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Conference Report: First European Nowcasting and Weather Forecasting Conference

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Abstract: The first European Nowcasting and Weather Forecasting Conference (ENWFC-2024) dedicated to nowcasting, seamless forecasting, statistical postprocessing and ensemble prediction took place in Oslo, Norway (Oslo Science Park) from 4 to 8 November 2024, organized by EUMETNET (European National Meteorological and Hydrological Services Network) within the Weather Forecasting Cooperation Programme (E-WFC). More than 70 participants attended the conference in person; and ca. 100 more were joining via livestream. 67 conference's presentations (45 oral and 22 posters) were given. The sections in this conference report summarize key topics and discussions of the ENWFC-2024 within: Innovations in satellite and radar technology, early warnings, and crowdsourced data; Advancements in statistical and AI-based weather forecasting; Verification and societal impacts; and Applications. A particular focus was provided to the use of Machine Learning techniques and their applications in the context of the listed key topics.

Keywords: nowcasting; (very short range) numerical weather prediction; seamless prediction; postprocessing; ensemble prediction system; observations; Machine Learning; Artificial Intelligence; application

1 Introduction

Held for the first time, the European Nowcasting and Weather Forecasting Conference (ENWFC) was conceived as a collaborative platform to bridge expertise from various EUMETNET (European National Meteorological and Hydrological Services Network) Modules dedicated to nowcasting, seamless forecasting, statistical postprocessing and ensemble prediction. By aligning methodologies, tools, and research goals, this joint effort seeks to strengthen the impact and coherence of ongoing work in the domain. Therefore, ENWFC-2024 was co-organized by three Modules of EUMETNET Weather Forecasting Cooperation (E-WFC), namely EUMETNET Nowcasting (E-NWC), Statistical Postprocessing (PP) and Short-Range Numerical Weather Prediction – Ensemble Prediction System (SRNWP-EPS). The idea was on the one hand to continue the biennial series of past European Nowcasting Conferences (ENC-2014, ENC-2017 cp. Wapler et al. 2017, ENC-2019 cp. Schmid et al. 2019, ENC-2022 cp. Schmid et al. 2022) which promoted recent advances in the theory and practice of nowcasting in Europe and other parts of the world, and on the other

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hand to foster exchange and use synergies between E-NWC, PP and SRNWP-EPS.

Participants from operational as well as research centres and forecast users were welcome to discuss methods for improving the quality of nowcasting, postprocessing and ensemble prediction systems in Europe. In total, more than 70 participants were on-site, and ca. 100 registered for the online streaming, representing mostly National Meteorological and Hydrological Services (NMHS) and universities/research institutes. The detailed program of the conference (also attached as supplementary material), book of abstracts and most of the presentations and posters are available online at the webpage https://enwfc-2024.met.no/, and the latter are referred to in the present conference report (i.e. name(s) only). ENWFC-2024 provided an information platform to exchange know how and discuss future cooperation capabilities within the research and application communities.

1.1 Opening session of ENWFC-2024

A short introduction was given to E-WFC (Schmid et al.) which contains four Modules in total: the three above mentioned ones and additionally the Cooperation on Short-Range Numerical Weather Prediction (C-SRNWP). All four Modules aim to enhance the forecasting capabilities in Europe by fostering collaboration in nowcasting, SRNWP, NWP, and seamless prediction systems, while also optimizing postprocessing and EPS. Key objectives of E-WFC include leveraging new data sources relevant to high-impact weather forecasting, integrating Artificial Intelligence (AI) and Machine Learning (ML) methods, addressing common training needs, and improving communication with users. The initiative facilitates short-term scientific missions for young researchers and hosts regular conferences such as the ENWFC-2024. Demaeyer and Vannitsem summarized the key activities of the PP Module that are about the benchmark of different statistical techniques for correcting weather forecasts, and the development of ready-to-use ensemble calibration techniques that will be available to the community, in particular using ML techniques.

The subsequent keynote talks focused on data-driven forecasting and early warning systems, illustrating how European NMHS are advancing nowcasting, statistical postprocessing, and probabilistic forecasting methodologies and products to enhance NWP and societal resilience in cooperation with users. Thus, the first keynote “It’s The End Of The World As We Know It (And I Feel Fine)”, highlighted MET Norway’s Bris model, an AI-driven forecasting system within ECMWF’s Anemoi framework (Kristiansen et al.). By using a stretched-grid design, Bris ensures high-resolution nowcasting while maintaining global coverage up to 21 days. It enhances forecast consistency for temperature, wind, and precipitation, by reducing errors. Future plans include ensemble forecasting, real-time data integration, and public access via the Yr weather service, showcasing AI’s potential to transform weather prediction.

The second keynote focused on KNMI’s Early Warning Centre (EWC), developed in response to the 2015 UN Climate Conference (Burgers et al.). Commissioned by the Dutch government, the EWC delivers multi-hazard, impact-based forecasts. The initiative involves internal restructuring, redefining forecaster roles, and enhancing collaboration. Stakeholder engagement ensures user-focused warning products, emphasizing the integration of science, communication, and user needs for effective early warning systems.

A more detailed view on these topics is based on the ENWFC-2024 contributions and presented in the following sections:

- section 2 reviews innovations in observations,
- section 3 summarizes advancements in statistical and AI-based weather forecasting,
- section 4 gives some new insights into verification and societal impact studies,
- section 5 shows some application examples,
- and section 6 provides some main conclusions from contributions and discussions.

2 Innovations in satellite and radar technology, early warnings, and crowdsourced data

Advancements in satellite and radar technology, severe storm monitoring, and crowdsourced data integration offer promising improvements for nowcasting and early warning systems. Combining next-generation satellite missions including enhanced lightning detection and citizen science initiatives paves the way for more accurate forecasting and disaster preparedness.

2.1 Advancements in satellite technology and nowcasting systems

Nowcasting and early warning systems are significantly enhanced by e.g. the Meteosat Third Generation (MTG) satellite system. These include MTG-LI (Lightning Imager), launched in 2022, which improves storm tracking, while MTG-S1 (Sounding 1; 2025), will introduce the first operational Infrared Sounder in geostationary orbit (Bojinski et al.). These innovations are complemented by AI-driven nowcasting models and training programs from EUMETSAT, supporting improved forecasts, especially in high-latitude regions. Enhanced lightning detection and new RGB (red, green and blue colours) imagery further contribute to severe weather monitoring (Nietosvaara et al.).

Rípodas et al. presented the adaptation of the Nowcasting Satellite Application Facilities (NWC SAF, nwc-saf.eumetsat.int) software to MTG-I data, enabling the generation of satellite-derived products for nowcasting. They highlighted improvements over the previous Meteosat Second Generation (MSG)-based products and outlined future enhancements leveraging MTG-LI capabilities, such as space-based lightning detection and the 0.9 µm channel for total water column estimation. García-Pereda et al. discussed NWC SAF products for polar satellites, including upcoming microwave-based products for the new EPS-SG-A and -B missions. They focused on the new Atmospheric Motion Vector product for polar satellites, using the same algorithm as the geostationary version and applicable across five polar satellite series. Key applications include NWP assimilation and climate studies.

2.2 Early warning systems and regional disparities

A recent survey on nowcasting and early warning systems (Salio et al.) as part of the World Meteorological Organization (WMO) Early Warning for All initiative underscores the disparities in forecasting capabilities across different regions. While some regions benefit from advanced technologies, others struggle with limited resources, highlighting the need for capacity-building and multi-sector collaboration to strengthen forecasting infrastructure globally. This effort is critical in enhancing the effectiveness of early warning systems and ensuring their reach and utility in diverse geographic areas.

Randriamampianina et al. introduced the weather-induced extremes Digital Twins developed within the EU's Destination Earth initiative, designed to enhance adaptation strategies to extreme weather events. By integrating high-resolution Earth system and impact models – covering domains like floods, air quality, and renewable energy – into a unified forecasting workflow, the system enables improved uncertainty quantification and targeted on-demand simulations. Initial results demonstrate the added value of these digital twins through case studies across Europe.

2.3 Integration of crowdsourced data in nowcasting and forecasting

Crowdsourced data is increasingly enhancing weather forecasting by complementing traditional observation methods. Neuville et al. showed that integrating consumer weather station data into MET Nordic's real-time analysis improves near-surface temperature and precipitation forecasts. Alternative data sources, such as mobile phone technology, aircraft meteorological data, and Internet of Things (IoT) sensors, are also boosting forecasting in regions with limited traditional networks (Kirk et al. 2020). Innovations like MET Norway's "neighbourhood lightning number" (Gulbrandsen et al.) and global hail collection projects (Li et al.) contribute to more accurate severe weather predictions. Additionally, Lussana et al. introduced a high-resolution near-surface weather dataset in Scandinavia, Finland, and the Baltic region, enhancing temperature and precipitation forecasts when integrated with MetCoOp Ensemble Prediction System (MEPS) outputs.

2.4 Discussion

With advancements in satellite technology (e.g. higher resolution, new systems), questions arose like how much accuracy and efficiency of weather predictions can be improved. New satellites offer higher resolution data (e.g. MTG FCI Flexible Combined Imager), allowing for detailed observations of weather patterns, cloud formations, and storm development, which leads to more precise forecasting. Additionally, faster data transmission systems enable near-real-time updates, improving the timeliness of weather warnings and forecasts. Modern satellites are also equipped with advanced atmospheric monitoring capabilities, such as hyperspectral sensors that measure temperature, humidity, and gas concentrations across multiple atmospheric layers, enriching weather models with more accurate inputs.

Another key element of modern meteorology is the integration of crowdsourced data, which brings both benefits and challenges. Alternative data sources, such as third-party data, mobile phone technology, aircraft meteorological data, and IoT sensors, are becoming increasingly important in weather forecasting, especially in regions with limited data availability (cp. Kirk et al. 2020) by providing real-time, high-density observations, and supplementing traditional meteorological measurements. However, challenges include data quality control (e.g. through Titanlib, which is freely available to support data verification, https://github.com/metno/titanlib, Båserud et al. 2020), standardization across diverse sources, and integration into existing forecasting models without introducing biases. Effective assimilation methods and error correction techniques are essential to maximize the reliability of such data.

Also, the European Severe Weather Database (ESWD, cp. Dotzek et al. 2009) plays an important role in extreme weather validation. Additionally, the World Weather Research Programme (WWRP) offers valuable insights from its research on nowcasting and mesoscale phenomena (Joe et al. 2024).

As weather forecasting enters a new era driven by rapid technological advancement, the role of the modern meteorologist might expand beyond traditional boundaries. Continuous training has become essential – not just in meteorology, but also in data science, ML / AI. To fully harness the potential of vast, complex datasets and enhance NWP models, forecasters might cultivate more these interdisciplinary skills. Equally important is the ability to handle and validate crowdsourced data, blending it thoughtfully with conventional observations while maintaining rigorous quality standards. Strong coding skills (e.g., Python, R) and familiarity with big data processing techniques are increasingly valuable in this evolving field.

Moreover, the determination of warning thresholds remains a critical factor in effective forecasting. Warning thresholds should be set based on historical data, local vulnerability assessments, and impact-based forecasting to ensure relevance and effectiveness. Key variables include climatological patterns, terrain, population density, infrastructure resilience, and socio-economic factors, which vary by region. In developing countries with limited resources, thresholds should be adaptable, leveraging low-cost monitoring tools, community input, and probabilistic forecasting to enhance disaster preparedness and response. Finally, the WMO Early Warning for All initiative aims to provide effective early warning systems to every country by 2027 considering the science-to-services value chain in early warning systems (cp. WMO 2024). To ensure that weather forecasts are translated into actionable warnings that effectively support communities worldwide, WMO Societal and Economic Research Applications (SERA) working group addresses these topics in the annual Weather & Society Conference (e.g. https://www.weatherandsociety.de/).

3 Advancements in statistical and AI-based weather forecasting

Significant progress has been made in ensemble postprocessing, probabilistic forecasting, AI-based extreme weather prediction, digital twins for climate adaptation, and high-resolution modeling in complex terrains and urban areas.

3.1 Ensemble postprocessing

Recent advances in ensemble statistical postprocessing have improved forecast accuracy. Möller et al. introduced Standardized Autoregressive Smooth Ensemble Model Output Statistics (SAR-SEMOS) and de-seasonalized EMOS (DAR-SEMOS), autoregressive EMOS extensions incorporating trend, seasonality and autoregressive behaviour simultaneously, thus allowing for longer static training periods instead of rolling ones. Furthermore, first attempts were presented of combining a time series based EMOS model such as SAR-SEMOS with a gradient boosting algorithm to account for additional predictors in the postprocessing. Jobst combined a generalized version of mixture regression models (MIXMOS and MIXSAMOS) with a gradient boosting approach, yielding the MIXSAMOS-GB method that allows for a multimodal predictive distribution accounting at the same time for a potentially large set of predictors by performing variable selection. Applied to observation and forecast data in Germany, MIXSAMOS-GB surpasses the benchmark models SAMOS and MIXSAMOS as well as the gradient-boosted extension SAMOS-GB. Biegert et al. demonstrated that postprocessed AI-based forecasts in the WeatherBench 2 framework (Rasp et al. 2024) outperform ECMWF ensemble predictions, particularly for short lead times, demonstrating once more that also in times of AI-based forecasts the research on postprocessing will still be required.

Dabernig and Atencia introduced an operational probabilistic seamless forecasting system for high-impact weather warnings, leveraging Standardized Anomaly Model Output Statistics (SAMOS) for calibrated forecasts from multiple NWP models. However, to ensure spatial and temporal consistency, they applied Ensemble Copula Coupling (ECC), reconstructing coherent forecast members to aid hydrological services and decision-making. Similarly, Evans et al. explored modifications to ECC and Schaake Shuffle techniques in the IMPROVER project (https://github.com/metoppv/improver), addressing multi-model dependency structures for physically consistent ensemble realizations. Parsakhoo et al. employed a high-resolution (1 km) ensemble forecasting setup nested within ICON-D2 to investigate the predictability of a severe convective event over southern Germany. Using a two-moment microphysics scheme, different configurations of convection parameterizations, and a tailored stochastically perturbed parameterization (SPP), the research systematically evaluates the impact of physical scheme variations and parameter uncertainties on forecast performance. Mlakar et al. presented a ML approach that enables probabilistic weather forecast postprocessing at arbitrary temporal resolutions, independent of the temporal granularity of the input ensemble forecasts. The method uses a learned interpolation in a high-dimensional embedding space, combined with normalizing spline flows, to flexibly model forecast uncertainty and generate well-calibrated probabilistic outputs. And Mazur explored enhancements to time-lagged ensembles (TLE) by introducing a weighting scheme that prioritizes newer model runs to mitigate the declining value of older forecasts. Using a logarithmic weighting function, the method improves forecast reliability while maintaining low computational cost.

All above mentioned approaches are part of an ongoing and growing interest to account for multivariate dependencies (e.g. in space, time, between ensemble forecasts, lead times, variables) in probabilistic forecasting approaches and NWP ensemble postprocessing models in particular. The aim is to obtain not only locally accurate/calibrated, but also physically realistic forecasts, that can help to improve weather warnings as well as political decision making in times of climate change and extreme weather events, see also the next subsection. However, it is important to mention that even if statistical postprocessing yields well-calibrated probabilistic forecasts, it requires adjustments in forecast visualizations and has limitations in severe weather forecasting, where discrepancies with official warnings can arise. Additionally, the operational complexity of maintaining data-driven methods, including model retraining and monitoring, poses ongoing challenges in ensuring reliable and effective forecasting (Bhend et al.).

3.2 AI and ML for extreme weather prediction

Deep learning continues to enhance extreme weather forecasting. Aguirre et al. emphasized that training methodologies, such as non-linear transformations and probability-weighted loss functions, have a greater impact on accuracy than specific neural architectures like convolutional Long Short Term Memory (LSTM), convolutional Gated Recurrent Unit (GRU), or Attention Residual (AR)-U-Net. Vahid Yousefnia et al. developed a deep learning-based postprocessing model trained on ICON-D2-EPS, improving thunderstorm forecasts by analyzing full atmospheric profiles instead of relying on derived variables like Convective Available Potential Energy (CAPE). On the basis of explainable AI (XAI), they further demonstrated consistency with well-established physical concepts of thunderstorm dynamics which provides a strong argument for generalizability, trustworthiness and application in critical decision making. Di Giacomo et al. employed XGBoost to enhance thunderstorm and fog detection using high-resolution NWP outputs and satellite observations. Odak et al. explored the integration of analog-based and ML methods to enhance postprocessing of wind speed and other meteorological variables, improving forecast accuracy. They also introduced the Neighborhood Ensemble Altitude (NEA) correction method, which significantly improves temperature forecasts in complex terrain without relying on observational data. Bölöni et al. explored replacing fuzzy logic with a ML approach for the assignment of warning categories to nowcasted storm cells, which could streamline adjustments and improve flexibility, particularly with the integration of new satellite observations.

Nowcasting innovations were highlighted in several contributions. Kruse et al. introduced an AI-powered framework for precipitation and solar radiation forecasting, promoting open-source collaboration and GPU-efficient architectures. Moret et al. detailed MeteoSwiss's initiative to integrate high-resolution NWP models (ICON at 1–2 km), Integrated Forecasting System (IFS), and nowcasting systems Integrated Nowcasting through Comprehensive Analysis (INCA) into a seamless forecasting framework. Their goal is to develop a unified gridded dataset to enhance warning systems, impact models, and hydrological predictions through ML integration. Miralles et al. explored the use of graph neural networks (GNNs) within ECMWF's Anemoi framework to improve high-resolution nowcasting in Switzerland's complex terrain. Inspired by GraphCast and Neural-LAM, the model represents atmospheric data as a graph to capture spatial interactions and enhance predictions of wind, temperature, and humidity. In collaboration with MeteoSwiss, ECMWF, and Swiss Data Science Center (SDSC), the research aims to set a new benchmark for operational nowcasting by comparing the GNN-based approach with existing methods.

Lerch et al. introduced a GNN architecture for ensemble postprocessing of NWP models, addressing limitations in traditional station-based methods by enabling better information sharing across locations. A case study on 2m temperature forecasts in Europe demonstrates that this approach significantly outperforms existing NN-based postprocessing methods, showing promising improvements in forecast accuracy. Šavli et al. developed a thunderstorm detection system for Slovenia using radar measurements and lightning discharges to optimize radar-based tracking and forecasting. Norman et al. described the UK Met Office's integrated nowcasting system, which combines optical flow-based nowcasts, NWP forecasts, and radar-based cell tracking to improve flood prediction. Poli et al. presented innovative nowcasting techniques by applying the GPTCast deep-learning model alongside pySTEPS (an open-source Python library for probabilistic precipitation nowcasting) to enhance short-term precipitation forecasts in Emilia-Romagna, Italy.

AI-driven statistical postprocessing and extreme weather forecasting were also addressed. Chen et al. introduced a deep learning prototype at KNMI to improve severe wind gust forecasts, incorporating XAI techniques to enhance forecaster trust. François et al. applied Extreme Value Theory (EVT) to ECMWF wind gust forecasts, improving predictions for extreme events. Elo et al. explored the deep neural network, which integrates radar, NWP models, and tipping bucket gauges to improve precipitation estimates, particularly in high-altitude regions. Aguirre et al. used U-Net neural networks to enhance radar-based rain rate predictions, outperforming traditional methods in extreme events. Similarly, Rakotomanga et al. developed a Convolutional Neural Network (CNN) based deep learning model trained on satellite data for convective storm nowcasting in data-scarce regions like the Western Sahel. Metzl et al. presented a study showing how physics prior knowledge and ML can be combined to improve thunderstorm nowcasting using satellite and lightning data. Despite the growing popularity of AI-based modelling approaches, Bölle et al. introduced a simple three-variable model of the deep-convection lifecycle and showed agreement with radar and satellite observations over Germany. This suggests that physics-based modelling still constitutes a valuable, insightful and relevant alternative to purely data-driven approaches.

3.3 High-resolution and global forecasting systems

High-resolution models improve forecasts in complex terrains and urban environments. Buzzi et al. developed a Gaussian Process-based wind model incorporating neural networks to enhance wind gust predictions in the Swiss Alps. Primo Ramos et al. created an ML-based downscaling method refining 2m temperature forecasts at 30m resolution, restoring subgrid-scale temperature variability and addressing mountainous region challenges.

Urban modeling efforts have also progressed. Bucchignani et al. assessed the ICON-LEM model with urban parameterization (TERRA-URB) at hectometric resolution over Naples, Italy. While increased resolution primarily improved wind direction forecasts, the Smagorinsky-Lilly turbulence scheme enhanced overall performance. Schmeits et al. refined ECMWF's AI Forecasting System (AIFS) using datasets like the Dutch Offshore Wind Atlas (DOWA), demonstrating that transfer learning enhances AI-driven high-resolution forecasts, particularly in data-sparse regions.

At the regional and global levels, Maldonado et al. reviewed the evolution of Argentina's NWP system since 2017, focusing on its transition to a regional data assimilation framework. By 2024, Argentina's 5-minute cycling data assimilation system will integrate radar and automated weather station data, improving high-impact weather prediction within the Argentina-Japan PREVENIR project. Duminuco et al. evaluated the WRF model's performance in forecasting extreme precipitation using object-oriented analysis techniques, contributing to improved early warning systems. Samos et al. enhanced storm forecasts in Greece by integrating radar reflectivity and cloud top height into a 3D variational (3D–VAR) data assimilation framework.

3.4 Discussion

The discussion highlighted advancements in AI and ML, benchmarking, computational efficiency, pilot study lessons, and future perspectives. AI models like convolutional LSTMs, graph neural networks, and transformers are improving nowcasting and weather forecasting by integrating physical prior knowledge, NWP and observational data. However, challenges remain in ensuring model interpretability, reliability, and uncertainty quantification, particularly in probabilistic forecasting and maintaining physical constraints (Bouallegue).

With the popularity of AI-based models growing, proper and objective benchmarking becomes increasingly essential. This will clearly establish any methodological advantages of AI compared to traditional approaches while unambiguously identifying the most promising avenues for future improvement. Benchmarking AI models against traditional NWP systems is essential, with initiatives like WeatherBench 2 (Rasp et al. 2024) and EUPPBench v1.0 (Demaeyer et al. 2023) facilitating comparisons using standardized datasets like ERA5, ICON, and ECMWF ensemble forecasts. Key metrics, such as CRPS, RMSE, and Brier scores, remain vital, and validation not only with reanalysis but also with observed satellite data is necessary. Balancing short-term accuracy with long-term consistency is crucial for operational forecasts. Pilot studies, including DeepMind's collaboration with the UK Met Office, show promise but highlight challenges like model reliability and integration into operational systems. Future developments focus on scaling up AI models into operational systems like AIFS, launched in February 2025, while continuing to balance resource efficiency with accuracy. Much less effort went into decisive benchmarking of observations-based nowcasting, while it has been revolutionized over the last couple of years by AI-based approaches. The actual benefit of AI-based over traditional modelling needs to be objectively established. Hybrid approaches will likely continue alongside data-driven models, with unbiased benchmarks and fair comparisons being critical for progress.

4 Verification and societal impacts

Severe weather warnings are a critical tool for mitigating risks and protecting lives, but their effectiveness depends on both their accuracy and perception by different user groups. Verification plays a key role in assessing the quality of these warnings, identifying their strengths and weaknesses, and guiding improvements. Studies mentioned in this section explored various approaches to evaluating severe weather warnings, focusing on both their physical accuracy and their societal impact.

4.1 Challenges and solutions in effective weather warning systems

From a methodological perspective, verification relies on statistical methods to compare forecasts with observed weather events. However, impact-based warnings introduce additional complexities (Wapler et al.). Beyond comparing meteorological values, it is essential to consider how warnings influence decision-making and risk reduction. The value of a warning depends on factors such as its accessibility, timeliness, clarity, and perceived trustworthiness. Users – including emergency services, civil protection authorities, and the general public – have diverse needs and expectations, making user-oriented evaluation essential for improving warning systems.

A case study from the WISER-EWSA project in Southern Africa highlighted the pivotal role of nowcasting in improving disaster preparedness (Murambadoro et al.). In Mozambique, Zambia, and South Africa, challenges such as inconsistent access to warnings, lack of standardized alerting protocols, and barriers in understanding warning messages – especially among marginalized groups – limit the effectiveness of nowcasts. Efforts to address these challenges include real-time testbed evaluations and collaboration with community weather observers.

The experience of Croatia's DHMZ with severe weather warnings provided another perspective (Klemenčić Novinc). The July 2023 derecho storm in northern Croatia tested the country's warning system, revealing gaps in public response despite timely alerts. Although warnings were issued via multiple platforms, many citizens did not take the threat seriously, highlighting the importance of improving public awareness and trust. The implementation of the SRUUK crisis management system, which includes Cell Broadcast/SMS alerts, marks a significant step toward enhancing public engagement with severe weather warnings.

Integrating user feedback, impact assessments, and case studies may enhance verification approaches. A better understanding of how warnings are perceived and acted upon can help NMHS refine their communication strategies, ultimately leading to more effective risk mitigation and disaster response.

4.2 Discussion

A key discussion was how verification methods can evolve to incorporate both accuracy and the societal factors influencing how warnings are received. Integrating user feedback from emergency services, civil protection, and the public is essential in improving warning systems and ensuring they meet diverse user needs and expectations.

Impact-based warnings introduce challenges in verification, as they go beyond meteorological data to consider human behavior and decision-making. Evaluating the effectiveness of these warnings requires new metrics that account for their societal impact – how they influence public actions and decisions. Addressing barriers to access and understanding, particularly for marginalized groups, is critical, with strategies like real-time testbeds and partnerships with community weather observers showing promise.

Case studies such as the WISER-EWSA project in Southern Africa and Croatia's experienced with the 2023 derecho storm highlight challenges in public response despite timely warnings, emphasizing the need to improve clarity, standardization, and timeliness across multiple platforms. Public engagement and education strategies are key to fostering trust in warnings, ensuring that communities are more likely to take them seriously when critical events occur.

Finally, enhancing disaster preparedness through more effective warnings and incorporating them into risk reduction strategies is essential. Collaboration between meteorological agencies, community leaders, and local authorities can build resilience and improve overall responses to extreme weather events.

5 Applications

Advancements in weather prediction and early warning systems rely on innovative methodologies and technological developments that also allow a deeper understanding of the underlying data-driving relationships, as presented in the earlier sections.

5.1 Improvements in forecast accuracy, lead time, and interpretability

One promising approach in the applications' part was the bivariate vine copula regression for statistical postprocessing wind vector forecasts, presented by Buchner et al. Vine copula based (regression) models offer a flexible framework to capture complex dependencies and perform data-driven variable selection at the same time, outperforming traditional techniques such as bivariate EMOS. Vine copula based models already have proven beneficial for temperature and wind speed postprocessing, where selection of suitable predictors for the model facilitated an enhanced understanding. By applying this novel bivariate method to wind vector data across multiple German stations, researchers demonstrate the advantages of modeling non-Gaussian dependencies in meteorological forecasting.

In Africa, efforts to enhance satellite-based nowcasting and early warning systems are gaining momentum. Msemo et al. discussed the ADVANCE initiative of the WMO's World Weather Research Programme, which aims to improve nowcasting using geostationary satellite data. The WISER-EWSA project is one of the projects in this effort, co-developing nowcast products with urban communities in Southern Africa to make thunderstorm warnings more accessible and actionable. A real-time forecasting testbed in Zambia allowed experts and end-users to evaluate and refine satellite-based nowcasts, shaping future warning dissemination strategies.

Another frontier in nowcasting is the use of diffusion models for image-based predictions. Hermes et al. adapted these generative AI models to predict dust storm movements using SEVIRI desert dust RGB composites in West Africa. Unlike conventional NWP models, diffusion-based nowcasting captures convective storms and dust outbreaks with higher accuracy and shorter lead times. This innovative approach could be extended to other satellite-derived weather products, broadening its impact on operational forecasting.

For public communication, the IMPROVER system enhances the way weather forecasts are presented (Moseley et al.). This probability-based postprocessing framework blends multiple forecast sources to generate seamless predictions up to 14 days ahead. A key application is the generation of intuitive weather summary symbols, refined through public research to improve clarity and usability. Atencia et al. presented a new forecasting system delivering seamless, calibrated probabilistic predictions of high-impact weather events, tailored for hydrological services, forecasters, and civil protection agencies. By combining radar-based nowcasting (via pySTEPS), data-driven uncertainty analysis, and NWP model integration through SAMOS, it offers reliable hourly forecasts with smooth transitions between nowcasting and longer-range predictions. The system supports targeted early warnings and has been validated to ensure added value in operational decision-making.

5.2 Practical deployment, public communication, and sector-specific impacts

In Belgium, radar-based convective gust warnings are strengthening real-time severe weather alerts. Reyniers et al. described the development of the Severe Weather Index within the INCA-BE nowcasting system at the Royal Meteorological Institute (RMI) of Belgium. Using reflectivity and radial velocity data from weather radar, this system triggers automated gust warnings, which are distributed via RMI's mobile app and national emergency channels. With up to 20 minutes of lead time, these alerts improve public preparedness for severe weather events.

Renewable energy forecasting was another key focus. Gfäller et al. designed a two-branch neural network, which works with limited external dependencies for solar irradiance nowcasting, supporting real-time grid management. Papazek et al. improved photovoltaic power forecasting using AI-driven approaches that integrate multiple meteorological datasets. Wieczorek et al. launched a public forecasting service in Poland, providing hourly wind and solar power predictions to support the country's transition to renewable energy.

Finally, several studies explored weather forecasting applications in transport and communication. Moseley et al. developed the Surface Transport Forecast (STF) project at the UK Met Office, integrating financial, logistical, and infrastructure data into weather forecasts to improve transport planning. Kann et al. optimized short-range weather forecasting for sustainable mobility through AI-driven approaches, refining route-specific predictions. Brambus examined best practices for communicating nowcasting information to the public, highlighting the challenges of balancing automated warnings with human oversight.

5.3 Discussion

By integrating statistical modeling, satellite nowcasting, AI-driven predictions, and enhanced public communication strategies, these applications demonstrate the ongoing evolution and improvement of weather prediction systems. They highlight the potential for interdisciplinary collaboration to bridge the gap between deficiencies in forecast accuracy and real-world decision-making, ultimately leading to more effective severe weather warnings.

6 Summary and conclusions

Nowcasting and weather forecasting R&D are rapidly advancing through multiple, interlinked innovations – as highlighted during ENWFC-2024. Key developments include:

- The deployment of advanced satellite systems like MTG, improving lightning detection, infrared sounding, and severe weather monitoring.
- AI-driven forecasting models and statistical postprocessing methods, such as SAR-SEMOS and MIXSAMOS-GB, enhancing forecast accuracy and enabling flexible probabilistic outputs.
- Integration of crowdsourced and alternative data sources, boosting forecasts in data-sparse regions.
- Deep learning, graph neural networks and the use of digital twins increasingly improving extreme weather prediction, nowcasting, and ensemble postprocessing, often combined with explainable AI for greater trustworthiness.
- High-resolution models refining forecasts in complex terrains and urban environments, supported by transfer learning and regional data assimilation frameworks.
- Emerging methods like bivariate vine copula regression and diffusion models, offering new ways to capture dependencies and improve image-based nowcasting.
- The crucial role of user-centered verification, emphasizing how warning accessibility, clarity, and public trust shape effective risk mitigation.
- Practical applications spanning renewable energy forecasting, transport planning, and real-time severe weather alerts, underscoring the societal relevance of these advances.

Looking ahead, future efforts should ensure that the integration of new technologies into operational systems i) improves forecasts in all weather conditions, especially high impact weather events, and ii) is seamless and user-friendly, allowing for efficient use of data and resources. A particular emphasis should also be on physical consistency and interpretability of data-driven models. Ongoing collaboration between NMHS, research institutions, community leaders, and local authorities will be essential in improving disaster preparedness and response. Ultimately, these advancements will lead to more effective weather warning systems, ensuring better protection for communities worldwide, and more resilient responses to extreme weather events. Therefore, the next ENWFC is planned for spring 2026 as a further meeting and discussion platform for the interested community.

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