Climate modeling
Forecasting the state of the atmosphere is done in many ways, by many groups and organizations, and over many time scales. The very long time scales of interest to climate modeling span decades and even centuries. Their focus is on predictions of future climate and how the climate will vary according to solar variability, the Earth’s Copernican motions, volcanic activity, and
of greatest public and political interest, controllable changes in anthropogenic emissions of greenhouse gases and aerosols. Climate models are general circulation models or GCMs that are not unlike those used in day-to-day weather forecasting [see box]. However, they must deal with the additional challenges that arise from their need to cover the full globe and very long periods of time. They must also include the interactions and feedbacks between the atmosphere, oceans, sea ice, land masses, and river flows. And they must do this in a way that will allow slowly varying, small-scale climate signatures of temperature and precipitation to be separated from the very large signatures and variabilities of short-term weather.

Paleoclimate modeling is a special type of climate modeling whose objective is to 'hindcast' – predict in reverse – the historical changes in climate that have been detected with ice cores and tree rings. Yet another special aspect of climate modeling is called downscaling. It is the process of forecasting regional climate features with greater spatial resolution than is available from the coarse low-resolution global climate forecasts. The highest resolution of the best global climate models is about 100-200 km, while today's downscaling activities attempt to resolve regional climate features on scales of about 40 km. Downscaling seeks to quantify climate change on these higher spatial scales in order to better reveal the impacts of climate change on agriculture, water supplies, fish habitats, sustainability and so forth.

Monthly and seasonal outlooks

Between forecasts of climate and weather are monthly and seasonal outlooks. Until recently, their typical focus has been on atmospheric temperature and precipitation, and how each will vary from average conditions for a month or a season. A big change occurred in 1997, when at least one national modeling center made an accurate forecast months in advance of the onset of the major El Niño event of 1997-98. An El Niño is a warm tropical episode that is highlighted by warm surface waters replacing the upwelling of cold water along the west coast of South America. Significant changes in global weather patterns accompany strong El Niño events as they also accompany its cold-event counterpart, La Niña. During major El Niño events, heavy precipitation and flooding can occur along the west coast of tropical South America, and at subtropical latitudes of North America (Gulf of Mexico) and South America (southern Brazil to central Argentina). At the same time, abnormally dry conditions occur over northern Australia, Indonesia and the Philippines in winter and summer. Drier than normal conditions are also observed over southeastern Africa and northern Brazil, during the northern winter season. During the northern summer season, Indian monsoon rainfall tends to be less than normal. If El Niño and La Niña forecasts can be made in the future with regularity and adequate skill, the benefits to the global community will be immense – countries susceptible to drought and flooding could do much to mitigate these prolonged and devastating natural hazards.

“Everyday” weather forecasts

Traditional synoptic weather forecasts are the forecasts that are most familiar to us. They are prepared twice daily and are issued four-to-six hours after the weather observations that they use. These forecasts extend out as far as seven or more days into the future (the forecast duration varies according to the particular weather service issuing the forecast – e.g. eight days in Australia and seven days in the U.S.). One-to-two day forecasts are considered to be short-range forecasts, medium-range forecasts are three days and longer. Special high-resolution forecasts called mesoscale forecasts are now just beginning to come into operational use in some sectors although they are still primarily a research and special-purpose forecasting tool. Mesoscale forecasts typically are valid for a period that extends from about three hours after the time of the weather observations that they use out to one-to-two days later. They also cover a smaller area (model domain) than synoptic forecasts. But their greatest attribute is their ability to provide very high spatial and temporal resolution – down to a few kilometers or less, and only tens of minutes.

Nowcasting

The important gap between current weather and the onset of validity for a mesoscale forecast is the domain of the nowcast. In approximate terms, the total period of interest to nowcasters ranges from a few tens of minutes up to three-to-six hours. But in practical terms, current nowcasting products for severe weather rapidly lose their validity after one hour (figure 2). The principle objective of nowcasting is to provide highly precise predictions of the intensity, location, onset and cessation of significant weather-related events. Rather than making a severe-weather forecast of, say, “scattered afternoon severe thunderstorms in the greater St. Louis area,” a nowcast seeks to predict the occurrence of a “severe thunderstorm with winds in
excess of 30 meters per second accomplished by golf-ball-size hail and intense lightning in the immediate vicinity of the St. Louis Arch between 3:30 pm and 4:15 pm today...."

We may not always be aware of it, but every one of us regularly makes our own personal nowcasts. We instinctively observe the types, amounts and changes in the clouds, the direction and speed of the wind, the humidity and temperature of the air. And then we make our very own nowcast – we project what the weather will be and how it will affect us over the next tens of minutes or over the course of the morning or afternoon. Science-based nowcasting has the same objectives, but seeks to use state-of-the-art-observing technologies together with expert systems, theoretical models and frequently also human intervention to make precise very-short-term forecasts.

Numerical forecasts of mesoscale and synoptic weather depend on numerical solution of a coupled set of equations for energy, momentum and mass conservation – see weather prediction box. They use observations to specify the initial atmospheric state and to aid in defining conditions at the boundary of the model domain. Observations are also assimilated into the numerical modeling process as a way to “tune” or adjust the model to the most recent changes in the state of the atmosphere. In contrast, nowcasting methods depend heavily on dense local observations of weather, winds, and state variables, coupled with a variety of empirical and rule-based formulations, and on a few theoretical equations and some numerical modeling as well. Nowcasting methods vary widely and are tailored to fit the application they are addressing. But the core of the nowcast is a set of highly resolved local measurements and observations. These typically are provided by weather radar, surface mesonets, lightning detectors, wind profilers, radiosondes and satellites, among others.

**Nowcasting thunderstorms**

Forecasting the development and movement of severe thunderstorms is a major focus of the nowcasting research community. These storms are both dangerous and difficult to predict with great specificity in regard to location, timing and severity. Individual single-cell storms are short-lived, lasting usually less than 30 minutes. On the other hand, about half of multi-cell storms typically last more than one hour with their cells splitting and merging throughout the lifecycle of the storm complex. And the very large storm complexes can last many hours and their movement can be extrapolated with skill. The challenge is to develop a suite of nowcasting methods that can be applied to the full spectrum of diverse storms. Different nowcasting methods have been created over the past 40 years with the goal of effectively predicting the initiation, evolution and dissipation of convective storm systems. These methods have yielded varying degrees of success and can be grouped into three broad categories: 1) extrapolation; 2) convection initiation and dissipation; and 3) explicit numerical prediction. Extrapolation methods are actually of two types; the steady-state approach assumes no change in cell movement, size and intensity, while a second type allows for change in intensity and size. The second nowcasting category involves the use of expert systems that seek to predict the initiation and dissipation of convection by monitoring convergence boundaries using radar, dense mesonets and visual observations of cloud development. It has been known for some time that human forecasters were frequently able to use these methods with greater skill than extrapolation. Recently, new methods are emerging that automate the convergence-detection and storm prediction process. They are likely to further increase predictive skill as scientific understanding of storm initiation becomes more complete, as detailed observations become more available, and as computational advances continue. The third cate-
ry of nowcasting convective storms involves explicit numerical simulation and prediction of thunderstorms. Some approaches are being developed that utilize radar observations of convergence lines to initialize the model, while others do not rely on these special observations. In both cases, explicit numerical modeling currently is an emerging nowcasting research tool that offers future promise.

After about one hour the skill level of the various nowcasting methods decreases rapidly for all convective storms. Skill levels are higher over longer periods for organized bands of convective storm cells and large mesoscale storm systems, but also for nowcasting of non-convective events such as freeze warnings. Let’s explore a few examples of other nowcasting methods and their applications.

**Vaisala’s IceBreak Nowcasting for roadways**

Vaisala is playing a significant role in nowcasting applications. One such application is ice prediction for roadways, which enables roadmasters to use proactive anti-icing operations rather than less effective reactive road maintenance practices. IceBreak is Vaisala’s fully physical heat-balance model that predicts site-specific road surface state and temperature. This allows users to closely monitor potential weather hazards and mobilize resources in sufficient time to take preventive treatment. The model may be run in either mesoscale forecasting mode (from 24 to 72 hours ahead) or 3-hour nowcasting mode. In mesoscale mode, IceBreak uses as its input data the standard short-range forecasts of atmospheric variables, typically from the nearest mesoscale model grid point. IceBreak is currently used in mesoscale mode by more than 10 national meteorological services, making it the most extensively used ice prediction method worldwide.

In nowcast mode, the input data are real-time local observations from Vaisala’s ROSA road weather stations. One extensive study of operational 3-hour nowcast performance revealed very encouraging results. Using temperature data from 74 stations over a five-month period from October 2000 through February 2001, the evaluation considered more than 37,000 individual nowcasts comprising almost 370,000 data pairs with the following results:

| Bias       | -0.19°C |
| Standard deviation | 0.92°C |
| Accuracy¹ | 91.30%  |
| Reliability² | 1.00   |
| Miss rate³  | 10.20%  |
| False alarm rate⁴ | 7.90%  |

Because the IceBreak model contains accurate physical representations of all major heat fluxes, its performance does not degenerate as quickly as rule-based nowcasting roadway applications. Indeed the model results demonstrate significant skill out to the end of the typical 3-hour nowcast period with a gradual increase of bias and standard deviation as far ahead as 6 hours.

**Vaisala’s SAFIR Lightning System**

Another Vaisala nowcasting capability focuses on early lightning and thunderstorm detection and forecasting. The Vaisala SAFIR Lightning System consists of a network of detection stations that is uniquely capable of locating at long range all lightning types—both Intra-Cloud (IC) and Cloud-to-Ground (CG). A central processing system computes the location of lightning discharges by triangulation, and also performs lightning activity analyses and storm nowcasts. Total lightning activity (IC + CG), with its dominant IC lightning component, is an early indicator of storm development. It also correlates closely with storm severity. This enables efficient early detection of storm cells, accurate tracking information and advance warning of imminent thunderstorm hazards. IC detection typically provides about 10 minutes advance warning before the onset of CG lightning activity as well as an order of magnitude more information for monitoring and tracking of thunderstorm cells.

Early detection, monitoring and mapping of storm total electrical activity, either alone or together with weather radar and other measurements, is a valuable nowcasting tool for many applications. Users include meteorological services (SAFIR is used by 12 national weather services around the world), as well as electric power and transmission companies, sensitive manufacturing industries, fire and personnel, flood management districts, and aviation.

Early lightning detection and warning is also critical to the recreation and outdoor entertainment sectors where large numbers of individuals can be exposed. In the U.S. alone, lightning caused an annual average of 163 deaths and three times as many injuries over the period 1940-1991. Lightning deaths in the U.S. exceed by 50% those from either tornadoes or floods, and are 400% greater than hurricane deaths.

**Flood forecasting**

Two other examples of operational nowcasting systems are flash flood prediction and emergency response. Flash flood analysis and prediction models are now coming into widespread use in some countries. Flash flood models represent the topography, surface conditions, soil moisture and stream networks of flood plains and basins.
and they rely on observations or model predictions of precipitation rates and duration to make short-term forecasts of flooding. Nowcasting methods use radar to track and extrapolate storm cell trajectories and estimate the amount and type of precipitation. Radar observations are not used in isolation but are frequently combined with surface and upper-air lightning detectors data from atmospheric soundings, surface weather stations, rain gauges, cloud radars, wind profilers, satellites and virtually any measurement system available in the area. The challenge is the availability of adequate and representative observations. We will return later to this important point.

Emergency response for chemical releases

Emergency response to the accidental or deliberate atmospheric releases of toxic chemicals or biological agents is an emerging nowcasting focus. Observations and mesoscale model predictions are used in conjunction with atmospheric dispersion models to predict ground-level exposures downwind of the release point. Public safety personnel rely on these predictions to quickly develop mitigation and protection strategies. For example, they must decide with very short notice what areas toordon off, and whether it is better to evacuate people in the affected areas or to "shelter in place" in by having them remain indoors. Nowcasting emergency response systems are being designed but very few operational systems exist at present. One notable exception is the National Atmospheric Release Advisory Center (NARAC) at the Lawrence Livermore National Laboratory in California. It has been in existence since 1979 and has assisted in supporting emergency response to more than 70 incidents, including radiation releases from the Three Mile Island nuclear power plant in 1979 and Chernobyl in 1986, as well as numerous chemical releases in the U.S. and throughout the world. The important challenge for the future is to provide similar capabilities at multiple locations, and to make available the critical atmospheric measurements required to characterize atmospheric transport and dispersion. This will be especially important because existing atmospheric measurement networks have been designed to support the prediction of severe weather. On the other hand, the most adverse dispersion conditions are associated with benign weather regimes.

The future

The development of advanced nowcasting systems for severe weather events is ongoing in several countries. Researchers are exploring several approaches to the problem of very short-range forecasts that are highly specific in time and space. These approaches vary widely, ranging from extrapolation to expert systems to explicit numerical modeling of storm cells. They all share three common needs: data, data and even more data! The observational data must be sufficient to characterize the storm and its environment in great detail. Herein lies the dilemma: how to ensure that the measurement systems will be available where and when they will be needed. Part of the answer lies in determining in advance what locations will be served by a nowcasting capability. But an equally important question is "Who will be responsible for supporting these nowcasting systems?" Will they be a public or a private enterprise? Or will there be public-private partnerships that emerge to meet these needs? One thing seems certain: nowcasting will be an even more important and valuable component of the weather forecasting paradigm.

References


Footnotes

1) Accuracy is the percentage of the time that a given atmospheric state (e.g. occurrence of frost vs. no frost) is correctly predicted.
2) Reliability is the ratio of the number of times that an atmospheric state is predicted relative to the number of actual occurrences.
3) Miss rate is the proportion of atmospheric events or states that were not predicted.
4) False alarm rate is defined as the proportion of atmospheric events or states that were predicted but did not occur.