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WEATHER

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Advances in weather prediction

Better weather and environmental forecasting will continue to improve well-being

By **Richard B. Alley**¹, **Kerry A. Emanuel**²,
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Weather forecasting provides numerous societal benefits, from extreme weather warnings to agricultural planning. In recent decades, advances in forecasting have been rapid, arising from improved observations and models, and better integration of these through data assimilation and related techniques. Further improvements are not yet constrained by limits on predictability. Better forecasting, in turn, can contribute to a wide range of

environmental forecasting, from forest-fire smoke to bird migrations.

In 1938, an intense hurricane struck the New England coast of the United States without warning, killing more than 600 people. Since then, death tolls have dropped dramatically even though coastal populations have swelled. Many people and organizations contributed to this improvement. But, as the American Meteorological Society celebrates its 100th anniversary, the improvement in forecasting stands out. Modern 72-hour predictions of hurricane tracks are more accurate than 24-hour forecasts were 40 years ago (see the figure), giving sufficient time for evacuations and other preparations that save lives and property. Similar improvements in forecasting tropical cyclone tracks have been achieved by other leading agencies worldwide.

Weather forecasts from leading numerical weather prediction centers such as the European Centre for Medium-Range Weather Forecasts (ECMWF) and National Oceanic and Atmospheric Administration's (NOAA's) National Centers for Environmental Prediction (NCEP) have also been improving rapidly: A modern 5-day forecast is as accurate as a 1-day forecast was in 1980, and useful forecasts now reach 9 to 10 days into the future (1). Predictions have improved for a wide range of hazardous weather conditions, including hurricanes, blizzards, flash floods, hail, and tornadoes, with skill emerging in predictions

of seasonal conditions. Investment in weather forecasting pays large dividends, ranging from 3 to 10 times the costs (2). A 2009 study, for example, found that the value of weather forecasts to U.S. households is US\$31.5 billion, from



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Advances in weather forecasting are helping to improve environmental forecast, for example, of wildfire activity.

public expenditures of just US\$3.4 billion and private expenditures of US\$1.7 billion (3). U.S. adults obtain weather forecasts at a rate of 300 billion times per year, from numerous sources (3).

WHY FORECASTS ARE IMPROVING

Key developments in observation, numerical modeling, and data assimilation have enabled these advances in forecast skill. Improved observations, particularly by satellite remote sensing of the atmosphere and surface, provide valuable global information many times per day. Much faster and more powerful computers, in conjunction with improved understanding of atmospheric physics and dynamics, allow more-accurate numerical prediction models. Finally, improved techniques for putting data and models together have been developed.

Because data are unavoidably spatially incomplete and uncertain, the state of the atmosphere at any time cannot be known exactly, producing forecast uncertainties that grow into the future. This sensitivity to initial conditions can never be overcome completely. But, by running a model over time and continually adjusting it to maintain consistency with incoming data, the resulting physically consistent predictions greatly improve on simpler techniques. Such data assimilation, often done using four-dimensional variational minimization, ensemble Kalman filters, or hybridized techniques, has revolutionized forecasting.

Sensitivity to initial conditions limits long-term forecast skill: Details of weather cannot be predicted accurately, even in principle, much beyond 2 weeks. But weather forecasts are not yet strongly constrained by this limit, and the increase in forecast skill has shown no sign of ending (4, 5). Sensitivity to initial conditions varies greatly in space and time, and an important but largely unsung advance in weather prediction is the growing ability to quantify the forecast uncertainty by using large ensembles of numerical forecasts that each start from slightly different but equally plausible initial states, together with perturbations in model physics.

Several features of the weather system are more persistent than day-to-day weather, allowing accurate predictions further into the future, from subseasonal to seasonal, annual, and interannual time scales and beyond, with even greater scope for improvement. For example, the Madden-Julian Oscillation (MJO) moves eastward

around the tropics over 30 to 90 days, affecting rain, wind, clouds, air pressure, the onset and demise of summer monsoons, and more, with important agricultural and other implications. Weather prediction models have now shown predictive skills for the MJO phenomena up to 5 weeks (5).

In parallel with improving forecasts, communication of the growing wealth of weather data has expanded greatly, enabling a timely flow of ever more detailed and accurate information to a rich diversity of users. Only a few decades ago, one had to wait for the morning newspaper or the evening news to get the latest forecast, and warnings of imminent arrival of severe weather were delivered mostly by flags, sirens, and police bullhorns. Today, detailed, geographically targeted weather information is available at the touch of a finger on a smartphone.

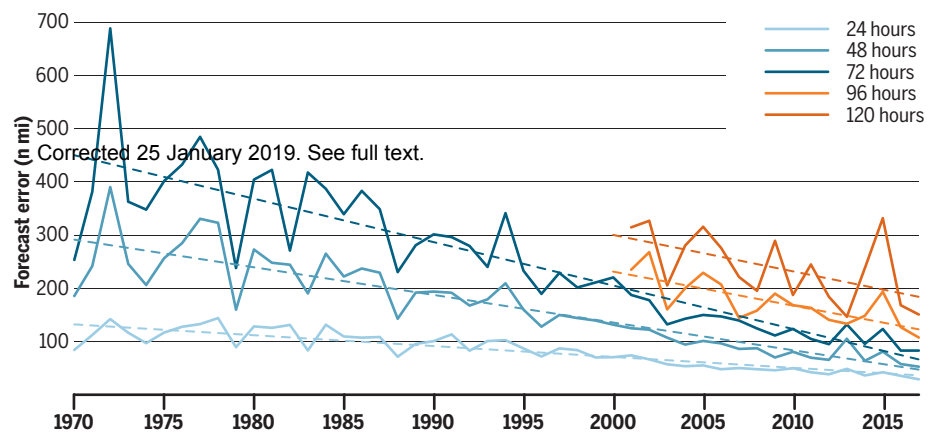
pressure interacting with the detailed coastal configuration. Dedicated surge forecasting driven by more-accurate weather predictions can fine-tune warnings.

Summertime sea-ice loss is opening the Arctic to shipping, recreation, resource extraction, and other activities. Seasonal sea-ice regrowth thus presents dangers for an increasing number of people. Recent work shows bright prospects for accurate sea-ice forecasts extending more than a month into the future, if the best available forecast systems are improved by reducing systematic model errors and advancing data assimilation (9).

Recently, many parts of the world have experienced high wildfire activity, degrading air quality. In the United States, NOAA is developing a coupled weather, fire, and smoke forecast system” to provide timely warnings to people vulnerable to health impacts,

Advances in hurricane prediction

Data from the NOAA National Hurricane Center (NHC) (13) show that forecast errors for tropical storms and hurricanes in the Atlantic basin have fallen rapidly in recent decades. The graph shows the forecast error in nautical miles (1 n mi = 1.852 km) for a range of time intervals.



TOWARD BETTER ENVIRONMENTAL FORECASTS

Weather-forecast improvement is the essential first step toward better predictions of many weather-related environmental phenomena. For example, over 40 million people in the United States—far more than previously believed—live where floods are expected more than once per century (6), and the global population in flood-prone basins has more than doubled over the past 30 years (7). Improvements in river forecasting, leveraging better weather forecasts, can provide great value predicting flooding from hurricanes (8) and other sources.

Coastal storm surge, so important in events such as Superstorm Sandy, is increasing with sea-level rise, but depends sensitively on tides, wind, and atmospheric

and to aviation and other affected groups.

Weather forecasting also plays an important role in renewable energy. Balancing electrical grids requires forecasts of the availability of sun, wind, and river flow, and forecasts of energy demand, a large part of which is driven by weather.

Weather causes many changes in animal behavior, which can be anticipated by weather forecasters. For example, forecasts of weather-driven bird migrations can now be used to reduce collisions with buildings, airplanes, and wind turbines; inform monitoring efforts; and engage the public (10).

Modeling centers are increasingly integrating efforts across time scales, from short-term weather to climate. There has been rapid progress in forecasting at the subseasonal-to-seasonal time scales (5),

which was legally mandated in the United States (to NOAA) in 2017.

Climate models have shown skill in projecting many changes, including global mean surface temperature and the rise of absolute humidity with the associated increase in especially intense precipitation when conditions are favorable. The models, however, remain challenged to project regional shifts and quantify uncertainties. Improvements in understanding physical processes and representing them in models that will benefit weather forecasts can also help climate modeling (11).

FURTHER IMPROVEMENTS

To more closely approach the limits of predictability for weather and associated hazards at various temporal and spatial scales, the weather forecasting community can strategize research and investments. Several areas are highlighted here, but many more exist. These all require effective two-way interaction between weather scientists and researchers and practitioners from broad disciplines, including, but not limited to, mathematical and physical sciences as well as remote-sensing and computational technologies.

Maintaining and improving data collection remain central, targeting regions and times of special interest. Increased use of unmanned aerial vehicles for measuring conditions in hurricanes and other extreme events offers great potential, for example.

These new data must be assimilated into models to be fully useful. For example, interactions with the ocean strongly influence hurricane evolution, but the ocean state is generally not updated through data assimilation in current prediction models. Assimilating available and new remotely sensed and in situ data in real time could greatly improve predictions of hurricane intensity. Similarly, remotely sensed cloud radiances such as those from the newest-generation geostationary satellites (GOES-R) are not yet routinely used for weather forecasts, but contain valuable information that can further advance prediction and warning (12).

Improving numerical prediction models requires better understanding of key physical processes such as air-sea and cloud-aerosol interactions. Machine learning and neural networks can help identify model uncertainties, perform bias corrections, and automate the forecast process.

Computation is essential in everything discussed here. Progress will involve larger ensembles of model runs at higher resolution leading to improved probabilistic forecasts, including those of hazardous weather. This can be realized if governments maintain a steady schedule of investment in high-speed computing, recognizing the strong evidence

that such investments will be repaid many times over in savings to the economy.

Operational weather forecasting has long relied on the results of academic research and on the pipeline of well-educated graduates. Improved integration with colleges and universities, providing smoother career tracks and improved incentives, can help bright young researchers bring their talents to the enterprise.

Great progress has been made in communicating forecasts to diverse audiences. However, the ability to quantify forecast uncertainty in probabilistic terms has arguably outrun the ability to communicate such forecasts of uncertainty. This feeds into the broader societal challenge of making forecasts actionable. Even a perfect forecast may be viewed as a failure if some people ignore it, choosing, for example, to stay in the path of a hurricane, endangering themselves and those called on to rescue them.

The developing world is especially vulnerable to weather disasters yet is underserved by forecasting. A World Bank report has highlighted the major opportunities for upgrading national meteorological and hydrological services. Meeting investment needs of at least US\$1.5 billion to 2 billion, and continuing costs of at least US\$400 million to 500 million per year, could save 23,000 lives per year and provide US\$3 billion to 30 billion per year in economic benefits (7). However, national efforts to force meteorological services to raise revenue by placing data products behind pay walls could thwart progress and hurt the most vulnerable people.

Strategic investments, including public-private partnerships, and open access to weather and environmental data can ensure a bright future for weather forecasting and related environmental services, thus helping to improve human well-being. ■

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QUANTUM SIMULATION

Transport with strong interactions

Motion of spin and charge is explored with cold-atom quantum simulations

By Jean-Philippe Brantut

How do quantum particles move when they are interacting with other, identical particles? This question arises often in condensed-matter physics, for example, when considering the conduction of electrons in ordinary solids such as metals or insulators. However, these questions can now also be studied by using a gas of neutral atoms cooled to ultralow temperature and trapped by lasers. In two papers in this issue, Brown *et al.* (1) on page 379 and Nichols *et al.* (2) on page 383 have used atoms to explore the transport of mass and spin in the Fermi-Hubbard model, a simple model of particles residing in a lattice and repelling each other when sitting on the same site. In these atomic systems, all of the microscopic parameters are known a priori, such that the findings provide a testbed for advanced numerical simulation methods and theories.

The properties of identical fermionic particles at low temperature, such as electrons in solids, are well understood when the particles are not interacting. Transport usually occurs through random walks, and these processes tend to produce a uniform distribution of particle density, spin, or other conserved quantities at a rate that depends on the nature of the particles and their potential energy landscape. This so-called “Drude model” is the basis of our understanding of most transport processes in materials (3).

What happens when one considers instead particles interacting with each other? The general answer, provided by Landau in the 1950s, is: not so much. Because of the Pauli principle, which does not allow more than one fermion to occupy the same quantum state, at least at low temperatures, the extra resistance that would be

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