Nowcasting: The Next Revolution in Weather Prediction

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Short BAMS 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.

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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, has made the distribution and application of real-time weather information possible nearly anywhere. Rapid increases in the volume and quality of surface, aircraft, and remote sensing data now provide a continuous description of atmospheric conditions from the synoptic to regional scales. New data assimilation approaches offer the potential to more effectively apply mesoscale observations and to produce high-resolution probabilistic 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 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 imagery (e.g., Browning 1982b), increasingly the subject has been broadened by the use of high-resolution numerical models driven by the assimilation of a wide range of mesoscale data (Benjamin et al., 2004).

More 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 continuous description of atmospheric conditions from the synoptic to regional scales. New data assimilation approaches, such as the ensemble Kalman filter (EnKF) technique, offers the potential to more effectively apply mesoscale observations and to produce high-resolution probabilistic 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 will describe these individual advances, the possible synergies of their combination, and how the forecast process might change as a result during the next few decades.

Previous Nowcasting Developments

The earliest work on nowcasting was mainly limited to the use of time extrapolation of meteorological radar data for short-term prediction of thunderstorm motions. Relatively primitive computer-based temporal extrapolation techniques (e.g., Noel and Fleisher 1960) evolved into more sophisticated algorithms for tracking individual cells (Wilson 1977, Wilk and Gray 1970, Barclay and Wilk 1970). The next generation of convection tracking algorithms were not limited to a steady state assumption but allowed for temporal changes in cell intensity and size (Dixon and Wiener 1993). 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-Nowcast System 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 and data availability, mesoscale data assimilation and short-term nowcasting/forecasting have become increasingly useful for nowcasting. One of the first operational implementations of such an approach was the Rapid Update Cycle (RUC), which, in 1994, began running at 80 km grid spacing with a three-hour assimilation cycle (Benjamin 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 developed at the University of Oklahoma Center for Regional Prediction of Storms (CAPS), where real-time mesoscale data assimilation was used to drive high-resolution short-term forecasts of their Advanced Regional Prediction System (ARPS) model (Wang et al., 1996, Xue 2003), with particular emphasis on nowcasting of convective systems.

Several other operational systems have been developed that combine observational 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 resolution 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).

Both the summer and winter Olympic games have become important venues for testing and comparing nowcasting approaches. The first such nowcasting experiments took place during the 2000 summer Olympics in Sydney, where a wide range of quantitative precipitation nowcasting schemes, all based on radar extrapolation, were tested (Pierce et al., 2004). 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. More recently, permanent nowcasting testbeds unconnected with major sporting events have been established. For example, a comprehensive 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, and the data assimilation/forecasting 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 distribution of the 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. 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 allowed primitive weather graphics (such as radar loops) and limited text weather data to reach virtually any location. But the true breakthrough communication device for weather nowcasting is 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 communication either through contemporary cell phone networks or local WIFI, allowing the distribution of imagery, model output, and other data. Modern smartphones possess substantial computational capacity and virtually all keep track of their current location, either using cell tower triangulation or GPS. The position information is critical: with it, smartphones can download and display the meteorological information relevant to their surroundings, including site-specific warnings and forecasts.

Both the Federal government and private industry are moving aggressively to distribute forecasts and warnings through wireless technology. For example, the Federal Emergency Management Agency (FEMA) has begun the nationwide implementation of the Personalized Localized Alerting Network (PLAN) that will allow 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 weather information through text messages and smartphone applications (apps).

Improved communication technologies applicable for nowcasting 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 provides warnings about dangerous weather ahead or can actually control the speed of traffic to facilitate safe travel through or around inclement weather.

Social media, such as Facebook and Twitter, possess substantial potential for the distribution *and* collection of nowcasting information. Twitter, with its ability to geotag the location of a message, is ideal for providing short storm reports and weather information from observers. In turn, 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 and Environment Canada to provide weather warnings, as well as provide nowcasts for the near-term. 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 available across the U.S. each hour (NRC 2009). In addition to the backbone network run by the 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 then made the resulting data available through the Internet using services like 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).

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 aircraft ascent and descent (Figure 4). The U.S. Doppler network (WSR-88D) will soon gain dual-polarization capabilities, allowing precipitation type and improved rainfall estimates. The COSMIC GPS satellite network, soon to be expanded, provides hundreds of high-quality soundings each day across the U.S. and the new GOES-R geostationary satellite system will contribute a large increase in the amount of lightning data worldwide.

The combination of these new data sources will provide a hugely 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 description of what is happening now, and through data assimilation and modeling, what will occur during the next few hours.

The Data Assimilation and High-Resolution Forecasting Revolutions

Data assimilation, the synergistic marriage of observations and models, has advanced rapidly during the past decade. On the synoptic scale, massive increases in the quantity and quality of satellite observations, coupled with new data assimilation approaches such as 4DVAR and enhanced 3DVAR, 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 greatly increased in resolution, with many real-time predictions now using grid spacings of 4-12 km. Thus, for the first time operational mesoscale models possess the necessary resolution for modeling local features from convection to topographic flows. The skill of these high-resolution operational forecasts has been further enhanced by substantial improvements in models physics (e.g., microphysics and land-surface models) and 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. Such ensemble data assimilation methods provide flow-dependent covariances that relate different variables and are physically realistic, unlike the static, simplified convariances used in current methods like 3DVAR. Ensemble-based approaches also have the advantage of providing both probabilistic analyses and forecasts.

In the U.S., operational high-resolution data assimilation and forecasts are now available from the Rapid Update Cycle (RUC) system, which includes hourly data assimilation and frequent one-day forecasts on a 13-km grid (Benjamin et al 2004). During 2011 RUC will be replaced by the more advanced Rapid Refresh (RR) System over an expanded 13-km domain using the WRF model, with a High Resolution Rapid Refresh (HRRR) domain that will downscale RR to 3-km over the U.S. Mesoscale EnKF systems are being tested at a number of U.S. universities (Torn 2008, Zhang et al 2009), Ancell et al. 2011) and have shown great promise compared to current operational data assimilation/nowcasting systems, such as RUC, that use 3DVAR. EnkF and related ensemble-based data assimilation systems (such as hybrid systems that use the EnKF covariances for distributing observation influence in space, but use nudging or variational approaches in time) hold great promise in making more effective use of increasing amounts of mesoscale observations. The impact of these developments in both mesoscale data assimilation and high-resolution forecasting is that the nowcasting in the near future will have available 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 changes. 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 on roadways. 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. 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. 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 heavy snow or icing conditions are imminent. These and many other examples illustrate a key fact: improvements in control and communications technologies now allow industry, government, and the population in general 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 outline three: changes in the National Weather Service, new approaches by the media, and the development of a new 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 National Weather Service resources and personnel. National Weather Service 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 when possible, sometimes results in 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. 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 an increasingly persuasive literature (e.g., Mass and Baars 2006) suggests that forecaster contributions are often small beyond 6-12 h due to the increasing skill of numerical weather prediction and post-processed model output. The short-term period is one in which subjective deterministic approaches (such as time extrapolation) make the most sense. 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. 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 the bulk of their time on 0-6 hr nowcasting, with longer-period predictions transitioning to objective, model-based guidance. In the new operations schedule, forecasters would provide at least hourly nowcasts of the current weather situation and how things were expected to evolve during the next few hours in a variety of formats: hourly gridded analyses/forecasts through 6-hr, prose descriptions, and an oral/video presentation available over the Internet (and accessible through computers, tablets and pad, smartphones, and other units). During particularly fast-changing and significant weather, updates would occur even more frequently. 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, regional weather events. Furthermore, 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 New Paradigm for the Private Sector Media in Weather Communication

The trend towards nowcasting should lead to a very different broadcast day for television weathercasters. Television weathercasting is dominated by regular broadcasts during commute times, lunchtime, and during the 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).

As viewers increasingly use automated websites to garner forecast information and probabilistic predictions, which are difficult to communicate briefly on-air, television weathercasters might well shift to mainly 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 computers or smartphones.

New Approaches for Dissemination of Weather Information

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.

<u>Internet-Based Nowcasting</u>

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 University of Washington has constructed a collection of Internet-accessible nowcasting applications to serve as prototypes for the delivery of weather information relevant to short-term decision making. One example is a series of “route 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 a day during winter-weather conditions.

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 6) 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 on an hourly basis 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 the alarm function of RainWatch, which emails operational SPU personnel when the thresholds are met.

The University of Washington has also built *WindWatch*, which provides high wind warnings based on either NWS forecasts or WRF model predictions (http://www.atmos.washington.edu/SCL/), for Seattle City Light (SCL) personnel, and is now building *SnowWatch*, to guide the Seattle Department of Transportation in advance of significant snow events.

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 specific 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, particularly if a smartphone can access a database of analyses and forecasts, or can acquire information based on the location and requirements of the user. A few vendors are working on this type of second-generation apps, such as the *WeatherBug Protect* system that not only warns for specific locations based on NWS predictions and warnings, 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 to the user. For example, a sophisticated *WeatherProtector™* app might watch 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 NCEP 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 inclement weather occurring.

Another possibility might be *AvalancheGuard* ™: This app would follow your progress in the mountains and provide warnings if you 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*™ would use calibrated radar data and past/current/future weather information or forecasts (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 used 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.

Many other weather-related smartphone apps are possible. 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 forecasts. Accurate information must not only be delivered rapidly to vulnerable populations, but must be clear, unequivocal and designed to provoke the correct responses. An effective nowcasting system thus requires appropriate social science research to determine best communication practices. There has been virtually no social science research on the nowcasting problem (Jeff Lazos, personal communication, 2011) and this deficiency must be addressed by NWS, NOAA and 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 around 5000 unique page views per day. A snow event was forecast on February 23, 2010 and an announcement was made early that day on the blog that a detailed updated would be made every few hours during the afternoon, with particularly detailed guidance during the evening rush hour. As documented in Figure 7, the response was enormous, with nearly 120,000 page views that day and over ten thousand each 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. Clearly, there is a considerable appetite and need for more detailed nowcasting information during major weather events such as the February 2011 western Washington snow event, 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 mesoscale weather information, rapid improvements in numerical modeling and data assimilation, and extraordinary enhancements in our ability to communicate graphical information and data to individuals at nearly any location. Coupled to 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.

Acknowledgments

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

Figure 7: Number of page loads (green), unique visits (blue), and returning visits (yellow) to cliffmass.blogspot.com during a major snow event during February 2011.

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

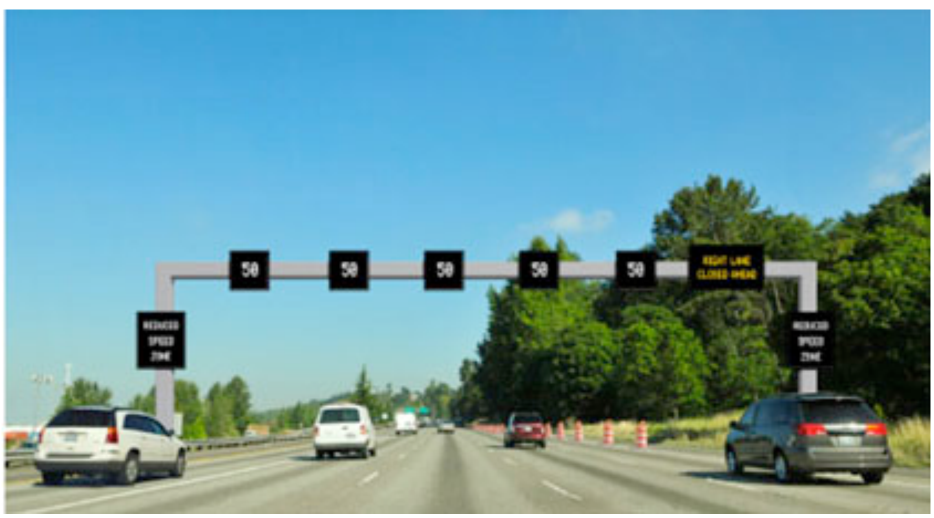

Figure 2: Highway readerboards offer rapid communication of roadway conditions and the control of speed limits.

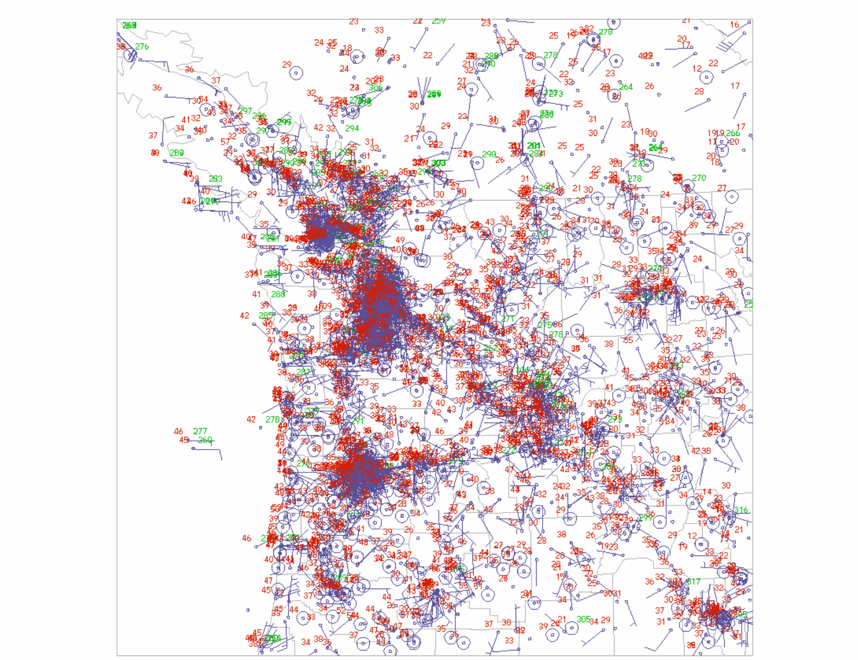

Figure 3: Surface weather observations collected for the hour ending 1800 UTC 10 February 2011

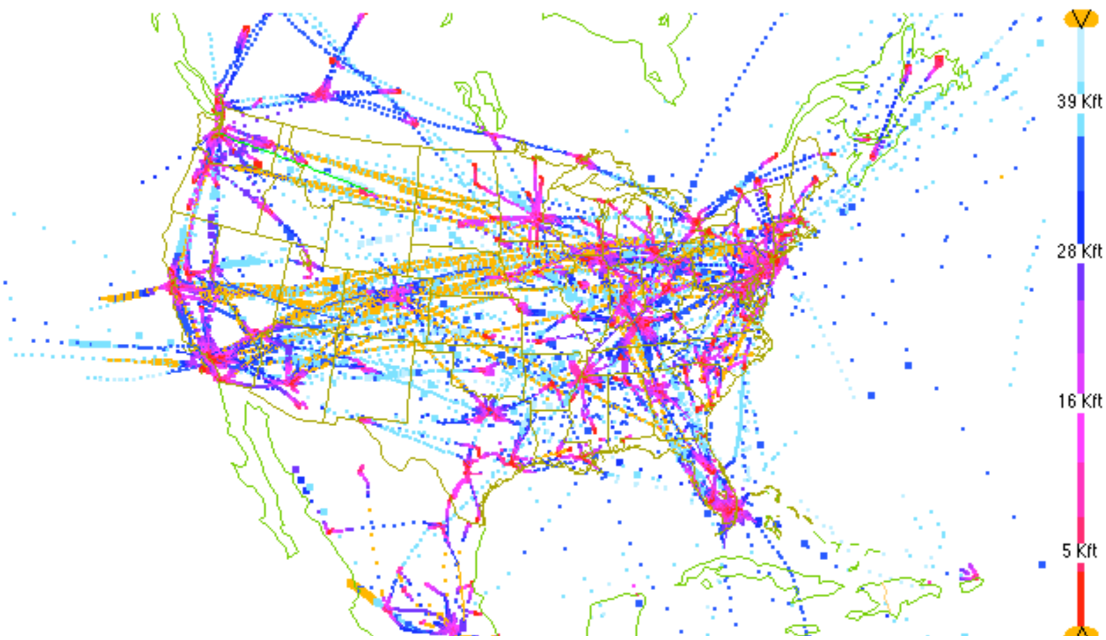

Figure 4: ACARS aircraft observations between 0100 UTC and 0459 UTC 9 February 2011. Heights (kft) indicated by color shading.

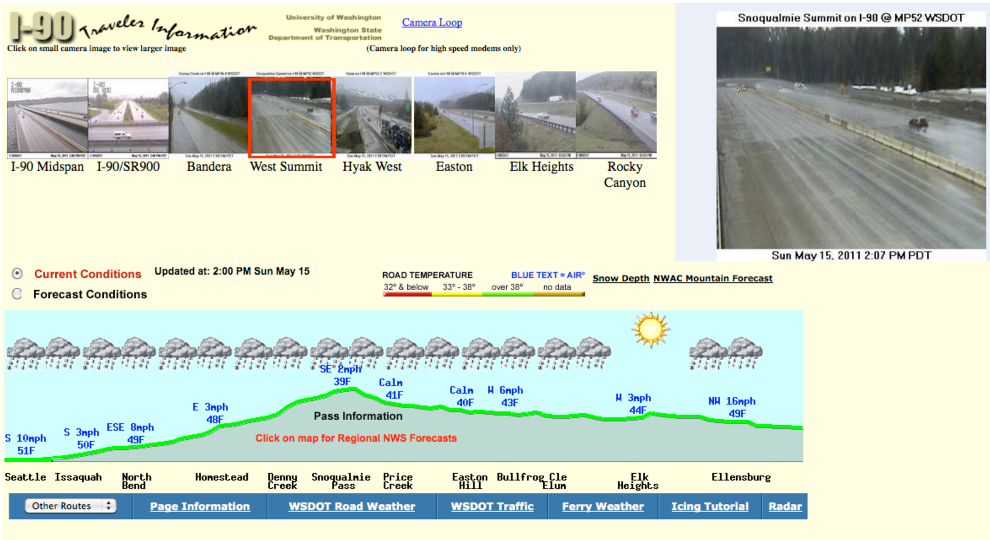

Figure 5: I-90 route page, produced in real-time by the University of Washington for the Washington State Department of Transportation

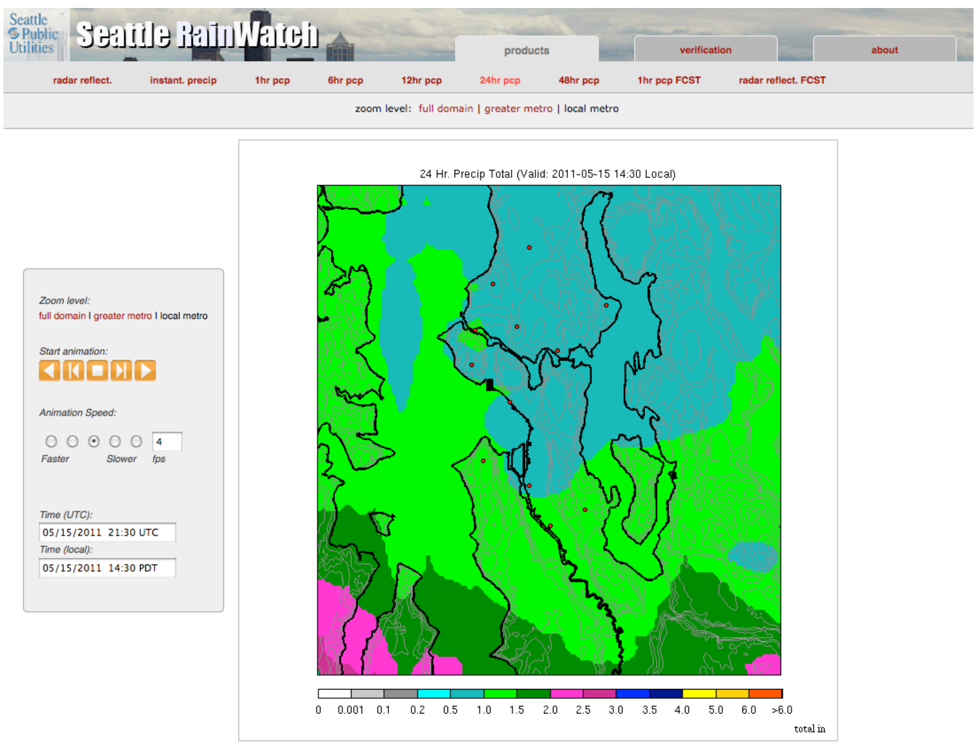

Figure 6: Seattle RainWatch, built by the University of Washington for Seattle Public Utilities, provides regional precipitation information based on calibrated radar data.

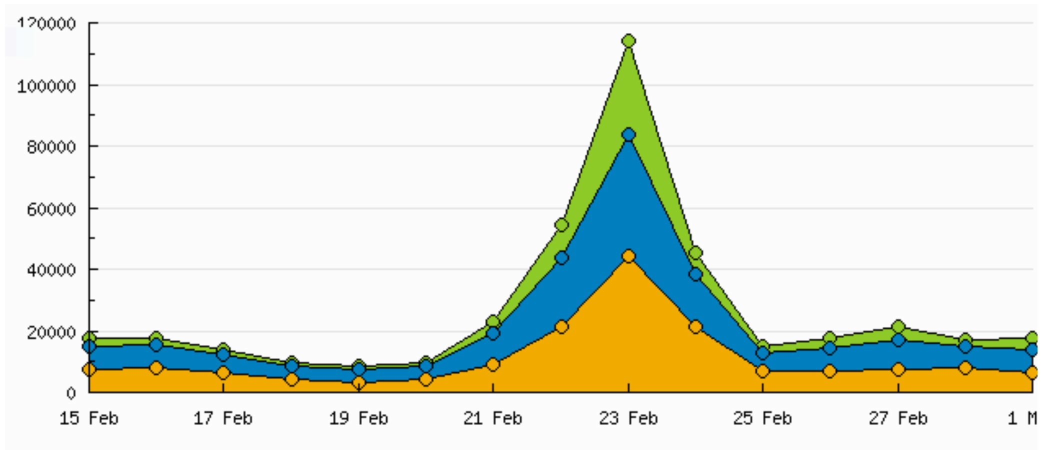

Figure 7: Number of page loads (green), unique visits (blue), and returning visits (yellow) to cliffmass.blogspot.com during a major snow event during February 2011.