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Profitable Prophecy: Advances in Weather Prediction

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Rapid advances in weather-forecast accuracy are paying large benefits for society, with potential for even greater payoffs from targeted investments.

Abstract. Weather forecasting provides societal benefits that greatly exceed costs. 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, and can be enabled by targeted investments in this successful public-private partnership. Better forecasting in turn can contribute to a wide range of valuable environmental forecasting, from forest-fire smoke to bird migrations, improving well-being in numerous and sometimes surprising ways.

Eighty years ago, an intense hurricane struck New England without warning, killing more than 600 people. Since then, even though coastal populations have swelled, death tolls have dropped dramatically.

Many people and organizations contributed to this improvement, from first-responders to architects and drafters of zoning codes. But, as the American Meteorological Society prepares to celebrate its 100th anniversary, the improvement in forecasting stands out. Modern 72-hour predictions of hurricane tracks are more accurate than 24-hour forecasts just 40 years ago (Figure 1a), giving sufficient time for evacuations and other preparations that save lives and property.

The authors routinely hear jokes about prediction errors from people who wouldn't dream of planning an outdoor activity without first checking the weather forecast. Those forecasts from leading numerical weather prediction centers such as NOAA's National Centers for Environmental Prediction (NCEP) and the European Centre for Medium-Range Weather Forecasts (ECMWF) have been improving rapidly—a modern 5-day forecast is as accurate as a 1-day forecast in 1980, and useful forecasts now reach 9-10 days into the future (Figure 1b) (1). Predictions have improved for a remarkably broad range of hazardous weather conditions, including hurricanes, blizzards, flash floods, hail, and tornadoes, with skill emerging in predictions of seasonal conditions.

A 2009 study found that US adults obtain weather forecasts an astounding 300 billion times per year, from a great range of sources (2). That study also found the value of weather forecasts to US households is $31.5 billion, from public expenditures of just $3.4 billion and private expenditures of $1.7 billion, yielding benefits more than 6 times costs (2). Studies in other nations similarly have found that the investment in weather forecasting pays large dividends, ranging from 3 to 10 times costs (3). The value of weather predictions is further confirmed by the rapid growth of businesses purchasing customized commercial forecasts from the private weather enterprise, which is increasing in capitalization, employment and innovation (4).

Why forecasts are improving

Three key developments enabled these advances in forecast skill: Better and more extensive observations, better and much faster numerical prediction models, and vastly improved methods of assimilating observations into models. Remote sensing of the atmosphere and surface by satellites provides valuable information around the globe many times per day. Much faster computers and improved understanding of atmospheric physics and dynamics allow greatly improved numerical prediction models, which integrate the governing equations using estimated initial and boundary conditions.

At the nexus of data and models are the improved techniques for putting them together. 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 can 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 places strong limits on long-term forecast skill—the details of weather cannot be predicted accurately, even in principle, much beyond roughly two weeks. But weather forecasts are not yet strongly constrained by this limit, leaving optimism for continuing forecast improvement (5). Sensitivity to initial conditions varies greatly in space and time, and an important but largely unsung advance in weather prediction is our growing ability to quantify the uncertainty by using large ensembles of numerical forecasts starting from slightly different but equally plausible initial states, together with perturbations in model physics.

Several features of the weather system are notably more persistent than day-to-day weather, allowing accurate predictions further into the future with even greater scope for improvement. For example, the Madden-Julian Oscillation (MJO) moves eastward around the Earth's tropics over 30-90 days, affecting rain, wind, clouds and air pressure, the onset and demise of summer monsoons (6), and more, with important agricultural and other implications. El Nino/La Nina (ENSO) variability, with a typical 4-6-year recurring cycle and varying intensity, significantly affects economies around the world by impacting most weather-dependent human activities, so increased predictive skill could be used in myriad ways to improve well-being (7).

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 were delivered mostly by flags, sirens, and police bullhorns. Today, detailed weather information is available at the touch of a finger on a smartphone, which is rapidly becoming a vehicle for instant, geographically targeted weather alerts.

Opportunities for Further Improvement

Weather-forecast improvement is the essential first step that will enable valuable improved predictions of a great range of related environmental phenomena. For example:

→Hurricanes Harvey and Florence, among others, highlighted the immense damages from precipitation-driven flooding. With over 40 million people in the US living in the 100-year floodplain, far more than previously believed (8), the value of improving flood forecasts is high, requiring improvements in forecast models to better predict flooding from hurricanes (9) and other sources.

→Storm surge, so important in events including Superstorm Sandy, is increasing with sea-level rise, but depends sensitively on tides, wind, and atmospheric pressure interacting with the detailed coastal configuration, requiring dedicated forecasting driven by accurate weather predictions.

→Summertime sea-ice loss is opening the Arctic to shipping, recreation, resource extraction and other activities, but seasonal sea-ice regrowth heightens dangers; recent work shows bright prospects for sea-ice forecasts extending more than a month into the future (10).

→Wildfire activity has been high recently, with important air-quality impacts. NOAA is developing the High Resolution Rapid Refresh-Smoke (HRRR-Smoke) system to provide timely warnings to people vulnerable to health impacts, and to aviation and other affected groups.

→Weather drives many changes in animal behavior, which can be anticipated by weather forecasters to good effect. For example, forecasts of bird migrations can now "…reduce collisions with buildings, airplanes, and wind turbines; inform a variety of monitoring efforts; and engage the public" (11).

→As renewables come to play an increasing role in power systems, forecasting the availability of sun, wind, and river flow will take on increased importance, as will forecasts of energy demand, a large part of which is driven by weather.

Modeling centers are increasingly integrating efforts across timescales, from short-term weather to climate. Forecasters are progressing rapidly at the subseasonal to seasonal time scales, on MJO (12) and other phenomena. In the US, additional efforts by NOAA to improve forecasts at the subseasonal to seasonal scale were legally mandated 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. While one cannot guarantee that improved weather forecasts will lead to improved regional projections, progress seems likely (13).

Ways forward

To take advantage of the growth opportunities listed above, and more closely approach the limits of predictability for weather and associated hazards at various temporal and spatial scales, the entire community can strategize research and investments. The following areas are likely to be especially fruitful:

→Maintain and improve data collection, targeting regions and times of special interest, and assimilating targeted observations into models. For example, satellites and UAV observations can focused on hurricanes, providing better predictions of their tracks and intensities.

→ Improve understanding of key physical processes that are currently not well represented in numerical prediction models (e.g., air-sea and cloud-aerosol interactions). Explore the potential use of big-data science including machine learning and neural networks to identify model uncertainties, perform bias corrections, and automate the forecast process.

→ Further develop advanced data assimilation techniques, to more accurately and efficiently assimilate existing and future observations. For example, cloud radiances from satellites are not commonly utilized at appropriate scales. Data assimilation can be applied more broadly to data-model integration and model development.

→Use advances in computer technology to produce higher resolution forecasts with larger ensembles, 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.

→Accelerate research and development of operational weather forecasting by improved integration with academic research and education, providing smoother career tracks and improved incentives for bright young researchers to bring their talents to the enterprise.

→Bring advanced communication methods to bear on the important task of delivering weather forecasts. Our ability to quantify forecast uncertainty in probabilistic terms has arguably outrun our ability to communicate such forecasts of uncertainty, but increasing engagement of communication experts is leading to much improved ways of communicating probabilistic weather information to those who need it.

With strategic investments, the future of weather forecasting and related environmental services is bright, as public-private partnerships improve our well-being.

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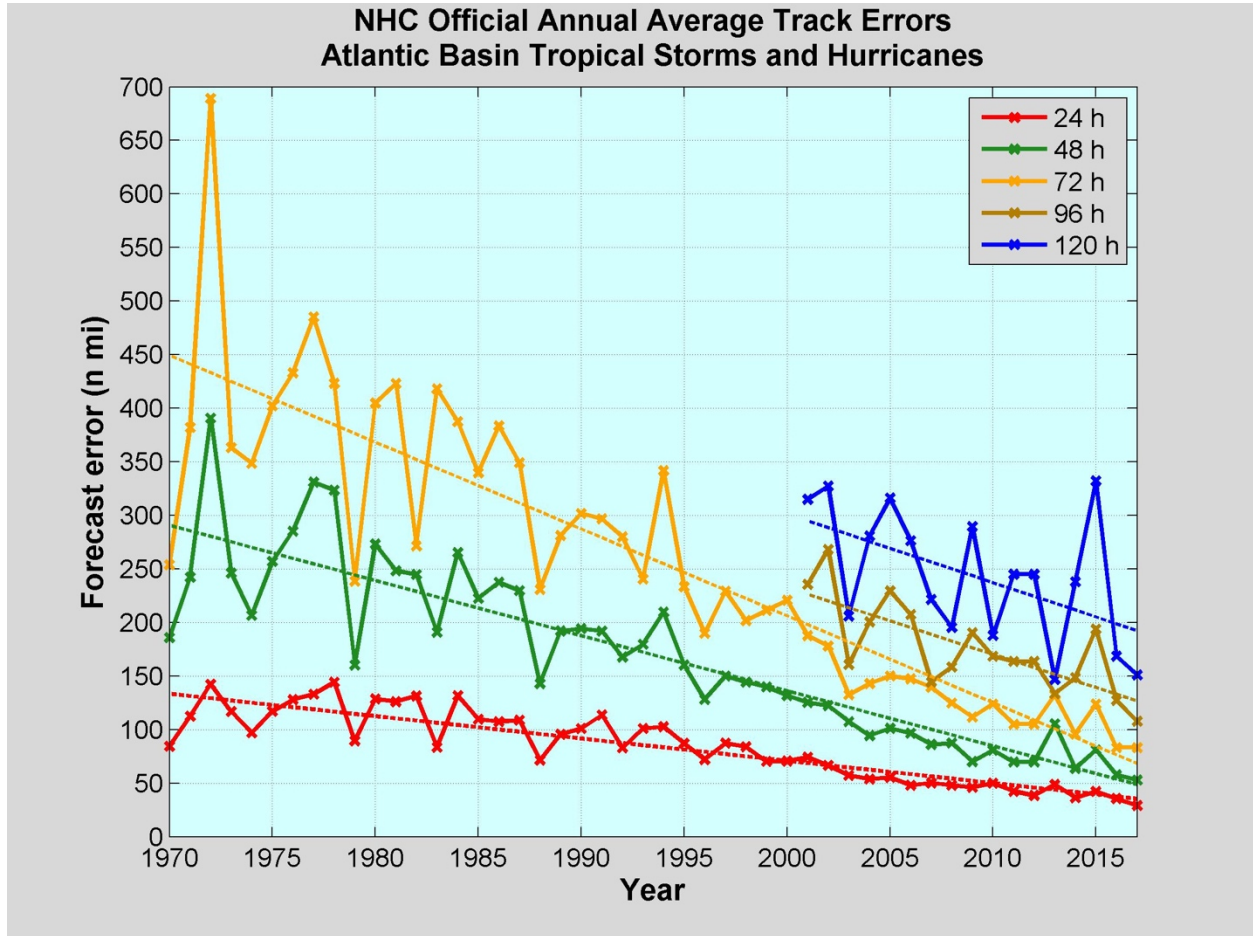13. G. Krinner, M.G. Flanner, *Proc. Natl. Acad. Sci. U.S.A.* **115**, 9462 (2018).

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Figure 1a. NOAA National Hurricane Center forecast errors for Atlantic basin tropical storms and hurricanes, showing the rapid improvement in accuracy.
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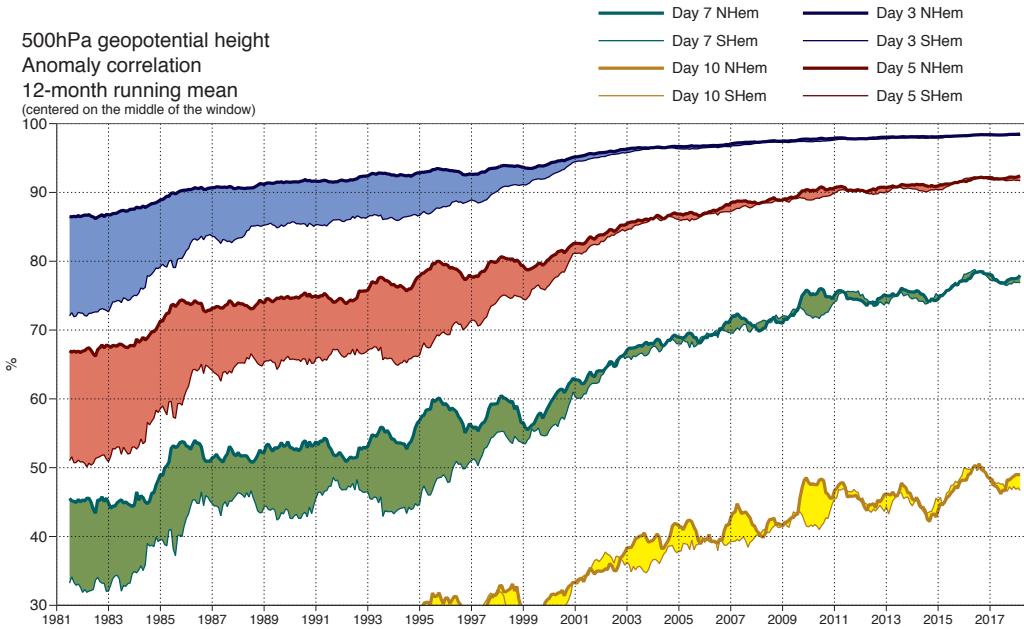
5   https://www.weather.gov/disclaimer

Figure 1b. Improvement in forecast accuracy over time. The correlation between forecasts and subsequent weather is shown for forecasts 3, 5, 7 and 10 days into the future, for northern and southern hemispheres. A value of 60% is generally considered useful, and 80% is highly accurate. Updated from (1).

https://www.ecmwf.int/en/forecasts/charts/catalogue/plwww_m_hr_ccaf_adrian_ts?facets=undefined&time=2018101100