4B.1 An Examination of the Life Cycle of Actionable Weather Information

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ABSTRACT

This paper examines the life cycle of actionable weather information from the time raw observations are made to the time a user receives the actionable information. A review of historical advances is provided; specific emphasis is placed on the challenges of providing timely warning information and how different segments or components of the life cycle impact the amount of time available to generate the warning. The life cycle is broken into components and the interactions and contributions of the components are examined with regard to the end-to-end process. Several examples of specific warning types are examined to analyze user impacts.

The analysis of specific warnings includes a look at the types of observations and the time component of assimilating these observational data into differing prediction models. In addition, some warnings rely on the timely dissemination of observational data for geospatial evaluation by a field expert. Each of these prediction processing methods affects the overall actionable weather information life cycle.

A connection between the potential improvements for each portion of the life cycle and the user is also discussed. The emphasis is how to improve each life cycle component to ultimately provide more timely warning information to the end user. The consideration of these improvements will potentially influence further technical studies paving the way for extended lead times and the increased likelihood of protecting life and property.

I. Introduction

The challenges associated with producing weather data products for the end user lie not only in the amount of time required to disseminate these products but also with the entire end-to-end life cycle of weather data observation, data assimilation, numerical modeling, and value added processing. This paper examines this life cycle from a historical perspective and also looks at some of the current challenges associated with shortening the time required to complete the cycle and distribute end user products. A number of past technological and organizational improvements paved the way to the current observational and data modeling methods. However, this paper examines potential areas where advances are possible regarding the use of models and observational methods to improve accuracy and decrease the amount of time required for product distribution. In addition, a summary of potential user benefits to be realized from improving the life cycle is provided. Ultimately, as the historical perspective will show, the user benefits are the primary driving force behind improvements in environmental data processing and end user services.

II. Historical Perspective [1]

The formative years of the United States (U.S.) include seminal weather observations and forecasts. Several of the founding fathers- including George Washington, Thomas Jefferson and Benjamin Franklin- were involved in these activities. These actions led the way to basic instrumentation and limited meteorological observation networks in the early 1800s. However, the organized implementation of observing and forecasting services, like those provided today by the National Weather Service and NOAA, have their roots in both civilian and government activities starting in the middle 1800s. This staring point was primarily an outgrowth of the implementation of the telegraph service, enabling transmission of observations from all over the country to a central location. This combination of instrumentation and a means to collect and distribute data led to the first practical application of operational meteorology.

In 1849 The Smithsonian Institution paved the way for a more widespread and organized observing network by supplying weather instruments to telegraph companies. This led to a network of 150 voluntary observation and reporting stations sending the data directly to the Smithsonian via telegraph. By 1860 the network evolved into 500 stations that included state weather services. These 500 stations sent their reports via telegraph directly to the Washington Evening Star. Eventually a telegraph service in Cincinnati collected the observations and generated charts of the observed data. The need for a more structured approach to collecting the observations and managing the data and charts led to the decision to form a government oversight agency. Thus in 1870 the Secretary of War was chartered by a Joint Congressional Resolution, signed into law by President Ulysses S. Grant, to organize the effort to manage meteorological observations services for much of the country. The resolution also included the provision to notify Great Lakes and coastal regions of approaching storms. This agency was in effect the first U.S. Weather Bureau.

Significant environmental events such as the Johnstown, PA flood of 1889 and the Galveston, TX hurricane of 1900 raised awareness within the government of the Weather Bureau benefits. This led to advancements in organizational management by the government and additional public services. The

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first daily weather map was published in 1895 and a hurricane warning network was established in 1898. In 1901 the Weather Bureau used the Post Office Department to distribute 3-day forecasts for the North Atlantic along with other forecasts such as frost and freeze information. The Marconi Company provided an additional advancement in 1902, the broadcast of maritime forecasts using wireless telegraphy. In 1909, the Weather Bureau organized the free-rise balloon observation program. These two advancements, coupled with the observation network and the forecast distribution services, are largely responsible for establishing the backbone of data dissemination and forecast services provided today by the National Weather Service (NWS).

Additional advancements since the early-to-mid 1900s led to the modernization of both forecast services and observational capabilities. Some of the more significant advancements include the first aviation forecasts in 1918, Coast Guard ocean weather stations in 1940, the U.S. River Forecast Centers in 1946, the first use of a computer and facsimile map transmission in 1948, the Severe Weather Warning Center in 1951, the Joint Numerical Weather Prediction Unit at Suitland, MD in 1954, and the first dedicated weather radar (AN/CPS-9) in 1954.

The era of weather satellite observations began in 1960 with Television and Infrared Observation Satellite (TIROS) 1. With satellite technology a proven capability, the TIROS program advanced to provide Automatic Picture Transmission of worldwide cloud images. In 1967, the new NWS, a part of the Environmental Science Services Administration (ESSA), recognized the value of satellite technology. In 1970 ESSA became the National Oceanographic and Atmospheric Administration (NOAA). Satellite advancements continued under NOAA and in 1975 the first Geostationary Operational Environmental Satellite (GOES) was launched. Advancements in weather radar technology led to the Joint Doppler Operational Project in 1976 which resulted in the current Next Generation weather Radar (NEXRAD) network. In the late 1970s additional modernization was needed to support data storage needs, computational needs, and the increased number of forecast services. The pinnacle of these modernization efforts was the 1979 adoption of Numerical Weather Prediction (NWP) models such as the Nested Grid Model (NGM), the Global Data Assimilation System (GDAS), and the Automated Forecast and Observing System (AFOS).

Critical weather and environmental events from the middle 1970s through the 1990s proved the necessity of these technological advancements. The 1974 Xenia, OH tornado, Mt. St. Helens' eruption in 1980, Hurricane Hugo in 1989, the 1989 solar storm induced power failure and blackout in Canada, Hurricane Andrew in 1992, the "Perfect Storm," and the Mississippi River floods of 1993 all raised public and governmental awareness of the need for accurate and timely environmental warning information to promote personal safety and resource protection. Even more recent events such as the Asian Tsunami of 2004, Hurricane Katrina in 2005, and annual fire dangers in the Western U.S. continue to underscore the need for continued improvements in observational, forecast, and distribution capabilities.

The significance of the historical perspective presented above lies in four main areas: (1) increasing data observation capabilities and quantity; (2) advancements in computing needs and capacity; (3) increased user needs in products and forecast services; and (4) the significant environmental events driving the need for continuous improvements. This paper examines these topics and identifies potential areas for the next generation of improvements.

III. Data Observation and Assimilation

Weather and environmental data observation is the basic foundation of all forms of environmental scientific prediction [2]. Observations form the initial conditions and inputs to the numerical model three-dimensional grids and are processed for the time-phased prediction of the observed environmental parameters. A number of challenges exist with regard to the collection of the basic observational data. The first challenge is ensuring a robust communications network is available to transmit the observations from the source. Considering the observations now are in forms ranging from basic textual data to large satellite data sets, this challenge has a high degree of complexity. Terrestrial and satellite communication networks have evolved remarkably in the last several decades. This allows high-speed transmission of weather and environmental observations to central facilities such as the National Centers for Environmental Prediction (NCEP). These centers assimilate observational data of all types and prepare the data for NWP processing. This initial data preparation is where erroneous observations are discarded or corrected and involves not only statistical methods but also some form of physical evaluation of whether the data is in agreement with general atmospheric dynamic theory. Other methods are used to check data accuracy to ensure the stability of NWP model initial conditions. Modern, super-computing technologies make this critical error checking process possible.

Assimilating environmental data is a huge task if only looked at from the perspective of the raw numbers of observations. Table 1 provides a sample of the observations taken four times a day over the month of January in 2007 as recorded by the NCEP GDAS [4]. Each observing platform transmits their data via communications networks to a collection facility. The communication may be direct, but more likely will include several intermediate switches to pass the data along the route. Once the data are received at the collection point they are placed in a temporary location until the NWP computer is ready to begin the assimilation process. Consider that the numbers in Table 1 are for only one month of data. The amount of archival storage and infrastructure required to manage these data on an annual basis and from year to year is part of the challenge.

January 2007 Sample Observational Statistics	
Data Type	**Number of Observations**
Land Surface	206,611
Marine Surface	47,149
Land Soundings	8,193
Aircraft	144,761
Satellite Soundings	4,738
Satellite Winds	437,910
DMSP SSMI Radiances	692,429
NASA TRMM Data	8,905,131
All Satellites Assimilated	13,933,209

Table 1. Sample GDAS observational statistics from January 2007.

An additional challenge is the growth of these observational data in both size and quantity as additional observation platforms, both surface, airborne, and space-borne, are fielded. Table 1 provides a current reference point, but the obvious realization is that environmental satellite observations will continue to increase in quantity, size, and coverage of the Earth's atmosphere. These satellite observations are used by global models to provide a more realistic initial data snapshot to feed the NWP models. Solutions to this challenge are in the continued modernization of computing technology used to process these large quantities of data and the communication methods used to transmit these data to centers such as NCEP. These improvements will increase the computing capacity and allow even more observations to be assimilated into the NWP models. In addition, the increased computing power decreases the overall assimilation time and also the time to complete the observation to user product cycle. Thus the overall time to process data and produce NWP output for value-added adjustment and communicate decision making information to the end user is decreased.

IV. Numerical Weather Prediction and Value-Added Product Distribution

Numerical weather and environmental prediction schemes and their output accuracy are highly dependent on both computational capabilities and the fidelity of science used in the embedded numerical algorithms. Today these numerical algorithms are highly specialized to account for the changes in domain scale from global models to national models to regional or relocatable models and also for all the different types of environmental prediction. In almost all domains the fundamental basis of NWP starts with initial conditions from the global model coupled with the assimilation of the domain-scale observational data. Once the initial conditions are set, the NWP computer processing takes over to produce the first forward time step of the predicted data and continues with subsequent prediction steps until the model prediction period is complete. Most models also include, as part of the prediction process, a methodology to validate the initial forward time step of data to minimize the errors in the prediction and decrease the potential for propagating these errors over the entire forecast cycle.

Tropical storm prediction models are good examples of how the NWP prediction process works and how the forecaster adds value to the numerical prediction data. Typically the regional tropical model is overlaid on the global model to take advantage of the larger scale general circulation data as the initial conditions. Once these initial conditions are set, the observations from the regional, tropical domain are assimilated into the tropical NWP model and the predictions are completed for the specified model time period. This means the tropical forecaster now has the information needed to identify trends in storm movement and intensity. In addition, with a series of these NWP forecasts produced over a period of time, forecasters can determine trends in accuracy and adjustment from one model forecast to another. This process, formerly a manually intensive process, is now achieved in some instances with computer automation. In addition, to improve the overall NWP process, the use of ensemble models is growing in popularity and operational application [5].

NCEP includes eight different and functionally specific modeling and prediction centers. Each of these centers has a specific suite of NWP models or model products used to support their functional users. The challenge for each of the centers and NCEP as a whole is to continually upgrade not only the computing resources, but also the infrastructure required to operate effectively and meet the growing demands of civilian and government users. This infrastructure includes the capability to generate and disseminate NWP model forecasts and other types of environmental prediction products to the users.

Computing improvements are also providing the capability to take advantage of higher resolution or finer grid scale NWP models. In most cases these high resolution models focus on a particular geographic area such as regions of complex terrain or areas with high severe weather threats. Some high resolution models such as air pollution models look at the local county or city scale and use the local terrain are used to provide highly accurate specialized pollution predictions. These higher resolution models use specialized physical processes in their calculation and require dedicated computing resources to generate forecasts in very short periods of time such as minutes. The rapid forecast output capability is designed to maximize the amount of time decision makers have to take preventative actions. In some cases the high resolution models are owned by commercial agencies that also have their own localized observing network to use as input into the models. Current research into higher resolution models, along with investigations of the computing architectures required to execute the models over increasingly larger domains, will continue to be an active pursuit for the foreseeable future. Improvements in these areas will also provide users with more accurate prediction products and allow more time (hours versus minutes [6]) to take preventive actions.

NWP models, although not perfect, provide the most timely and accurate forecasts possible for short, medium, and extended range environmental prediction. Additional accuracy is possible through the understanding of the strengths and weaknesses of these models when applied over different local, regional, national, or hemispheric domains and with varying seasonal conditions. This is true of all types of environmental prediction from basic weather forecasts, to flood prediction, and solar environmental prediction. Experts in the specific environmental modeling fields have the responsibility to apply the NWP model based on their experience and provide the real value-added information to increase the fidelity of the information for a specific user application. Any future improvements in speed gained from computing technology or the efficiency of the scientific algorithms will likely provide the valuable time needed to distribute higher fidelity value-added products to the user and lead to the critical information for decisions that save lives or allow resource protection measures to be taken. A summary of the end user applications, the final step in the actionable weather information life cycle, is discussed in the next section.

V. Value-added Product Users and Impacts to User Needs

Value-added products must instill user confidence in them for them to be fully effective. Improved and enhanced forecast products need to have improved verification rates and greater lead times, but they must also foster the perception of greater reliability and better ease of use for the communities those products serve. It is imperative that forecast product reliability, lead-time, and effectiveness all be improved. This is a key performance objective of the NOAA 2006-2011 Strategic Plan for weather and water mission goals [6].

Communities and populations must believe forecast products are reliable and provide users high quality information in order for the weather forecast production systems to be accepted and employed. Products are useless unless the information they provide are accepted and acted upon by the customer. This is achieved by forecast products establishing proven track records through high verification and validation rates. Consumers must have faith in the products being disseminated. New technologies will need to be infused into all facets of the production cycle, with streamlined dissemination and communication systems ensuring users receive the correct information when and where it is needed, and in the correct format and context for immediate use. Environmental literacy will become increasingly important in user implementation of weather product improvements; users must understand the products they are receiving, even as these products become progressively more complex. Products must relay actionable information, resulting in a sense of urgency on the part of users to take necessary steps to mitigate weather events' effects. We will survey six broad categories of value added products and impacts to users.

Flooding. Three quarters of all Federally declared disasters result from flooding. More than half the loss of life occurs as a result of vehicles being driven directly into flooded areas. Reductions in overall deaths could be realized by means of improved forecast lead times and enhanced flood warning accuracy, accompanied by more precise location of affected areas and better delineated evacuation routes communicated to the public. Warnings employing GIS overlays, or capable of being displayed on GPS systems, will provide the general public improved comprehension of when and where flood events will occur, while identifying the best evacuation routes. This would enable safe and timely exodus, associated flood risk avoidance, and give people time to move assets in advance of oncoming floodwaters. Greater lead times also give operators time to deal with infrastructure needs (shoring up levees, raising floodgates, putting up floodwalls, etc.) in advance of flood events and allow them to make more informed choices. Municipalities in flood-prone areas are starting to institute early warning systems to ensure populations receive the earliest possible information. An example of federal, state, and local cooperation is the Federal Integrated Flood Observing and Warning System (IFLOWS) [7]. IFLOWS is a cooperative venture between the National Weather Service (NWS) and flood-prone states. It was instituted to reduce flash flood deaths, lessen property damage, minimize economic impacts, and diminish impacts on everyday life. Cooperative forecast and warning systems like IFLOWS, integrated with more localized GIS warning systems, illustrate the possibilities of future improvements in forecast product systems.

Integrated systems such as IFLOWS will generate greater lead times and higher quality forecast products, enabling populations in affected areas to take greater steps to protect life and property. Additionally, the national implementation of the Advanced Hydrologic Prediction Service outlined in NOAA's 2004 Science and Technology Infusion Plan [8] is gauged to improve flood warnings and water resources forecasts, resulting in economic benefits of $520 million per year.

Severe Weather (Thunderstorm, Wind, and Hail). Early notification systems for directly disseminating NWS-provided tornado warnings in communities have made great strides toward reducing the casualty rates from tornadic outbreaks. Additionally, TV, commercial radio, and NOAA weather radio broadcasts of NWS warnings and advisories provide the populace with greater lead times, enabling improved storm avoidance and more time to seek shelter. Wind storm damage and hail effects can be reduced by moving property from the storm path and by securing assets from damaging weather, given adequate forecast lead times. Great strides in severe weather forecasting have been made since the 1952 establishment of the first Severe Local Storms (SELS) unit within the Weather Bureau. Advancements in forecast and modeling capabilities, improved with advances in storm analysis, Doppler radar deployment, weather satellite launches, interactive computing developments, distributed computer processing, storm modeling, and increased understanding of the interplay between storms and the environment.

Hurricanes. Longer forecast product lead times and more accurately pinpointed landfall strike probability forecasts will reap results similar to those resulting from flooding forecast improvements. Populations will be able to evacuate more knowledgably and affected communities will be more accurately identified. More accurate landfall strike zone probability forecasts will be identified, conveying to communities where the most damaging winds, storm surge, and hazardous weather conditions will occur. The benefits resulting from these forecast improvements include more selective evacuations, better choices for evacuation routes, and identification of collateral impacts (flooding, public utility impacts, and transportation disruption). Increased forecast quality and greater lead times will also enable property asset movement and protection measures which will reduce damage within stricken communities.

Space Weather Impacts. Improved space weather characterization, through added sensors, enhanced space weather forecast models, and greater knowledge of space weather effects will result in longer product lead times. More effective forecast products will result in improved charged particle event monitoring, better identification of space weather events and their impacts to user activities. Coronal Mass Ejection (CME) impacts include identification of CMEs that will result in disturbances impacting the Earth. CMEs can cause radio communication disruptions, impact satellite orbits, damage satellite components, and cause geomagnetic storms on the Earth. Radio propagation at high frequencies, used by marine and aviation interests, can incur disruptions including short wave fades and Polar Cap Absorption. Satellite communications can also be affected by scintillation due to solar activity. Geomagnetic storm effects include power system outages, spacecraft charging events, satellite tracking disruptions, satellite uplink/downlink impacts, satellite navigation changes, and low frequency radio propagation disruptions. Extra Vehicular Activities may be curtailed due to the increased threat of astronaut radiation exposure. Satellite drag, resulting in satellite orbital changes, is the result of changes in ionospheric conditions due to solar activity. Solar events can also bring about spacecraft charging and other anomalous spacecraft events and spacecraft disruption. A very notable disruption is impacts to the GPS constellation, given our increased dependence on the GPS constellation. Improved forecast quality and longer lead times will enable satellite controllers and ground stations to issue commanding sequences to put spacecraft in shielded positions or components in safe mode. Improved forecasts and enhanced observation products will also allow ground stations to mitigate impacts of solar weather events. The ACE satellite, NASA’s STEREO mission, and similar advances in space weather satellite programs are just the beginning of improved capabilities in characterizing and forecasting space weather effects on both the ionosphere and near earth environment.

Aviation and Surface Weather Parameters. Secure, effective transportation is a critical component of the U.S. economy. Annual economic impacts greater than $4 billion are attributed to weather-related air traffic delays. Injuries, fatalities, and property damage from weather-related crashes total $42 billion each year; twenty-four percent of the more than 6.4 million vehicular crashes annually are weather-related [9]. Additionally, there are an estimated 544 million vehicle-hours of delay per year, nationwide, with an estimated 23 percent of non-recurring highway delays due to snow, ice, and fog.

Improved aviation forecast quality and longer lead times will decrease impacts to aviation and commercial transportation, with fewer delays and flight cancellations. Weather forecast product improvements will decrease impacts to national and regional aviation, long haul trucking concerns, regional transportation, railroads, metropolitan mass transit, and personal vehicular travel.

Weather parameters impacting transportation concerns include low ceilings, surface visibility reductions (due to fog, precipitation, smoke, or dust), low level wind shear, wind gusts, precipitation (rain, sleet), and icing (surface or aloft). Seventy-five percent of weather-related crashes occur on wet pavement. State and local agencies spend more than 2.3 billion dollars on snow and ice mitigation techniques. More than 30.6 billion vehicle hours are lost annually by trucking companies as a result of weather-related congestion in the nation's major metropolitan areas. The economic impacts of weather-related delays to trucking companies are estimated at between 2.2 billion dollars to 3.5 billion dollars annually [9].

Great strides have been made in aviation weather forecast products. Highway and commercial transportation interests will be similarly served by the Clarus Initiative [10]. The Clarus Initiative is a joint effort of the U.S. Department of Transportation and NOAA; its goal is the creation of an integrated road weather observing system providing standardized transportation weather across the entire US. This effort to develop and demonstrate an integrated surface transportation weather observation data management system is analogous to the creation of the integrated FAA – US Weather Bureau aviation weather program in 1961. Advancements in both surface and atmospheric weather observation, modeling, and forecasting necessitate integration of multi-scale networks with standardized parameters for collection, reporting, dissemination, and feedback.

VI. Conclusions

Forecast products have made great strides during the last 30 years. Tornado warning lead times have increased to an average 12 minutes, with more than 30 minutes in some cases. Flash flood warnings have increased lead time from 8 minutes to near 1 hour. Hurricane forecast products have improved lead times to 3 days, with a decrease in the average 72 hour storm track forecast error from 450 nm to 190 nm. In addition to the advances in weather data collection, analysis, and forecast production capabilities, enhanced community preparation, response, and mitigation strategies have brought about reductions in the annual cost of storm-related disasters by 10% per year [6].

By 2025, NOAA hopes to realize tornado warning lead times of one hour. Severe thunderstorm warnings will see lead times increase to 18 minutes for large areas and up to 2 hours for cities. Advances in flash flood warnings will enable 45 to 60 minute lead times. Hurricane warnings for landfalls will improve from hours to over 3 days. Transportation interests will see improvements in lead times also; ceiling and visibility lead times will improve to 6 hours and turbulence and icing forecast products will have 5 hour lead times. Space weather indices will evidence similar improvements, with geomagnetic warning lead times growing to 5 days and solar radiation lead times advancing to 2 days [6].

Technological advancements in collection, processing, analyses, compression, storage, retrieval, and dissemination will require capital and intellectual investment. These are wise investments taking into consideration the potential benefits they will provide, in lives saved, resources protected, and both direct and indirect cost savings. These returns on investment are the direct result of improving the quality of environmental predictions and shortening the production life cycle for actionable weather information.

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