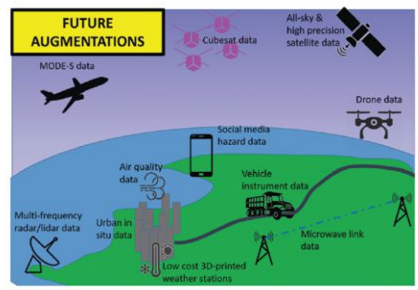
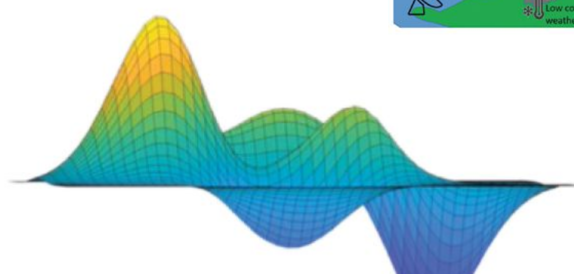
BAMS

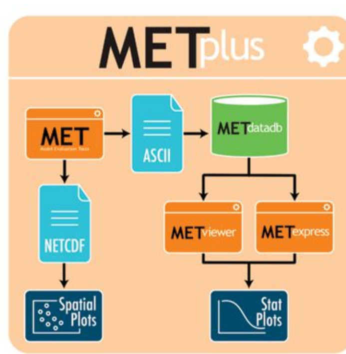
Bulletin of the American Meteorological Society

Volume 103, Number 10, October 2022

FEATURES







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The Bulletin of the American Meteorological Society (ISSN 0003-0007) is published monthly by the American Meteorological Society, 45 Beacon St., Boston, MA 02108- 3693. Periodical postage paid at Boston, MA, and at additional mailing offices. Subscription price to members is included in annual dues. Subscription price to nonmembers is available on request; single issues are $12.50 each for members, $20 for nonmembers (prices incl. shipping and handling). Address all business communications to the Executive Director, AMS, 45 Beacon St., Boston, MA 02108-3693 (617-227-2425).

POSTMASTER: Send address changes to Bulletin of the American Meteorological Society, 45 Beacon St., Boston, MA 02108-3693.


Sharan Majumdar in the Everglades, Florida.

> "Unlike perhaps most *BAMS* readers, I had no interest in meteorology until my mid-twenties, as I grew up in the UK under mostly benign weather. But I knew that I wanted to apply mathematics to something of direct importance to society. Through a couple of summer internships at CSIRO in Australia, which included a chance meeting with a professor from Penn State (Craig Bohren) at a train station, I switched into meteorology as a new postdoc at Penn State in 1997, working with Craig Bishop on targeted observations to improve forecasts of high-impact weather."

—Sharanya J. Majumdar, University of Miami

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Multiscale Hazard Forecasts

The Status and Challenges of Predicting High-Impact Weather

Key messages from "Multiscale Forecasting of High-Impact Weather: Current Status and Future Challenges," by **Sharanya J. Majumdar** (University of Miami), **Juanzhen Sun**, **Brian Golding**, **Paul Joe**, **Jimy Dudhia**, **Olivier Caumont**, **Krushna Chandra Gouda**, **Peter Steinle**, **Béatrice Vincendon**, **Jianjie Wang**, and **Nusrat Yussouf**. Published online in *BAMS*, March 2021. For the full, citable article, see https://doi.org/10.1175/BAMS-D-20-0111.1.

In 2015, the World Meteorological Organization (WMO) launched the 10-year HIWeather project, "to promote co-operative international research to achieve a dramatic increase in resilience to high impact weather, worldwide, through improving forecasts for timescales of minutes to two weeks and enhancing their communication and utility in social, economic and environmental applications." This is the significant holistic challenge from scientific, systemic, and societal perspectives, and is at the heart of early warning and disaster reduction initiatives.

As HIWeather Multiscale Hazard Forecasting project members and collaborators, we illustrated four high-impact events around the world, involving urban flooding, localized extreme wind, and wildfires. Challenges encountered included predicting intense precipitation, communicating hazards, monitoring and predicting impacts such as the bursting of banks of rivers by floodwaters, operationalization of hazard forecasting systems, and timely public warnings. Four requirements emerged (also see Table 1): (1) early information to enable preparation; (2) early information to enable actions (e.g., evacuation); (3) precise information to enable targeted response; and (4) information on the nature of the threat. We

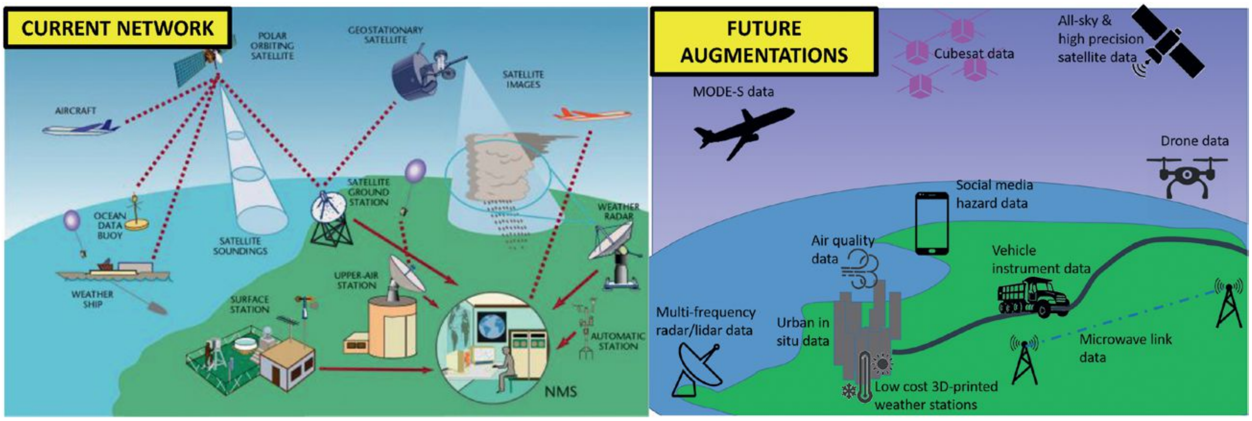
Common forecasting challenges for high-impact weather events.

Challenge 1: Early information to enable preparation. Information is needed by emergency managers and by those who will be affected. Early information is necessarily uncertain. The better the information is about the nature of that uncertainty, the more appropriate the preparation as the event approaches. Improving numerical modeling and multiscale ensemble prediction are the keys to meet this challenge.

Challenge 2: Early information to enable early action. To avert a major disaster, costly and time-consuming actions, including evacuation, may be needed. Information available at the time is critical to determine the scale of evacuation, safe evacuation routes and destinations, and to persuade reluctant people to move. This challenge requires improved numerical modeling, multiscale ensemble prediction, data assimilation, and coupled modeling.

Challenge 3: Precise information to enable targeted response. Emergency managers respond dynamically to the specific impacts of the hazard as it develops. In urban areas this detailed information is ultimately required at block level. Monitoring and very short-range forecasting of the hazard provide the situational awareness required for a fast and effective response. The key areas of improvement required to meet this challenge are hazard observations and nowcasting.

Challenge 4: Information on the nature of the threat. Decision-makers need to know what the hazard will be and what impact it will have. Aspects of the weather that create hazards are not those typically focused on by forecast verification. Coupling weather and hazard models can help the detection and correction of weaknesses in weather forecasts, such as biases in the extremes. Improvements in coupled data assimilation, modeling, and ensemble prediction are necessary for this challenge.



(left) The current global observing network provides in situ and remotely sensed data for hazard monitoring, nowcasting, and data assimilation. Observing methods are standardized to ensure that results are compatible for use in specifying the climate and the initial state for global weather prediction. (right) Potential future sources of weather and hazard observations that may need to be accommodated in hazard monitoring and forecasting systems. (Source: World Meteorological Organization)

summarize here several facets of multiscale forecasting with an emphasis on warning for rapidly developing events, which requires the provision of timely, high-resolution information to forecasters and emergency managers.

Accurate observations on all scales are required for forecasting, warning, verification, and physical understanding. Observations for environmental and **hazard monitoring** are made by human observers (including social media and other verification data), in situ instrumentation, and remote sensing platforms. Examples include radars and mesonets, and satellites scanning weather systems on convective scales every 1–10 minutes. Deficiencies that are exacerbated in convective weather include limited spatial and temporal sampling, restricted vertical resolution, limited sampling below cloud tops, and the attenuation of radiation in precipitating systems. Novel observation types include lidar technologies, crowdsourcing, and CubeSats.

Observation-driven nowcasting is directed toward rapidly developing storms and their hazardous elements. One example is radar imagery, which can be extrapolated to 0–2-h predictions. Observations on short time scales are perishable, requiring many observations temporally. Moving beyond the current empirical approach will require advances in observation systems and networks, data quality processing, interfaces, data assimilation, and new approaches such as machine learning, in order to integrate observations into the numerical weather prediction (NWP) and forecasting process at fine scales.

Multiscale data assimilation of observations is necessary, given that high-impact forecasts depend on analyses on all scales. Several NWP centers utilize both global and convection-permitting regional data assimilation with 1–3-hourly update cycles. Techniques include variational, ensemble, and hybrid schemes, which are usually reliable only when the dynamics are quasilinear. To account for nonlinearity, which may dominate at convective scales, new schemes such as particle filters are in development. Latest development of data assimilation applications include polarimetric and phased-array radar observations, cloudy satellite radiances, and various aircraft data. We identified four foci as priorities: integrated assimilation of multiple types of observations, quantifying uncertainties, approaches for multiscale data assimilation, and advanced techniques for convective-scale data assimilation.

Ensemble predictions are necessary since high-impact weather forecasting requires a quantitative uncertainty assessment, tying risks to specific locations and times. They produce a range of scenarios that can be used to predict the likelihood of a hazardous weather situation. Requirements for tackling uncertainty in short-range forecasts are different from those that formed the basis of medium-range ensembles. Convection-permitting ensembles, with 2–3-km grids, more frequent update cycles, calibration of probabilities to remove biases, and retention of large-scale information, are being developed. Challenges include surface and physical processes, uncertainty quantification on kilometer scales, and the initiation and maintenance of convective processes.

Coupled hazard modeling is achieved using flood, storm surge, and fire models, among others, that couple atmospheric composition and their processes, the ocean, the waves, and hydrology with the atmosphere. Hazard models are generally run separately using inputs from NWP. There is now a movement toward integration, although modeling the coupled environment is challenging across their disparate spatial and temporal scales. Advances include the representation of soil moisture gradients, atmosphere–ocean–wave modeling, and aerosol modeling, and are currently mostly employed in medium-range forecasting. Suggested foci include observations of atmospheric composition and hydrology information, coupled data assimilation to maintain consistent initial states, and advanced coupled modeling techniques.

We conclude by suggesting the following priorities:

1) advanced urban observation monitoring, ubiquitous sensing, and social media analysis for better situational awareness, and reporting of severe weather and related hazards;
2) novel application of techniques including machine learning to identify the conditions that precede severe weather development;
3) achievement of physically consistent multiscale initial states and ensemble forecast distributions for kilometer-scale models;
4) closer coupling of hazard prediction models with NWP models;
5) more effective communication and use of probabilistic forecast information in the formulation of warnings and decision support products; and
6) greater research and development focus on the specific requirements of emergency responders and societal behavior to hazard warnings.

METADATA

BAMS: What would you like readers to learn from this article?

Sharanya J. Majumdar (University of Miami): *I would like readers to learn about the many facets of hazard forecasting for high-impact weather events, the impressive progress that has been made in each of these facets, and the challenges that lie ahead. I hope that the recommendations compiled by my coauthors can be used to coordinate priorities within and across disciplines and agencies. I also hope that every reader involved in the forecasting and warning process recognizes the importance of their own work in the broad context of multiscale hazard forecasting, and is excited to provide future meaningful contributions.*

BAMS: How did you become interested in the topic of this article?

SM: *For 25 years, I have been interested in forecasting high-impact weather for the benefit of society. The WMO HIWeather project provided an excellent opportunity to interact with like-minded colleagues around the world, and our team agreed to collaborate on a synthesis of the field. What especially excited me was the global perspective, the opportunity to learn from colleagues about topics outside my expertise, and the privilege of contributing to the field in a broader sense.*

BAMS: What surprised you the most about the work you document in this article?

SM: *What surprised and impressed me most is the sheer breadth and depth of recent progress in observations, data assimilation, and modeling on the small scales (1–10 km) around the world. Examples include CubeSats and unmanned aircraft, particle filters, and advanced modeling of severe convective storms. Now the big challenge nationally and internationally is to build coordinated efforts to integrate together all these pieces for the benefit of society.*

BAMS: What was the biggest challenge you encountered while doing this work?

SM: *The biggest challenge was synthesizing literally hundreds of papers on different topics and trying to integrate them into a cohesive and readable document. Given the extreme breadth of the study, it was challenging to provide substantial depth while keeping the paper at a manageable length.*

Sharanya Majumdar (far left) and his University of Miami research team enjoying lunch at the local Asian bistro in Key Biscayne, Florida.

"I look forward to having discussions with agencies and scientific leaders on priorities in hazard forecasting. I am eager to see how this field will evolve over the next decade, and especially the gains in hazard forecasting that are realized through the advances documented in our review."

—Sharanya J. Majumdar, University of Miami

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