monitoring of instability from hyperspectral sounders, using IASI in view of MTG-IRS. Study performed by Hungarian meteorological service (OMSZ). EUMETSAT contract number EUM/CO/18/4600002186/TA. Available from: https://www.eumetsat.int/media/47972

EUMETSAT. (2020b) Hyperspectral sounding for severe storm forecasting; testbeds to assess the potential and practical requirements in Europe. Study performed by the European Severe Storms Laboratory. EUMETSAT Contract number EUM/-CO/18/4600002214/TA. Available from: https://www.eumetsat.int/media/47966

EUMETSAT. (2021a) The EUMETSAT advanced retransmission service (EARS). Available from: https://www.eumetsat.int/media/45740

EUMETSAT. (2021b) The EUMETSAT NWCSAF – support to nowcasting and very short range forecasting. Available from: https://www.nwcsaf.org/ [Accessed 23r December 2021]

EUMETSAT. (2021c) The convection working group. Available from: https://cwg.eumetsat.int/ [Accessed 23rd December 2021]

Fabry, F. (2004) Meteorological value of ground target measurements by radar. *Journal of Atmospheric and Oceanic Technology*, 21, 591–604.

Farnell, C. & Rigo, T. (2020) The lightning jump algorithm for nowcasting convective rainfall in Catalonia. *Atmosphere*, 11, 397. Available from: https://doi.org/10.3390/atmos11040397

Fink, A.H., Brücher, T., Ermert, E., Krüger, A. & Pinto, J.G. (2009) The European Storm Kyrill in January 2007: synoptic evolution and considerations with respect to climate change. *Natural Hazards and Earth System Sciences*, 9, 405–423.

Gaia, M., Della Bruna, G., Hering, A., Nerini, D. & Ortelli, V. (2017) Hybrid human expert and machine-based thunderstorm warnings: a novel operation nowcasting system for severe weather at MeteoSwiss, 2nd European nowcasting conference, Offenbach, 3–5 May 2017. Available from: http://eumetnet.eu/enc-2017/

Gatzen, C., Fink, A.H., Schultz, D.M. & Pinto, J.G. (2020) An 18-year climatology of derechos in Germany. *Natural Hazards and Earth System Sciences*, 20, 1335–1351. Available from: https://doi.org/10.5194/nhess-2019-234

Germann, U., Zawadzki, I. & Turner, B. (2006) Pre- dictability of precipitation from continental radar images. Part IV: Limits to prediction. *Journal of the Atmospheric Sciences*, 63, 2092–2108.

Gundersen, P. & Simon, A. (2018) ASIST, WA4 report on application and user aspect, Report, EUMETNET. 38 pp.

Gustafsson, N., Janjić, T., Schraff, C., Leuenberger, D., Weissmann, M., Reich, H. et al. (2018) (2018) survey of data assimilation methods for convective-scale numerical weather prediction at operational centres. *QJRMS*, 144, 1218–1256. Available from: https://doi.org/10.1002/qj.3179

Haiden, T., Kann, A., Wittmann, C., Pistotnik, G., Bica, B. & Gruber, C. (2011) The integrated nowcasting through comprehensive analysis (INCA) system and its validation over the eastern alpine region. *Weather and Forecasting*, 26, 166–183. Available from: https://doi.org/10.1175/2010WAF2222451.1

Hallegatte, S. (2012) A cost effective solution to reduce disaster losses in developing countries: hydro-meteorological services, early warning, and evacuation. Policy research working paper 6058. Washington, D.C., World Bank.

Han, Y., Zhang, G.J., Huang, X. & Wang, Y. (2020) A moist physics parameterization based on deep learning. *Journal of Advances in Modeling Earth Systems*, 12, e2020MS002076. Available from: https://doi.org/10.1029/2020MS002076

Hintz, K.S., O'Boyle, K., Dance, S.L., Al-Ali, S., Ansper, I., Blaauboer, D. et al. (2019) Collecting and utilising crowdsourced data for numerical weather prediction: propositions from the meeting held in Copenhagen, 4-5 December 2018. *Atmospheric Science Letters*, 20, e921. Available from: https://doi.org/10.1002/asl.921

HIWeather. (2021). Available from: http://hiweather.net/ [Accessed 23rd December 2021].

Hoegh-Guldberg, O., Jacob, D., Taylor, M., Guillén Bolaños, T., Bindi, M., Brown, S. et al. (2019) The human imperative of stabilizing global climate change at 1.5°C. *Science*, 365(6459), eaaw6974. Available from: https://doi.org/10.1126/science.aaw6974

Holmlund, K., Grandell, J., Stuhlmann, R., Bojkov, B., Munro, R., Lekouara, M. et al. (2021) Meteosat Third Generation (MTG): continuation and innovation of observations from geostationary orbit. *BAMS*, 102, E990–E1015. Available from: https://doi.org/10.1175/BAMS-D-19-0304.1

Horváth, Á., Geresdi, I., Németh, P. & Dombai, F. (2007) The constitution day storm in Budapest: case study of the August 20, 2006 severe storm. *Időjárás*, 111, 41–65.

Husnoo, N., Darlington, T., Torres, S. & Warde, D. (2021) A neural network quality-control scheme for improved quantitative precipitation estimation accuracy on the U.K. weather radar network. *Journal of Atmospheric and Oceanic Technology*, 38(6), 1157–1172 Available from: https://journals.ametsoc.org/view/journals/atot/38/6/JTECH-D-20-0120.1.xml

IBM. (2021) IBM GRAF fact sheet. Available from: https://www.ibm.com/weather/industries/cross-industry/graf [Accessed 23rd December 2021]

James, P.M., Reichert, B.K. & Heizenreder, D. (2018) NowCastMIX: automatic integrated warnings for severe convection on nowcasting time scales at the German weather service. *Weather and Forecasting*, 33(5), 1413–1433 Available from: https://journals.ametsoc.org/view/journals/wefo/33/5/waf-d-18-0038_1.xml

Johns, R.H. & Hirt, W.D. (1987) Derechos: widespread convectively induced windstorms. *Weather and Forecasting*, 2, 32–49.

Kendon, E., Roberts, N., Fowler, H., Roberts, M.J., Chan, S.C. & Senior, C.A. (2014) Heavier summer downpours with climate change revealed by weather forecast resolution model. *Nature Climate Change*, 4, 570–576. Available from: https://doi.org/10.1038/nclimate2258

Kitchen, M. & Jackson, P.M. (1993) Weather radar performance at long range - simulatedand observed. *Journal of Applied Meteorology*, 32, 975–998. Available from: https://doi.org/10.1175/1520-0450(1993)032<0975:WRPALR>2.0.CO;2

KNMI. (2021) Available from: https://adaguc.knmi.nl/, https://demo.opengeoweb.com/ [Accessed 23rd December 2021].

Kox, T., Gerhold, L. & Ulbrich, U. (2015) Perception and use of uncertainty in severe weather warnings by emergency services in Germany. *Atmospheric Research*, 158-159, 292–301.

Kumjian, M. (2013) Principles and applications of dual-polarization weather radar. Part II: Warm- and cold-season applications. *Journal of Operational Meteorology*, 1(20), 243–264.

Lawson, J.R., Kain, J.S., Yussouf, N., Dowell, D.C., Wheatley, D.M., Knopfmeier, K.H. et al. (2018) Advancing from convection-allowing NWP to warn-on-forecast: Evidence of progress. *Weather Forecasting*, 33, 599–607. Available from: https://doi.org/10.1175/waf-d-17-0145.1

Lee, H., Kim, J., Kim, E.K. & Kim, S. (2021) A novel convective storm location prediction model based on machine learning methods. *Atmosphere*, 12, 343. Available from: https://doi.org/10.3390/atmos12030343

Leinonen, J., Hamann, U., Germann, U. & Mecikalski, J.R. (2021) Nowcasting thunderstorm hazards using machine learning: the impact of data sources on performance. *Natural Hazards and Earth System Sciences*, 22, 577–597. Available from: https://doi.org/10.5194/nhess-2021-171 in review.

Li, P.W. & Lai, E.S.T. (2004) Short-range quantitative precipitation forecasting in Hong Kong. *Journal of Hydrology*, 288(1–2), 189–209. Available from: https://doi.org/10.1016/j.jhydrol.2003.11.034

Majumdar, S.J., Sun, J., Golding, B., Joe, P., Dudhia, J., Caumont, O. et al. (2020) Multiscale forecasting of high-impact weather: current status and future challenges. *BAMS*, 102, 1–65. Available from: https://doi.org/10.1175/BAMS-D-20-0111.1

Marsigli, C., Ebert, E., Ashrit, R., Casati, B., Chen, J., Coelho, C.A. S. et al. (2021) Review article: observations for high-impact weather and their use in verification. *Natural Hazards and Earth System Sciences*, 21, 1297–1312. Available from: https://doi.org/10.5194/nhess-21-1297-2021

Martinez, S.M. & Pallarès, A.C. (2019) NowcRadiation seamless nowcasting solar radiation using satellite and high resolution numerical model output. 3rd European Nowcasting Conference, Madrid, 24–26 April 2019.

Masson, V., de Coning, E., Steinle, P., Roberts, R. & Sokhi, R.S. (2020) WMO research demonstration project "Paris Olympic Games 2024". 15th Symposium on the Urban Environment.

Met.no. (2020) Crowdsourced data improves temperature forecast on yr.no Crowdsourced data for quality control and nowcasting - early studies by Met Norway (wmo.int). [Accessed 23rd December 2021].

METEOALARM. (2021). Available from: www.meteoalarm.org [Accessed 23rd December 2021].

Miglietta, M.M., Carnevale, D., Levizzani, V. & Rotunno, R. (2020) Role of moist and dry air advection in the development of Mediterranean tropical-like cyclones (medicanes). *Quarterly Journal of the Royal Meteorological Society*, 147, 876–899. Available from: https://doi.org/10.1002/qj.3951

Moseley, S., Rust, F., Evans, G., Ayliffe, B., Hurst, K., Howard, K. et al. (2022) *IMPROVER: a probabilistic, multi-model post-processing system for meteorological forecasts*. Vienna, Austria: EGU General Assembly 2022, pp. 23–27 EGU22-8706. Available from: https://doi.org/10.5194/egusphere-egu22-8706

Mosier, R.M., Schumacher, C., Orville, R.E. & Carey, L.D. (2011) Radar nowcasting of cloud-to-ground lightning over Houston, Texas. *Weather and Forecasting*, 26(2), 199–212.

MunichRe. (2021) Available from: https://www.munichre.com/en/risks/natural-disasters-losses-are-trending-upwards.html [Accessed 23rd December 2021].

Murphy, M.J. & Said, R.K. (2020) Comparisons of lightning rates and properties from the U.S. National Lightning Detection Network (NLDN) and GLD360 with GOES-16 Geostationary Lightning Mapper and advanced baseline imager data. *Journal of Geophysical Research: Atmospheres*, 125, e2019JD031172. Available from: https://doi.org/10.1029/2019JD031172

Nerini, D., Foresti, L., Leuenberger, D., Robert, S. & Germann, U. (2019) A reduced-space ensemble Kalman filter approach for flow-dependent integration of radar extrapolation Nowcasts and NWP precipitation ensembles. *Monthly Weather Review*, 147(3), 987–1006. Available from: https://doi.org/10.1175/MWR-D-18-0258.1

Nisi, L., Ambrosetti, P. & Clementi, L. (2013) Nowcasting severe convection in the alpine region: the COALITION approach. *Quarterly Journal of the Royal Meteorological Society*, 140, 1684–1699. Available from: https://doi.org/10.1002/qj.2249

NOAA. (2021) Available from: https://ufscommunity.org/ [Accessed 23rd December 2021].

Persson, A. (2013) The future role of the weather forecaster. *Weather*, 68(2), 54–54. Available from: https://doi.org/10.1002/wea.2069

Pucik, T., Castellano, C., Groenemeijer, P. & Kühne, T. (2019) Large hail incidence and its economic and societal impacts across Europe. *Monthly Weather Review*, 147, 3901–3916. Available from: https://doi.org/10.1175/MWR-D-19-0204.1

Pucik, T., Groenemeijer, P., Rädler, A., Tijssen, L., Nikulin, G., Prein, A.F. et al. (2017) Future changes in European severe convection environments in a regional climate model ensemble. *Journal of Climate*, 30, 6771–6794. Available from: https://doi.org/10.1175/JCLI-D-16-0777.1

PySTEPS. (2021). Available from: https://pysteps.github.io/ [Accessed 23rd December 2021].

Pytroll. (2021). Available from: https://pytroll.github.io [Accessed 23rd December 2021].

Rautenhaus, M., Kern, M., Schäfler, A. & Westermann, R. (2015) Three-dimensional visualization of ensemble weather forecasts – part 1: the visualization tool Met.3D (version 1.0). *Geoscientific Model Development*, 8, 2329–2353. Available from: https://doi.org/10.5194/gmd-8-2329-2015

Ravuri, S., Lenc, K., Wilson, M., Kangin, D., Lam, R., Mirowski, P. et al. (2021) Skilful precipitation nowcasting using deep generative models of radar. *Nature*, 597, 672–677. Available from: https://doi.org/10.1038/s41586-021-03854-z

Reyniers, M. (2008) Quantitative precipitation forecasts based on radar observations: principles, algorithms and operational systems. Technical publication No. 52, RMI Bruxelles, Belgium.

Rudlosky, S., Goodman, S., Calhoun, K., Schultz, C., Back, A., Kuligowski, B. et al. (2020) Geostationary Lightning Mapper value assessment. *NOAA Technical Report NESDIS*, 153, 46p. Available from: https://doi.org/10.25923/2616-3v73

Ruti, P., Tarasova, O., Keller, J.H., Carmichael, G., Hov, Ø., Jones, S.C. et al. (2020) Advancing research for seamless earth system prediction. *BAMS*, 2020, E23–E35. Available from: https://doi.org/10.1175/BAMS-D-17-0302.1

Ryzhkov, A.V., Schuur, T.J., Burgess, D.W., Heinselman, P.L., Giangrande, S.E. & Zrnic, D.S. (2005) The joint polarization experiment: Polarimetric rainfall measurements and hydrometeor classification. *Bulletin of the American Meteorological Society*, 86(6), 809–824.

Saltikoff, E., Haase, G., Delobbe, L., Gaussiat, N., Martet, M., Idziorek, D. et al. (2019) OPERA the radar project. *Atmosphere*, 2019(10), 320.

Schmid, F., Banon, L., Agersten, S., Atencia, A., de Coning, E., Kann, A. et al. (2019) Conference report third European nowcasting conference. *Metz*, 28(5), 447–450. Available from: https://doi.org/10.1127/metz/2019/0983

Seneviratne, S.I., Zhang, X., Adnan, M., Badi, W., Dereczynski, C., Di Luca, A. et al. (2021) Weather and climate extreme events in a changing climate. In: Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S.L., Péan, C., Berger, S. et al. (Eds.) *In climate change 2021: the physical science basis. Contribution of working group I to the sixth assessment report of the intergovernmental panel on climate change*. United Kingdom and New York, NY, USA: Cambridge University Press, Cambridge, pp. 1513–1766. Available from: https://doi.org/10.1017/9781009157896.013

Siewert, C., Koenig, M. & Mecikalski, J. (2010) (2010) application of Meteosat second generation data towards improving the nowcasting of convective initiation. *Meteorological Applications*, 17, 442–451. Available from: https://doi.org/10.1002/met.176

Sivle, A., Agersten, S., Schmid, F. & Simon, A. (2022) Use and perception of weather forecast information across Europe. *Meteorological Applications*, 29, e2053. Available from: https://doi.org/10.1002/met.2053

Smith, T.M., Lakshmanan, V., Stumpf, G.J., Ortega, K.L., Hondl, K., Cooper, K. et al. (2016) Multi-radar multi-sensor (MRMS) severe weather and aviation products: Initial operating capabilities. *Bulletin of the American Meteorological Society*, 97, 1617–1630. Available from: https://doi.org/10.1175/BAMS-D-14-00173.1

Sønderby, C.K., Espeholt, L., Heek, J., Dehghani, M., Oliver, A., Salimans, T. et al. (2020) Metnet: a neural weather model for precipitation forecasting. arXiv Preprint arXiv:2003.12140. Available from: https://arxiv.org/pdf/2003.12140.pdf

Stano, G.T., Gravelle, C.M., Foster, M., Bruning, E., Rudlosky, S.D., Zajic, J.K. et al. (2018) Early assessment of the Geostationary Lightning Mapper. 99th AMS conference, Phoenix AZ, USA, TN64434_Copy (nasa.gov).

Strauss, F. & Wang, Y. (2013) European nowcasting systems, presentation. Meteorological science days, Budapest, 21–23 November 2013.

Sugier, J. (2019) EMN/STAC19/Doc3, "EUMETNET Observation CA Research & Development Plan", 29th Oct 2019.

Sulik, S. (2022) Convective environment and development of a tornadic supercell in The Czech Republic on 24 June 2021. *Meteorology Hydrology and Water Management*, 10(1), 60–72. Available from: https://doi.org/10.26491/mhwm/150023

Sun, J., Xue, M., Wilson, J.W., Zawadzki, I., Ballard, S.P., Onvlee-Hooimeyer, J. et al. (2014) Use of NWP for nowcasting convective precipitation. *BAMS March*, 2014, 409–426. Available from: https://doi.org/10.1175/BAMS-D-11-00263.1

Urbich, I., Bendix, J. & Müller, R. (2020) Development of a seamless forecast for solar radiation using ANAKLIM++. *Remote Sensing*, 12, 3672.

Wang, Y., Meirold-Mautner, I., Kann, A., Šajn Slak, A., Simon, A., Vivoda, J. et al. (2017) Integrating nowcasting with crisis management and risk prevention in a transnational and interdisciplinary framework. *Meteorologische Zeitschrift*, 26, 459–473.

Wapler, K. (2018) Proceedings of the 2018 EUMETSAT meteorological satellite conference. In: *Temporal and spatial distribution of Total lightning densities in thunderstorms in conjunction with overshooting tops*. Estonia: Tallinn, pp. 17–21.

Wapler, K., De Coning, E. & Buzzi, M. (2019) *Nowcasting, reference module in earth systems and environmental sciences*. Elsevier. Available from: https://doi.org/10.1016/B978-0-12-409548-9.11777-4

Wastl, C., Simon, A., Wang, Y., Kulmer, M., Baár, P., Bölöni, G. et al. (2018) A seamless probabilistic forecasting system for decision making in civil protection. *Meteorologische Zeitschrift*, 27, 417–430. Available from: https://doi.org/10.1127/metz/2018/902

Weathley, D.M., Knopfmeier, K.H., Jones, T.A. & Creager, G.J. (2015) Storm-scale data assimilation and ensemble forecasting with the NSSL experimental warn-on-forecast system. Part I: radar data experiments. *Weather Forecasting*, 30, 1795–1817. Available from: https://doi.org/10.1175/WAF-D-15-0043.1

Whan, K., Sillmann, J., Schaller, N. & Haarsma, R. (2020) Future changes in atmospheric rivers and extreme precipitation in Norway. *Climate Dynamics*, 54, 2071–2084. Available from: https://doi.org/10.1007/s00382-019-05099-z

Witt, A. (1998) An enhanced hail detection algorithm for the WSR-88D. *Weather Forecasting*, 13(2), 286–303.

WMO. (2014) WWOSC 2014 report: seamless prediction of the earth system: from minutes to months, WMO-No. 1156, Chapter 22.

WMO. (2015a) Valuing weather and climate: economic assessment of meteorological and hydrological services. WMO-No. 1153, 2015.

WMO. (2015b) WMO guidelines on multi-hazard impact-based forecast and warning services, WMO, WMO- No. 1150, 23 pp.

WMO. (2017) Guidelines for nowcasting techniques. WMO-No. 1198, WMO Geneva, 2017.

WMO. (2019) Vision for the WMO integrated global observing system in 2040. WMO-No. 1243, WMO Geneva, 2020.

WMO. (2020) Statement of guidance for nowcasting and very short-range forecasting. Available from: https://wmoomm.sharepoint.com/:b:/s/wmocpdb/EWQvFEQPEwFMrK2Jgsc20qAByo8ZV5YHvJ5G2z6-doZ_Vw?e=nPEQ1a [Accessed 23rd December 2021]

WMO. (2021a) Observing systems capability analysis and review (OSCAR) tool: surface database. Observing Systems Capability Analysis and Review Tool (OSCAR) (wmo.int) and Requirements Database. Available from: https://space.oscar.wmo.int/requirements [Accessed 23rd December 2021]

WMO. (2021b) Joint working group on forecast verification and research, world weather research programme, WWRP JWGFVR|World Meteorological Organization (wmo.int) [Accessed 23rd December 2021].

WMO. (2022) Global basic observing network (GBON). Available from: https://community.wmo.int/activity-areas/wigos/gbon [Accessed 29rd August 2022]

Wong, W.K., Cheng, V.T. & Woo, W. (2016) Community SWIRLS nowcasting system (com-SWIRLS). WMO WWRP 4th International Symposium on Nowcasting and Very-short-range Forecast 2016 (WSN16), Hong Kong, China, 25–29 July 2016.

Zhang, S.Q., Zupanski, M., Hou, A.Y., Lin, X. & Cheung, S.H. (2013) Assimilation of precipitation-affected radiances in a cloud-resolving WRF ensemble data assimilation system. *Monthly Weather Review*, 141(2), 754–772. Available from: https://doi.org/10.1175/mwr-d-12-00055.1

How to cite this article: Bojinski, S., Blaauboer, D., Calbet, X., de Coning, E., Debie, F., Montmerle, T., Nietosvaara, V., Norman, K., Bañón Peregrín, L., Schmid, F., Strelec Mahović, N., & Wapler, K. (2023). Towards nowcasting in Europe in 2030. *Meteorological Applications*, *30*(4), e2124. https://doi.org/10.1002/met.2124