Nowcasting: The Promise of New Technologies of Communication, Modeling, and Observation

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Capsule Summary

Major advances in data collection, data assimilation, high-resolution modeling, communication, and real-time response set the stage for large improvements in nowcasting and societal use of short-term forecasts.

Abstract

Nowcasting combines a description of the current state of the atmosphere and a short-term forecast of how the atmosphere will evolve during the next several hours. A convergence of technical developments has set the stage for a major jump in nowcasting capabilities and the ability to apply those advances to important societal needs. New communications technologies, including broadband Internet, wireless communication, social media, and smartphones, have made the distribution and application of real-time weather information possible nearly anywhere. Rapid increases in the quantity and quality of surface, aircraft, and remote-sensing data now provide a real-time description of atmospheric conditions from the global to regional scales. Improved modeling and data assimilation offer the potential to more effectively apply mesoscale observations and to produce high-resolution analyses and forecasts. Finally, improvements in communication, computation, and control have provided society with the ability to effectively use nowcasting information for the protection of life and property, as well as facilitating commerce and recreation. This paper describes these individual advances, the synergies of their combination, and how the forecast process might change as a result during the next few decades.

Introduction

Nowcasting encompasses a description of the current state of the atmosphere and the prediction of how the atmosphere will evolve during the next several hours. Nowcasting is not a new concept, with references to the term as far back as the mid-1970s (e.g., Lushine 1976) and a comprehensive book on the subject published a few years later (Browning 1982). Although much of the early work on nowcasting dealt with the temporal extrapolation of radar (e.g., Browning et al. 1982) and satellite imagery (e.g., Purdom 1976, Smith et al. 1982), increasingly the subject has broadened to encompass high-resolution numerical models driven by the assimilation of a wide range of mesoscale data (Benjamin et al. 2004).

Recently, a confluence of technical developments has set the stage for a major jump in nowcasting capabilities and the ability to apply those advances to important societal needs. New communications technologies, including broadband Internet, wireless communication, and smartphones, has made the distribution and application of real-time weather information possible at nearly any location. Exponential increases in surface, aircraft, and remote sensing data now provide a description of atmospheric conditions from the global to regional scales. Advances in modeling and data assimilation, such as the ensemble Kalman filter (EnKF) technique, offer the potential to more effectively apply observations and to produce high-resolution analyses and forecasts. Finally, improvements in communication, computation, and control have provided society with the ability to effectively use nowcasting information for the protection of life and property, as well as to facilitate commerce and recreation. This paper describes these individual advances, the possible synergies of their combination, and how the forecast process might change as a result during the next few decades.

The Evolution of Nowcasting

The earliest work on nowcasting was mainly limited to the subjective interpretation and temporal extrapolation of meteorological radar (Wilson 1966, Battan 1973, Wilson and Wilk, 1982) and satellite (e.g., Purdom 1976) imagery for short-term prediction of the motion and evolution of convection. Many of the early studies on satellite-based nowcasting was completed at the University of Wisconsin and NOAA/NESDIS, with the vast majority dealing with convective initiation and development (e.g., Mecikalski et al., 2007, 2008; Scofield 1987).

Initial attempts at computer-based temporal extrapolation were relatively primitive (e.g., Noel and Fleisher 1960), neglecting system evolution, and later evolved into more sophisticated algorithms for tracking individual cells (Wilk and Gray 1970, Barclay and Wilk 1970). During the 1980s and 1990s the UK Met Office introduced the FRONTIERS (Browning and Collier 1989), the NIMROD (Golding 1998) and the GANDOLF (Pierce et al 2000) convective nowcasting systems, all based on radar tracking and temporal extrapolation of convection, with the latter using model and satellite data to aid in forecasting development and movement. In the U.S., the *Thunderstorm Identification Tracking and Analysis and Nowcasting* (TITAN) system was also not limited to a steady state assumption but allowed for temporal changes in cell intensity and size (Dixon and Wiener 1993). The second-generation systems such as TITAN included the combination of radar extrapolation techniques with NWP model precipitation to produce an extended short-period forecast that was consistent with larger scale and longer-period forecasts (Golding 2000). A number of new radar-based nowcasting systems have been developed during the past few decades, with perhaps the most sophisticated being the National Center for Atmospheric Research (NCAR) Auto-Nowcaster that combines radar, satellite, upper air, and surface data to forecast convection during the next few hours (Mueller et al. 2003).

During the past twenty years, enabled by parallel improvements in model resolution, data availability and computing resources, mesoscale data assimilation and short-term modeling have become increasingly useful for nowcasting, and has allowed nowcasting to move beyond convection. One of the earliest developments was the Local Analysis and Prediction System (LAPS) by the NOAA Forecast Systems Lab (FSL, now the Earth Systems Research Laboratory, ESRL) during the 1990s (Albers 1995, Albers et al. 1996). LAPS has the ability to ingest a wide variety of observations (mesonetworks, conventional data, remote sensing data) and to provide three-dimensional analyses using a variety of techniques. The analyses can then be used to initialize mesoscale models for short-term forecasts. LAPS has been used around the world and is available at all National Weather Service forecast offices.

A complementary approach for analyzing observations and providing short-term predictions is the NOAA Rapid Update Cycle (RUC) system, in which analyses are made at regular intervals, using short-term forecasts from the previous analysis time as the first guess. RUC, developed at ESRL, began running at 80 km grid spacing with a three-hour assimilation cycle (Benjamin et al. 1991). Continuous upgrades have occurred during subsequent years so that RUC is now run at 13-km grid spacing, with one-hour updates. Another major center of real-time data assimilation and short-term forecasting has been the University of Oklahoma Center for Regional Prediction of Storms (CAPS), where real-time mesoscale data assimilation has been used to drive high-resolution short-term forecasts of their Advanced Regional Prediction System (ARPS) model (Wang et al., 1996, Xue et al. 2003), with particular emphasis on nowcasting of convective systems.

Several operational nowcasting systems have been developed that combine observation nudging (also known as Four Dimensional Data Assimilation, FDDA) with high-resolution prediction. For example, the Rapidly Relocatable Nowcast Prediction System (RRNPS), developed mainly for U.S. Army applications around the world, has been applied successfully at single-digit (km) grid spacing using the Pennsylvania State/NCAR Mesoscale Model, MM5 (Schroeder et al., 2006). A similar system (the Four Dimensional Weather System, 4DWX) has been developed by NCAR for use at U.S. Army test ranges (Liu et. al 2008).

Perhaps the earliest nowcasting demonstration project was the Chesapeake Bay Nowcasting Experiment that took place during summer field periods of 1974-1976 (Scofield and Weiss 1977). In this experiment high-resolution satellite imagery, radar data, and an expanded mesonetwork of surface observations were used to create mesoscale analyses and predictions that were communicated to the public on an hourly basis.

Both the summer and winter Olympic games have become important venues for testing and comparing nowcasting approaches. During the 1996 summer Olympics in Atlanta, mesoscale models were run every three hours, and a high frequency of weather bulletins, tailored to the needs of the various sports and venues, were provided (Rothfusz et al., 1998). The 2000 summer Olympics in Sydney brought the first testing of a wide range of quantitative precipitation nowcasting schemes, all based on radar extrapolation. The Beijing Forecast Demonstration Project during the 2008 summer Olympics included a mix of radar echo extrapolation methods, numerical models, techniques that blended numerical model and extrapolation methods, and systems incorporating forecaster input. Wilson et al. (2010) found that without assimilation of real-time radar reflectivity and Doppler velocity fields to support model initialization, it was very difficult for models to provide accurate forecasts during the 2008 Olympics.

Another important nowcasting testbed has been the Spring Forecast Experiment, a joint effort among NOAA's Storm Prediction Center (SPC), the National Severe Storm Laboratory (NSSL), and the Center for Analysis and Prediction of Storms (CAPS) at the University of Oklahoma, held under the umbrella of NOAA's Hazardous Weather Testbed (HWT) (Coniglio et al. 2010, Kain et al., 2003, 2010). During this annual, one-month experiment a range of high-resolution, state-of-the-art, numerical model and analysis tools are provided to teams of researchers and forecasters making daily short-term predictions of convective systems over the central U.S. Finally, a comprehensive nowcasting testbed has been built for the region encompassing Helsinki, Finland (Koskinen et. al., 2011).

The Nowcasting Revolution

Although interest in nowcasting extends back decades, the coincidence of a number of trends makes it particularly promising today: the communications revolution, the weather data revolution, the data assimilation/numerical modeling revolution, and the adaptive-society revolution. Lets consider these components separately and the considerable synergy of their combination.

The Communication Revolution

Until recently a major roadblock to effective nowcasting was the inability to rapidly distribute weather information to the user community—in their homes, offices, schools, while driving or commuting, and during recreational activities. When television and radio broadcasts, supplemented by newspaper weather pages, were the main communication technologies, distribution of real-time weather information was difficult, and often impossible. NOAA Weather Radio, initiated in 1969, provides basic weather information and warnings from approximately 1000 transmitters around the U.S., with such receivers found in roughly 20% of U.S. households (Ted Buehner, National Weather Service (NWS), private communication). This technology offers excellent coverage over the eastern and central U.S., but with significant gaps over the West. In the 1990s, the spread of the Internet, first through dial-up modems and then through hard-wired connections, furnished an approach for providing real-time weather data to fixed locations. During the past decade the extension of the Internet to cell phones and other wireless connections allowed weather graphics (such as radar loops) and text weather data to reach virtually any location.

But the true breakthrough communication device for weather nowcasting may be the smartphone and the robust data rates increasingly available with them. It would be hard to imagine a better device for distributing weather information and for building portable weather applications. Smartphones (Figure 1) generally possess high-resolution screens for easy viewing of complex graphics, as well as high bandwidth communications either through cell phone networks or local wireless (Wi-Fi) links, allowing the distribution of imagery, model output, and other data. Modern smartphones possess substantial computational capacity and most keep track of their current location, either using cell tower triangulation or the Global Positioning System (GPS). Such position information is critical: with it, smartphones can download and display the meteorological information relevant to their surroundings, including location-specific warnings and forecasts.

Both the Federal government and private industry are moving aggressively to distribute forecasts and warnings through wireless digital technology. For example, the Federal Emergency Management Agency (FEMA) has begun the nationwide implementation of the Personalized Localized Alerting Network (PLAN) that will provide site-specific warnings of major weather hazards through cell phones and smartphones. As described later, a number of private sector vendors have developed the capabilities to provide local warnings and associated weather information through text messages and smartphone applications (apps).

Improved communication technologies applicable for nowcasting location-specific information are not limited to smartphones and wireless networks. For example, electronic readerboards have become widespread along many of the nation's roadways (Figure 2). Such electronic signage could provide warnings about dangerous weather ahead or control the speed of traffic to facilitate safe travel through or around inclement weather, such as heavy precipitation, roadway icing, strong winds, or reduced visibility.

Social media, such as Facebook and Twitter, possess substantial potential for the distribution *and* collection of nowcasting information. Twitter, with its ability to identify the location of a message (geotag), is ideal for providing short storm reports or other weather information from the field. Furthermore, Twitter can be used to broadcast immediate, terse warnings and forecast information to large groups. Facebook has been used by both the National Weather Service (NWS) and Environment Canada to provide weather warnings, as well as nowcasts. By using RSS (Really Simple Syndication) or SMS (Short Message Service) feeds, users can be notified of and secure real-time weather updates from Facebook or other social media sites.

The Weather Data Revolution

Effective nowcasting demands a high density of weather information, particularly at the surface. During the past several decades there has been an exponential increase of real-time surface data so that tens of thousands of observations are now available across the U.S. each hour (NRC 2009). In addition to the backbone network run by the Federal Aviation Administration (FAA) and the NWS at U.S. airports, utilities, departments of transportation, air quality agencies, television stations and others have installed weather networks with real-time communication. In addition, many individuals have installed high-quality weather instruments and made the data available through the Internet using services such as the *WeatherUnderground*. As an illustration, at the University of Washington, data from over seventy networks are collected in real-time, with typically 3000-4000 observations gathered each hour for Washington and Oregon alone (Figure 3). A major development has been the NOAA Meteorological Assimilation Data Ingest System (MADIS) in which more than 60,000 observations from local, state, and federal agencies, as well as numerous private networks, are collected, quality-controlled, archived and distributed.

The mesoscale weather data revolution is not limited to surface observations. Instrumented commercial aircraft, reporting through the ACARS (Aircraft Communications Addressing and Reporting System) and TAMDAR (Tropospheric Airborne Meteorological Data Reporting) systems now provide numerous soundings at airports around the country during ascent and descent (Figure 4). The U.S. Doppler radar network (Weather Surveillance Radar 1988 Doppler, WSR-88D) not only provides reflectivity and Doppler winds, but is now installing dual-polarization capabilities, allowing precipitation type and improved rainfall estimates. The Constellation Observing System for Meteorology, Ionosphere and Climate (COSMIC) GPS-based satellite network, soon to be expanded, provides high-quality soundings around the world, with hundreds across North America each day. Finally, the upcoming Geostationary Operational Environmental Satellite (GOES-R) will contribute a large increase in the amount of lightning data worldwide through the deployment of the Geostationary Lightning Mapper (GLM). Furthermore, the Advanced Baseline Imager (ABI) on GOES R will provide full disk coverage from 16 channels with 5 minute temporal resolution and "flex modes" that could provide 30 second coverage for mesoscale events.

These new data sources will provide a greatly enhanced capability to describe mesoscale structures over land, as well as improved data availability over the oceans. Such observations will greatly facilitate nowcasting since they provide a dramatically improved mesoscale description of what is happening now, and through extrapolation, data assimilation and modeling, what will occur during the next few hours.

High-Resolution Forecasting and Mesoscale Data Assimilation Advances

Data assimilation, the synergistic marriage of observations and models, has advanced rapidly during the past decades. On the synoptic scale, massive increases in the quantity and quality of satellite observations, coupled with data assimilation approaches such as Three Dimensional Variational Data Assimilation (3DVAR) (Derber et al. 1991) and Four Dimensional Variational Data Assimilation (4DVAR) (Rabier et. al., 2000) has led to greatly improved synoptic-scale analyses and forecasts. Such refined synoptic-scale guidance has led to improved high-resolution forecasts, since mesoscale models usually receive their initial and boundary conditions from larger-scale models.

On the mesoscale, limited-area operational models have increased greatly in resolution, with many real-time prediction systems now using grid spacings of 4-12 km. Thus, for the first time operational mesoscale models possess or will soon possess the necessary resolution for resolving local features from convection to topographic flows. The skill of these high-resolution operational forecasts has been further enhanced by substantial improvements in model physics (e.g., microphysics and land-surface models) as well as rapidly increasing volumes of mesoscale data, as noted previously in this paper.

New ensemble-based data assimilation approaches, such as the Ensemble Kalman Filter (EnKF), offer the potential for major improvements in mesoscale data assimilation (Torn and Hakim 2008). Such ensemble data assimilation methods provide flow-dependent background error covariances on the mesoscale that relate different variables and are physically realistic, unlike the static, simplified convariances used in current methods such as 3DVAR. Mesoscale EnKF systems are being tested at a number of U.S. universities (e.g., Zhang et al 2009, Ancell et al. 2011) and have shown great promise compared to current operational data assimilation/nowcasting systems that use 3DVAR. EnkF and related ensemble-based data assimilation systems (such as hybrid systems that use EnKF covariances for distributing observation influence in space, but apply nudging or variational approaches in time) hold great promise in the more effective use of increasing amounts of mesoscale observations (Liu 2011). Ensemble-based data assimilation also has the advantage of providing *both* probabilistic analyses and forecasts. As nowcasting matures during the next decade, information about analysis and forecast uncertainty will become more central for a wide variety of products and applications.

As noted earlier, operational high-resolution data assimilation and short-term forecasts are now available in the U.S. from the RUC system, which includes hourly data assimilation and frequent short-term forecasts on a 13-km grid (Benjamin et al 2004). During 2012 RUC will be replaced by the more advanced Rapid Refresh (RR) system over an expanded 13-km domain using the Weather Research and Forecasting (WRF) model (Skamarock et al., 2005), and by 2015 a High-Resolution Rapid Refresh (HRRR) domain (Smith et al 2008) will downscale RR to 3-km over the U.S. These developments will lead to nowcasting supported by far better mesoscale analyses and short-term predictions.

The Adaptive Society Revolution

The advances in computation and communication that make improved nowcasting possible also allow society to react more quickly and effectively to weather challenges.

For example, when radar or other observational assets indicate inclement weather over roadways (e.g., heavy precipitation, icing, dust storms), dynamically changing readerboards and speed signs, as well as flow management systems, can control the speed and number of cars. The proposed FAA NEXGEN air traffic control system foresees the use of real-time weather information to enable aircraft to fly more efficiently and safely through the nation's airspace, adapting their routes and speed in response to the changing environment. The coordination of power generation by weather-dependent renewables (e.g., wind and solar) and reserve power sources (e.g., gas turbines or hydro) can be closely controlled in real-time based on weather observations and short-term forecasts, while "smart grid" technologies in homes can modify electrical demand. Local municipalities can use short-term forecasts of heavy precipitation to mitigate sewer overflows and to protect vulnerable low-lying areas, while departments of transportation can position trucks and material as well as preparing roadways in advance when snow or icing conditions are imminent. These and many other examples illustrate a key fact: improvements in control and communications now allow industry, government, and the general population to adapt based on real-time weather information in a way that would have been impossible a decade ago. Even decisions about recreation and ordinary daily tasks (e.g., bicycle commuting) can be informed and improved by enhanced weather guidance provided through the new forms of communication.

Moving Towards An Effective Nowcasting Capability

With the potential for nowcasting growing rapidly and the essential technologies in place, there is a range of specific initiatives that could make the effective use of such short-term weather guidance a reality. This section will describe three: changes in the

National Weather Service, new approaches by the media, and the development of a next generation of nowcasting applications (apps) for portable electronic devices. Finally, one additional requirement is noted: the need for social scientists to define the best approaches for communicating short-term forecasting information and for eliciting the most effective responses in the population.

A Change of Direction for the National Weather Service

The unfolding of the nowcasting revolution and the rapid evolution of weather prediction technology suggests a more effective approach for the use of NWS resources and personnel. NWS forecasting operations are based around a 6-h cycle, which corresponds with the normal frequency of forecast updates. In most offices, the bulk of forecaster time is spent preparing gridded forecasts out to 168 hr at either 6-h or 3-h time resolution (hazards are described at 1-h intervals to 72h). These grids, prepared at either 5 or 2.5 km grid spacing, can be updated as needed, with forecasters responsible for revising hundreds of grids on a typical shift. When the potential for threatening weather exists, forecasters often put less effort into the grid updates as they prepare special statements, advisories, watches, or warnings as frequently as required.

The basic 6-h forecast update cycle, and the tendency to maintain forecast consistency, sometimes results in short-term forecasts being at odds with observed weather. Furthermore, important local weather details, which can change rapidly, are sometimes not mentioned or discussed in forecast products, especially during active weather periods. Thus, in quickly changing weather situations, the public and other users often are unaware of significant changes in local weather that could benefit their decision-making. As a result, only highly educated users, familiar with weather technologies and the interpretation of weather observations (radar, satellite, etc.) are in a position to make optimal weather-based decisions.

Not only are short-term forecast needs sometimes unmet, but some studies (e.g., Baars and Mass 2005) suggest that forecaster contributions are on-average modest beyond 6-12 h due to the increasing skill of numerical weather prediction and post-processed model output. It appears that humans can improve significantly over raw model output for extreme precipitation events for multi-day forecasts, with only a small improvement over Model Output Statistics (MOS) for non-extreme variables such as maximum temperature (David Novak, Science and Operations Officer, Hydrometeorological Prediction Center, 2011, personal communication). The ability of humans to interpret satellite and radar imagery and to make useful short-term forecasts is unequalled by any automated system, a situation that should not change for many years. Thus, the short-term period (0- 3h) is one in which subjective approaches make the most sense. Beyond 3-6 hr, when there is rapid growth in mesoscale uncertainty, probabilistic prediction, mainly dependent on post-processed ensemble forecasts, is clearly the direction the National Weather Service must take, and the value in human intervention in such probabilistic forecasting is uncertain.

An alternative vision of a future National Weather Service forecast office is one in which forecasters spend much of their time on 0-6 hr nowcasting, with longer-period predictions transitioning to objective, model-based guidance; the main exception to this approach would be during extreme, highly unusual events. In the new operations schedule, forecasters would provide at least hourly nowcasts of the current weather situation and how the situation was expected to evolve during the next few hours in a variety of formats, including hourly gridded analyses/forecasts through 6-hr and prose descriptions. Furthermore, a regular oral/video discussion could be available over the Internet (and accessible through computers, tablets and pad, smartphones, and other units). During particularly fast-changing and significant weather, update frequency would increase, as it does today for tornadic situations. In this approach forecasters would be spending the bulk of their time on what they do best: coupling the extraordinary graphical interpretation capabilities of humans with an understanding of weather systems, and *communicating* this information to other humans. The transition towards greater forecaster intervention in nowcasting will produce enhanced forecaster situational awareness for short-period, local weather events. This transition should be accompanied by more emphasis on enhanced communication approaches for short-term forecasts, including NWS apps for smartphones and other digital devices.

A reviewer of this manuscript asked why the National Weather Service, supported by public resources, should provide nowcasting services through new technologies, when "the private sector weather industry is already doing this and doing it well." This can be answered in several ways. First, it is not clear that the private sector is doing this task uniformly well, though there have been some attempts by television outlets and private sector firms to provide some nowcasting services. But in any case, the NWS is now forecasting at all time scales and will continue to do so. As technology changes, the optimal role of humans can and will change, and the means of communication will evolve as well. It is not reasonable to expect that the NWS, by law responsible for providing warning capabilities to the entire nation, should be prevented from using the most modern approaches and technologies in fulfilling its mission.

In an enhanced nowcasting environment, warn-on-forecast (WOF) will be increasingly applied when severe weather is predicted (Stensrud et al. 2009). WoF aims to provide longer lead times for severe convective weather than the realizable limit of ~20 minutes from warn-on-detection approaches, thereby helping emergency decision makers. The WoF approach requires the ability to continuously update skillful, high-resolution NWP models, a direction consistent with the marriage of data assimilation and high-resolution modeling noted above.

A New Paradigm for the Broadcast Media

The trend towards nowcasting should lead to a very different broadcast day for television weathercasters. Television weathercasting is dominated by regular broadcasts during commute periods, lunchtime, and during the late evening. Generally limited to 2-3 minutes, television weathercasts usually provide a broad, but superficial, description of recent weather, short-term local forecasts, and an outlook for the days and week ahead. The only exception to this schedule is during truly severe weather (e.g., tornadoes) when local television stations often go into nowcasting mode, providing continuously updated descriptions of severe storm evolution using radar, spotters, and occasionally traffic helicopters. Such severe-storm nowcasting has proven to be highly effective during several major convective outbreaks (Smith 2010). Local radio stations often provide frequent weather reports, frequently coupled with traffic information; updated weather information could be enhanced on such regular segments, including their provision by meteorologists rather than untrained news staff.

As viewers increasingly use automated websites to garner forecast information and probabilistic weather predictions, the latter being difficult to communicate on-air, television weathercasters might well shift to providing frequent (perhaps every half hour) local nowcasts so people could have continuously updated information for planning their lives. Such nowcasts could be available on air and online through web sites or smartphones. Clearly, the future of commercial weathercasting lies in the seamless integration of broadcasting, Internet, and wireless modes of communication.

Nowcasting Applications: Some Examples

The availability of dense networks of mesoscale observations, high-resolution data assimilation and modeling, and high-bandwidth modes of communication makes possible a whole range of powerful approaches for disseminating nowcasting information. This section will review some nowcasting applications available today, with particular attention to those created for the Pacific Northwest, and will discuss potential avenues for innovation.

Internet-Based Nowcasting

During the past decade, a number of groups have developed nowcasting web sites in support of a variety of weather-related activities. For example, the NWS Aviation Weather Center (AWC) maintains a *Flight Path Tool* that provides a real-time view of current and future weather conditions aloft across the United States, including user-defined flight paths (http://aviationweather.gov/adds/flight_path/). AWC also supports the online *Aviation Digital Data Service (ADDS)*, which makes available text, digital and graphical short-term forecasts, analyses, and observations of aviation-related weather variables to the aviation community. Staff at the University of Washington has constructed a collection of Internet-accessible nowcasting applications to serve as prototypes for the automated delivery of weather information relevant to short-term decision-making. An example is a series of web pages developed for the Washington State Department of Transportation (WSDOT) for major travel routes across the state. One such route covers Interstate 90 from Seattle eastward across the Cascade Mountains (Figure 5, available in real-time at http://i90.atmos.washington.edu/roadview/i90/). At the top of the page is a series of cams illustrating current weather conditions along the route (click on any of them to see a larger image and time-lapse video for that location). The lower portion presents the topographic cross section for the roadway. Observed surface conditions are shown at weather stations and roadway temperatures, calculated using an energy-balance model, are shown by colors. Using radar and satellite data, as well as surface observations, the weather conditions (clouds and precipitation) along the route are indicated by appropriate icons. Clicking on any route location provides the latest National Weather Service forecast, and selecting forecast conditions on the left provides future forecasts along the route based on high-resolution WRF model output. Finally, real-time pass conditions and snow depth are also available on this page. It is not unusual for this web site to receive hundreds of thousands of hits per day during winter-weather conditions.

A number of states offer real-time weather and surface conditions for major state highways through the 511 SafeTravel consortium, using technology developed by

Meridian Environmental Technology, Inc. For example, a web page provided by the Montana's Department of Transportation shows real-time road conditions (e.g., wet, slushy, icy, windy) and information on accidents and road closures (Figure 6)

Another Northwest U.S. example of a dedicated nowcasting site is *RainWatch*, run at the University of Washington for Seattle Public Utilities (SPU). Following the tragic death of a woman in her basement during a period of intense urban flooding and responding to the need for better management of surface run-off during extreme precipitation events, SPU joined with the University of Washington to create a real-time precipitation application (Figure 7) that helps protect public safety and reduces economic loss associated with short-term precipitation events (http://www.atmos.washington.edu/SPU/). *RainWatch* begins with NEXRAD Level-2 data from the NWS Camano Island radar and a standard Z-R relationship to determine precipitation intensity. This precipitation intensity information, available every 6 minutes, is then calibrated using high-quality rain gauge information, provided by SPU and others. The spatial distributions of precipitation totals for the past 1, 6, 12, 24 and 48 h are available in real time, as well as one-hour forward temporal extrapolations. A variety of precipitation intensity criteria are used for an alarm function of RainWatch, which emails operational SPU personnel when specified thresholds are met.

Smartphone Apps

There is a wide range of smartphone weather apps available today, and an increasing number of them deal with weather nowcasting. Currently, over one thousand weather-related apps are available for iPhone or Android smartphones. A number of them allow viewing of local observations, the latest radar image, or the updated forecast for a specified location. Several take advantage of GPS or cell-tower navigation to determine the appropriate observations or forecasts to display (e.g., *WeatherBug Mobile*). These first-generation weather apps are quite useful, but much more is possible. For example, the *WeatherBug Protect* system not only provides warnings for specific locations based on NWS guidance, but also examines nearby observations for problematic conditions and bases warnings on criterion set by the users. A major problem in selecting weather apps is to choose among the huge collection of offerings, with widely varying quality and capability.

One can imagine a range of even more advanced smartphone apps that provide detailed, site-specific weather guidance that reflects the unique requirements of the user. For example, a sophisticated *WeatherProtector*^{TM} app might monitor the weather that will be affecting the location of the smartphone, using time-extrapolated radar/satellite data and information from high-resolution data assimilation forecasting systems, such as the NWS Rapid Refresh or other advanced data assimilation systems. If dangerous weather is approaching or forecast, or if some preset criterion is reached (e.g., wind over 30 knots, precipitation over .25 inches), the user would be warned. Even more advanced versions could make use of probabilistic forecast guidance, providing the odds of specific weather conditions occurring.

Another possibility might be *AvalancheGuard*: This app would follow a skier's progress in the mountains and provide warnings if they are entering an area of avalanche danger. This app would work by examining high-resolution terrain data and real-time information on the depth/stability of the snowpack and meteorological conditions.

GardenKeeper could use calibrated radar data, weather observations, and forecasts (of temperature, wind, precipitation, sunshine) to tell when watering was necessary at some location. The types of plants concerned and the exposure of the garden could be entered to enhance the app's performance. Furthermore, this app could use forecasts to warn when freezing conditions are imminent during the winter and when certain plants should be mulched or covered. Clearly, the potential of weather apps on smartphones, working with high-resolution meteorological databases, is enormous and could be the basis of significant new businesses.

The Need for Social Science Research

Nearly as important as collecting reliable nowcasting information and producing dependable short-term forecast guidance is finding the means to effectively communicate rapidly changing weather situations and eliciting an effective response during threatening weather. As shown by the catastrophic tornado outbreak of April 26, 2011, the Joplin tornado of May 24, 2011, or the landfall of Hurricane Katrina, substantial loss of life and injury can still occur even with excellent nowcasts and short-term forecasts. Accurate information must not only be delivered rapidly to vulnerable populations, but must be clear, unequivocal and designed to provoke the correct actions. Furthermore, with the wide availability of raw weather information is there a threat of untrained individuals misinterpreting and misusing such information? An effective nowcasting system thus requires appropriate social science research to determine best communication practices. There has been little social science research on the nowcasting problem (Jeff Lazo, personal communication, 2011) and this deficiency must be addressed by NWS, the

National Oceanic and Atmospheric Administration (NOAA) and the National Science Foundation (NSF) support of psychologists and other social scientists.

A Nowcasting Test

The author put the nowcasting concept to the test during the winter of 2010-2011 using his blog (http://cliffmass.blogspot.com), which typically receives approximately 6000 unique page views per day. A snow event was forecast on February 23, 2011 and an announcement was made on the blog early that day that a detailed update would be made every few hours during the afternoon, with particularly detailed guidance right before and during evening rush hour. As documented in Figure 8, the response was enormous, with nearly 120,000 page views that day and over ten thousand an hour during the afternoon commute. Blog readers emailed or commented blow-by-blow accounts of the approaching snow and resulting driving conditions, information that was quickly communicated to others through the blog. Clearly, there is a considerable appetite and need for more detailed nowcasting information during major weather events, and certainly the same is true for severe convection and other types of major storms.

Concluding remarks

Today, the meteorological community faces an enviable problem: how to deal with a huge influx of weather data, rapid improvements in numerical modeling and data assimilation, and extraordinary enhancements in our ability to communicate weather information to individuals at nearly any location. Accompanying these capabilities is a society increasingly able to avoid or adapt quickly to weather-related stresses and dangers. The challenge during the next decade will be to combine the rapidly developing technologies of weather prediction and communication to create an effective nowcasting infrastructure. To do so will require changing the way the weather prediction enterprise does business, a change more profound than any since the advent of numerical weather prediction. It will also mean that human forecasters will increasingly rely on objective guidance for the longer-period forecasts in order to release time for the challenges of short-term, local nowcasting. The potential of this integration of data availability, numerical weather prediction, and communication are enormous, and could lead to the development of new weather-related businesses and applications that will save lives, enhance economic productivity, and improve quality of life.

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Figure Captions

Figure 1: Smartphones provide high-resolution graphics, robust communications, substantial computation capabilities, and location information.

Figure 2: Highway readerboards provide rapid communication of roadway conditions and the control of speed limits.

Figure 3: Surface weather observations collected at the University of Washington for the hour ending 1800 UTC 10 February 2011.

Figure 4: ACARS aircraft observations between 0100 UTC and 0459 UTC 9 February 2011. Heights (kft) indicated by color shading.

Figure 5: I-90 route page, produced in real-time by the University of Washington for the Washington State Department of Transportation.

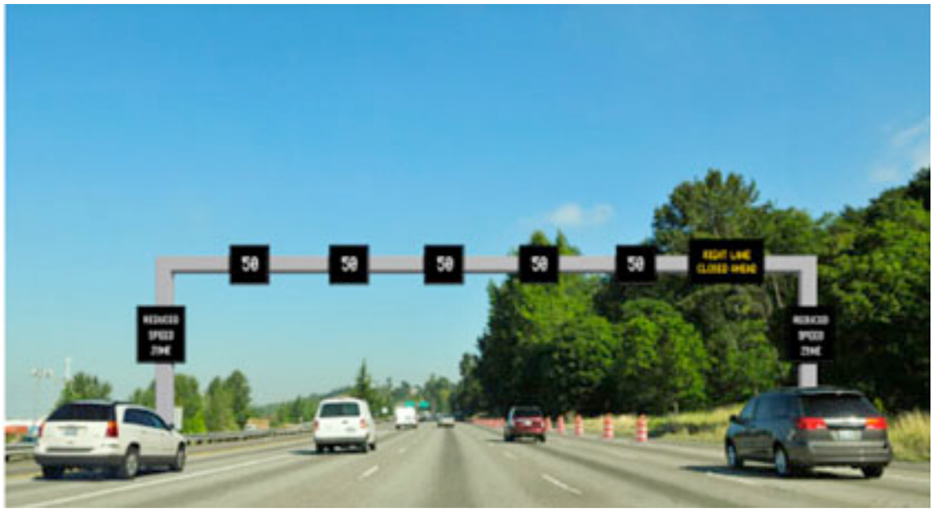
Figure 6: A web page provided by the Montana's Department of Transportation shows real-time road conditions and information on accidents and road closures

Figure 7: Seattle RainWatch, built by the University of Washington for Seattle Public Utilities, provides regional precipitation information based on calibrated radar data.

Figure 8: Number of page loads (green), unique visits (blue), and returning visits (yellow) to cliffmass.blogspot.com during a major snow event during February 2011.

Current Conditions Radar Forecast

Figure 1: Smartphones provide high-resolution graphics, robust communications, substantial computation capabilities, and location information.



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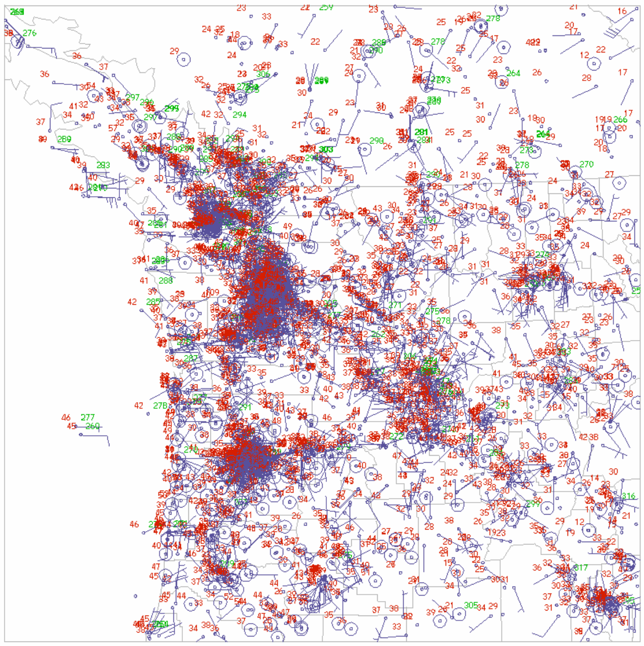
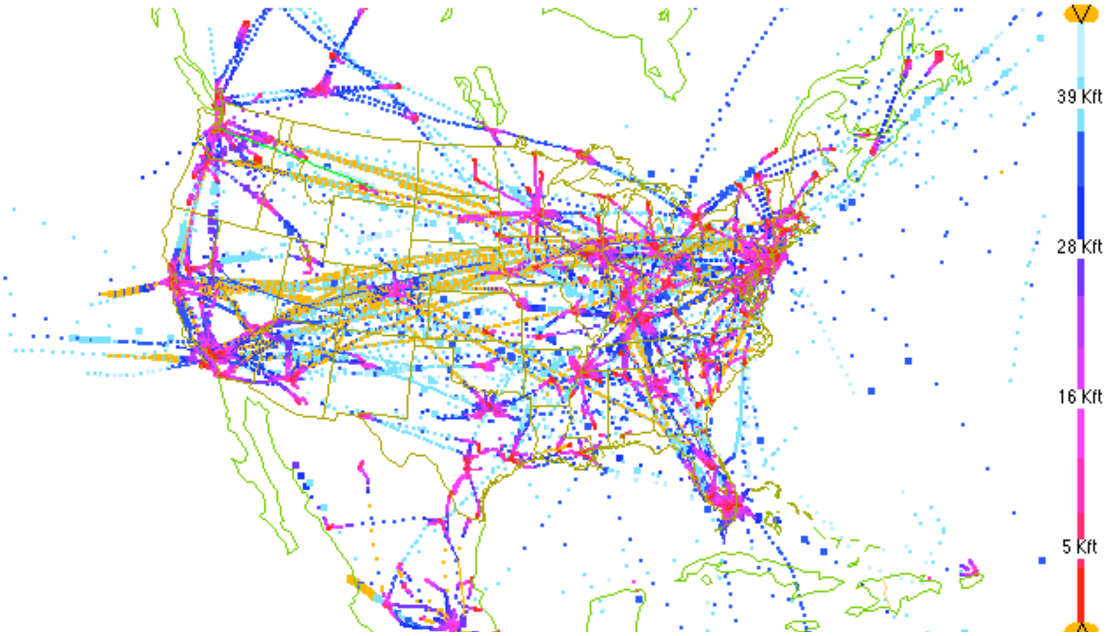


Figure 3: Surface weather observations collected at the University of Washington for the hour ending 1800 UTC 10 February 2011



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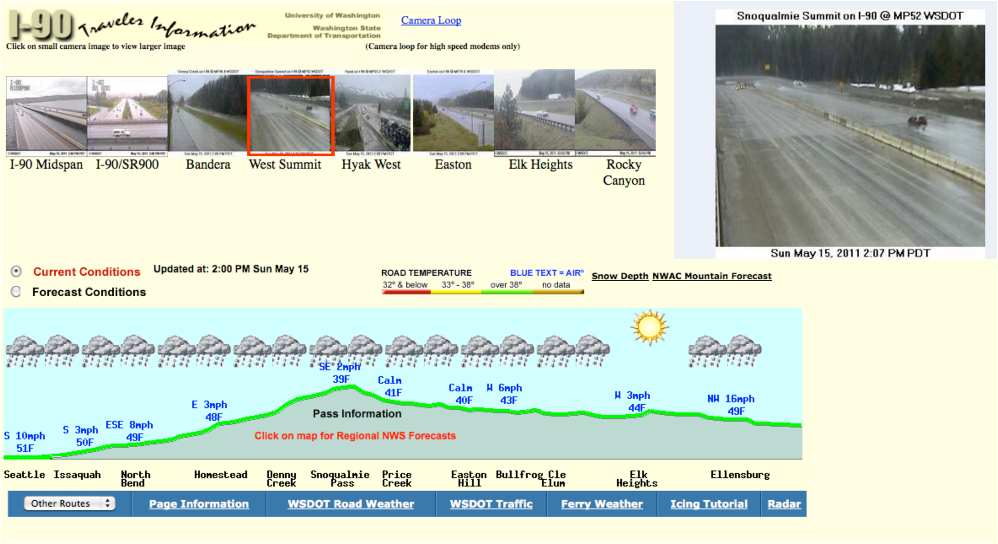


I-90 Traveler Information

Click on small camera image to view larger image

(Camera loop for high speed modems only)

Snoqualmie Summit on I-90 @ MP52 WSDOT

Sun May 15, 2011 2:07 PM PDT

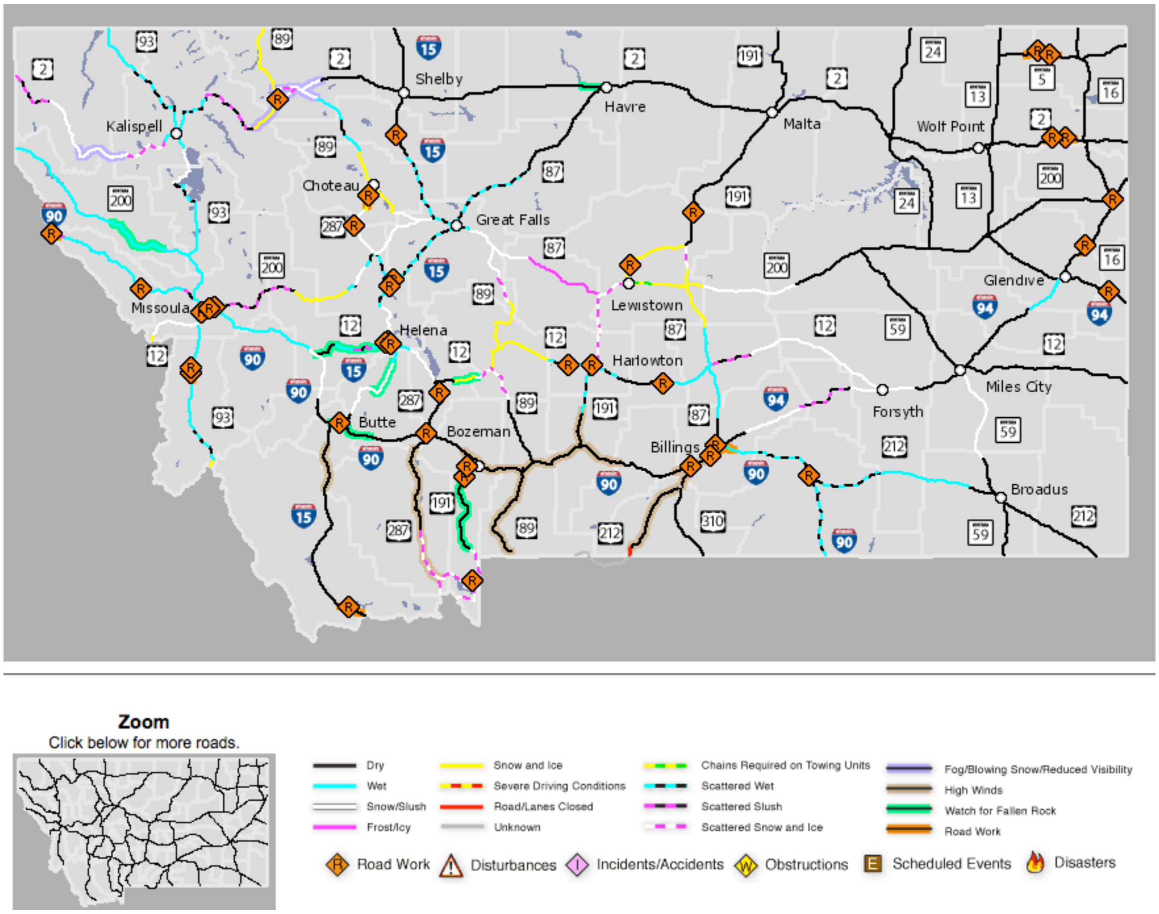
● Current Conditions

○ Forecast Conditions

Updated at: 2:00 PM Sun May 15

Click on map for Regional NWS Forecasts

Figure 5: I-90 route page, produced in real-time by the University of Washington for the Washington State Department of Transportation



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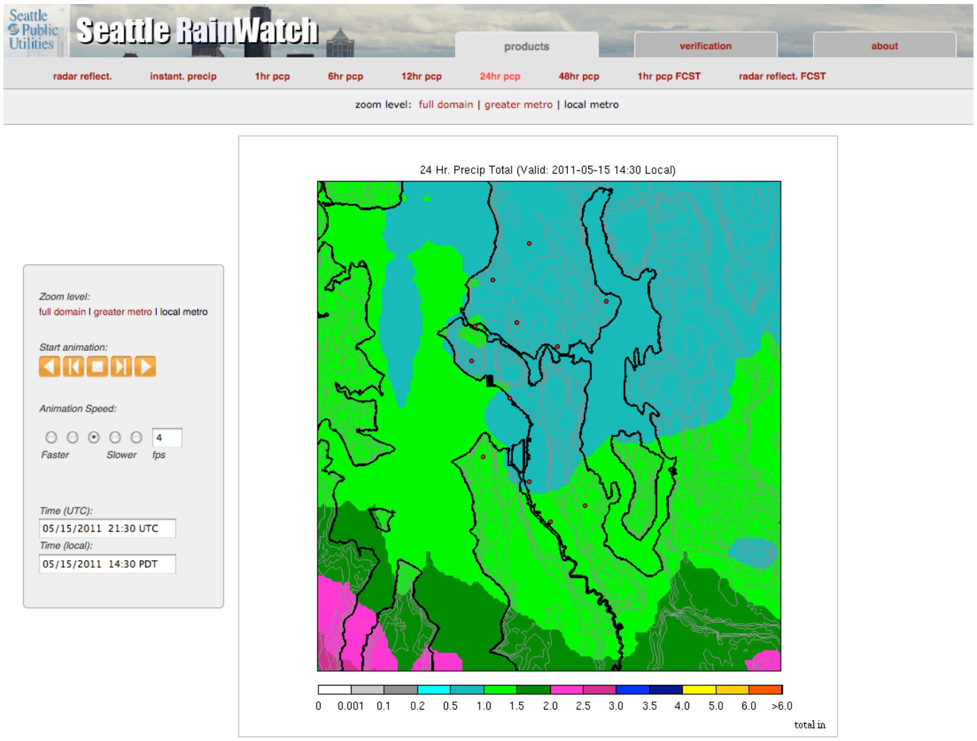

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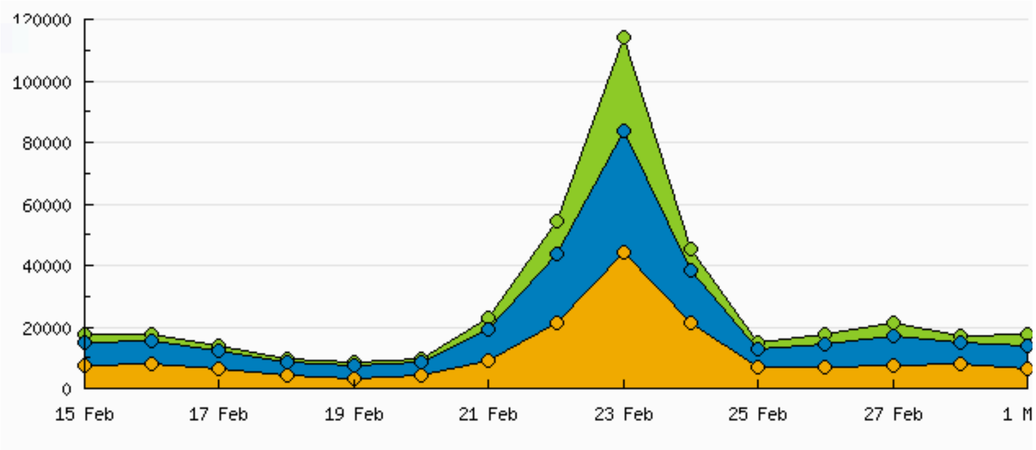

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