The Uncoordinated Giant: Why U.S. Weather Research and Prediction Are Not Achieving Their Potential

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Abstract

Although the large U.S. meteorological community has made significant strides in weather diagnosis and prediction, progress has been profoundly slowed by a lack of cooperation, coordination, and pooling of resources. This paper analyzes such problems in a number of areas, ranging from mesoscale modeling to forecast dissemination, and proposes an alternative approach of greater community involvement in decision making, coupled with closely coordinated research and operations, that might facilitate improvement in our ability to understand and predict the weather.

1. **Introduction**

There can be little doubt that weather prediction in the U.S. has improved considerably over the past several decades. Synoptic-scale numerical prediction models, such as the NCEP's Global Forecast System (GFS) model, are producing far more accurate forecasts of major cyclones and other large-scale features. High-resolution mesoscale models, such as MM5, COAMPS, and WRF, often predict realistic mesoscale structures, a situation unheard of a decade past. A national Doppler radar system (WSR-88D), even with substantial gaps, has afforded improved prediction of convective storms and better short-term precipitation forecasts over much of the nation. Burgeoning satellite data, from high-resolution imagery and water vapor/cloud track winds to multispectral vertical soundings, now provide considerable information over previously data-sparse volumes of the atmosphere, with the forecast accuracy in the southern hemisphere now approaching that of the northern. Ensemble prediction techniques have proven their value for synoptic-scale forecasts, and hurricane-track forecasts have improved steadily. Finally, the community has moved quickly to take advantage of the Internet as a means for distributing weather information and forecasts.

But in spite of these advances, there is a growing sentiment in the community that weather prediction research and operations in the U.S. have significant problems, and that progress in diagnosing and predicting the weather is far less than our discipline's potential. All too often the large American weather prediction enterprise, both in research and operations, has worked with insufficient coordination and cooperation, resulting in inadequate resources for key tasks, inefficient duplication of effort, slow progress developing essential technologies, and unproductive or inappropriate use of limited manpower. Significant problems have developed because key players in the weather enterprise—operational centers, academic researchers, government laboratories, the user community, and the private weather sector—have not worked together effectively. This paper explores these problems, evaluating both the successes and failures of the past few decades in synoptic/mesoscale prediction and research, and suggests possible approaches to address them.

2. The Changing Weather Prediction Community

During the past decades the composition of the weather prediction community has changed greatly. The private sector has grown rapidly, now standing as an equal to the government and academic sectors in both the number of members and the range of activities (Zevin and Seitter 1994, Mass 1996, NRC 2003). NOAA, and particularly the National Weather Service (NWS), still the dominant entity in weather prediction, now encompasses a smaller proportion of the community, although it still provides critical observing and modeling infrastructure.

As the weather prediction community has evolved, the boundaries between the various sectors have become more diffuse, with activities once dominated by one sector now shared by others. For example, a few decades ago only the NWS and military prediction centers were involved in operational numerical weather prediction (NWP), while today, real-time NWP is occurring at dozens of universities, private sector firms, and local forecast offices. Currently, all sectors disseminate real-time weather information and predictions to the public. For example, most university departments maintain web sites with extensive weather resources and the Pennsylvania State University even prepares the daily weather page in the New York Times, while a whole range of private sector firms (e.g., the Weather Channel, Accuweather, local TV stations) provide current forecasts and data over the web or through cellphones/PDAs. While in the past, weather data collection was monopolized by Federal agencies such as NOAA and the FAA, today all sectors of the community have active roles in collecting weather information. To illustrate, some universities (e.g., University of Oklahoma) maintain extensive regional networks (in this case, the Oklahoma mesoscale network of over 110 stations), while others --such the University of Utah (Mesowest) and the University of Washington (NorthwestNet)-- collect, archive and distribute the observations from a wide range of regional networks. Private sector firms are also involved in real-time data collection using operational networks, including AWS Convergence Technologies, Inc, which collects data from over 6,000 sites around the nation, and Vaisala, Inc., which collects and distributes real-time lightning data. Many state and local air quality agencies maintain weather observation networks, while thousands of weather enthusiasts with home weather stations provide their weather observations in real-time to services such as The Weather Underground[2].

Such increasing overlap between sectors of the weather prediction community can represent a very healthy development, promoting creativity and cross-fertilization. Alternatively, overlap can lead to conflict and tensions, as sectors invade each other's disciplinary domains (NRC 2003), or can result in duplication of effort that wastes limited resources. The potential for such conflicts are greatly enhanced if communication and coordination are inadequate. Some tensions have been evident in the community (most acutely between private sector forecasting firms and the NWS), but, as noted

[2] http://www.wunderground.com/

below, improved cooperation and dialog among members of the government, private sector, and research communities could go far in mitigating these problems.

As the skill and specificity of weather prediction has increased, so has the diversity and size of the weather user community. Weather information is now critical for an increasing range of industries, such as insurance, weather derivatives, transportation, wind energy, and agriculture, in ways unexpected only a few decades ago. With increasing dependence on weather information, such users might be expected to provide more resources for weather prediction research, the development of improved forecasting technologies, and for the maintenance of the weather prediction enterprise. But with increasing dependence on weather information and the provision of resources to the weather prediction community, the user community will also expect a place at the tables where decisions are made. The question of how the user community can contribute to the weather prediction enterprise and help in the decision-making process is an important issue that is considered later in this paper.

2. Some Warning Signs

There are a number of warning signs that U.S. weather prediction research and operational communities are not fulfilling their potential to provide the best possible weather information to the public and other users:

(1) The U.S. has lost leadership in global weather prediction

For a number of years the skill of the NWS National Centers for Environmental Prediction (NCEP) global weather prediction model (now called the GFS) has lagged that of the United Kingdom Meteorological (UKMET) Office and European Center for

Medium Range Weather Forecasting (ECMWF) global models. The lesser skill is particularly profound compared to the ECMWF model, with the GFS lagging by approximately one day of useful skill[3] (i.e., a seven day GFS forecast has equivalent skill to a eight-day ECMWF prediction). This second-place status is in contrast to that of the U.S. meteorological community, which in size, breadth and depth is far greater than either England's or that of the European community. The key factor that has allowed ECMWF to surpass the U.S. is an extensive cooperative effort characterized by pooling of experts and resources from the entire European community, coupled with clear strategies for concentrated development. The fact the ECMWF global model is the world's best speaks eloquently for such an organized approach.

(2) The decline and imminent "reset" of the United States Weather Research Program (USWRP)

Initiated in the early 1990s, the USWRP has had the goal of moving ideas and technology from the research arena to operational implementation in order to achieve improved weather prediction. Although the USWRP has made substantial contributions, it has generally not fulfilled expectations for reasons that will be examined below. Currently, the USWRP is under evaluation for termination or "resetting."

An early direction of the USWRP was to gather groups of scientists into Prospectus Development Teams (PDTs) to review and provide recommendations in key areas. During the first eight years of the USWRP there were ten PDTs, dealing with a

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[3] Comparative prediction information for various modeling centers' global models is available from a number of sources, including NCEP's own verification site: http://wwwt.emc.ncep.noaa.gov/gmb/STATS/STATS.html. It is important to note that a few hours of the ECMWF model enhanced predictability period is due to a later data cut-off compared to the NWS GFS model.

wide range of topics including heavy precipitation, hurricane forecasting, hydrometeorology, and societal impacts[4]. Although a good starting place, the PDT reports have become increasingly out of date and have not provided the ongoing guidance and active cooperation that was required to make effective progress on USWRP goals.

In an attempt to bring some focus to the USWRP and to appeal to funding agencies, three major research areas thought to be of interest and major impact were identified: hurricane landfall, precipitation, and observations/data assimilation. The hope that these areas would resonate with funding agencies and users groups, and thus bring substantial additional resources into the USWRP, has generally failed to be realized. Perhaps the greatest success of the USWRP has been the Joint Hurricane Testbed (JHT), which has funded research to accelerate technology infusion focused on hurricane analysis and prediction. The JHT has sponsored a number of research projects over the past four years that have resulted in innovations that have been transferred into operations. Unlike many of the other USWRP efforts, the JHT has enjoyed focus, larger funding resources, and clear paths to implementation.

The USWRP has been ineffective in public relations, failing to demonstrate the relation of ongoing research to improved prediction and not connecting inadequacies of current weather prediction with solutions that could be implemented with sufficient resources and cooperation.

In recent years the USWRP has evolved into a diffuse umbrella of initiatives and field programs without a central vision, community oversight, or clear priorities. There is

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[4] Many of the PDTs have been published in the Bulletin of the American Meteorological Society or can be accessed on the USWRP web site (http://box.mmm.ucar.edu/uswrp/PDT.html)

little sense of a community working together towards specific and important goals, other than "weatherproofing the nation." Efforts that receive little funding or direction from the USWRP are placed under the USWRP banner (e.g., IHOP[5]). A profound deficiency has been the lack of an USWRP oversight group representing the meteorological and user communities as a whole. Rather, a narrow collection of government agencies (the Interagency Working Group, IWG) has provided sporadic direction of the USWRP, with far too much stress on Federal agencies as both benefactors and beneficiaries. Considering the evolution and diversification of the weather prediction and user communities noted above, and the substantial personnel and financial resources they command, others should have had seats at the table.

In summary, the USWRP has not succeeded because, with the possible exception of hurricane landfall, it failed to create a close, active, and mutually beneficial connection between the research and operational/user communities. The USWRP never took on the role of determining the ongoing priorities of the research and operational communities, and then coordinating the necessary research and development. Without such an active connection, researchers lacked valuable feedback from users and the encouragement of seeing their work transferred to practical application, while the user community did not develop an appreciation for the value of research efforts and thus was not motivated to support them. Today, the USWRP is without a chief scientist, its monthly conference calls and newsletter have been suspended, and its program office has been disbanded.

(3) A large number of U.S. mesoscale modeling systems and insufficient cooperation has resulted in a lack of critical mass for solving key problems. Major deficiencies exist in

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[5] The International H20 Project

key forecast model parameterizations and there is insufficient community coordination and joint research to deal with them.

The history of mesoscale model development in the U.S. is characterized by many models, inadequate national cooperation, and the lack of critical mass for important tasks. Today there are over a half-dozen major mesoscale-modeling systems in use (e.g., NCEP Eta, NCEP NMM, NCAR/Penn. State MM5, CSU RAMS, UOK ARPS, Navy COAMPS, NCAR WRF-ARW, RSM). Although the U.S. is endowed with substantial depth in its weather modeling community, the existence of so many platforms has insured that sufficient resources for attacking key problems have not always been available. For example, it is well known that there are <u>major</u> problems in physics parameterizations (e.g., boundary layer, microphysics, convective parameterization) for virtually all modeling systems, particularly for grid spacings of 1-10 km. For example, most PBL schemes produce too much vertical mixing under stable situations, there are apparently major flaws in leading microphysics schemes (Stoelinga et al. 2004), and major questions exist regarding nesting and cumulus parameterizations (Colle et al. 2003). Even major operational centers such as NCEP have only a handful of individuals working on each of the key physics parameterizations. In contrast, the level of effort required to develop, test, and evaluate new parameterizations is at least an order of magnitude greater and often requires tailored field experiments to provide the detailed information necessary to diagnosis and improve model physics. Although modelers and physics specialists from the various groups do meet on occasion at conferences and workshops, the level of active cooperation and coordination between groups has clearly been inadequate for this large task. With a divided U.S. mesoscale modeling community, academic research advances have not flowed effectively into the operational models and operational centers have generally provided only minimal support to academic research. Poor technology transfer between the university community and NOAA has been a major roadblock for the improvement of NWS forecasts. In short, diversity can be a positive thing, spurring creativity and diverse solutions, but too much division of labor in a relatively small field can push past the point of diminishing returns.

A recent attempt to develop a true community mesoscale mode (WRF) has met with some success, but has suffered from lack of coordination, lack of resources, and insufficient pooling of resources. WRF was based on the premise that the operational and research communities should work together to build a next-generation joint model that would replace the aging MM5 and Eta. With limited funding, a general model infrastructure and a dynamical model core (known as the WRF Advanced Research WRF-ARW) have been developed at NCAR, with some assistance from FSL in the development of the preprocessing software (SI). The National Weather Service, nominally a participant of the WRF effort, has developed its own next-generation model (the Nonhydrostatic Mesoscale Model, NMM) to work within the WRF infrastructure. Thus, instead of having one community model there will be essentially two dynamical models under a single infrastructure "wrapper." With limited personnel and resources, WRF development has proceeded slowly, with nesting only becoming available recently and nudging, a facility important to the air quality and research communities unavailable for the immediate future. The physics packages of WRF are nearly all transfers from MM5 and Eta.

Recently, there been the complaints by NCEP and others that the WRF software infrastructure is difficult to understand and master, with only one individual (the developer) fully conversant with the system, and that the WRF infrastructure is not consistent with the new Earth System Modeling Framework (ESMF). If the operational, research, and model development communities had worked together from the initiation of the project in creating the specifications of the system and in building the foundation infrastructure of WRF, such post-development problems might have been avoided.

A community model requires community oversight, and this has been lacking for WRF. The WRF effort has been directed by a very limited collection of government agencies (NOAA, Navy, Air Force) and NCAR, with no direct representation of the academic and user communities. The WRF Science Board, which was tasked to supply scientific oversight, has met infrequently and has recently been terminated. Without broad representation of the groups that develop and use the model, non-optimal decisions are inevitable and the lack of ownership and involvement lessens the probability of garnering additional resources.

4. Lack of progress on probabilistic short-range forecasting

During the past several decades, the U.S. mesoscale prediction community has put the overwhelming majority of its resources into increasing resolution and improving model physics. However, with substantial uncertainties in initial state and model physics, coupled with the chaotic nature of the atmosphere, mesoscale prediction requires a probabilistic approach. It is deceptive to provide a single forecast solution as expected reality and we poorly serve our users by not providing them with information about the range of possible forecast events or forecast confidence. Unfortunately, the weather prediction community as a whole, and key Federal agencies in specific, have only put limited resources into short-range mesoscale ensembles and other probabilistic approaches. NCEP has supported a minimal Short-Range Ensemble Forecasting (SREF) effort with coarse (32-km) grid spacing and thus of marginal value for most mesoscale applications. Furthermore, the breeding method it uses to create initial condition variations is probably inappropriate for SREF use, being based on previously fastest growing modes, instead of the essential uncertainty of the initialization. The new National Weather Service forecast dissemination system (IFPS) was designed from a totally deterministic viewpoint and is incapable of providing probabilistic information for any field other than precipitation. Only through indirect means, such as the local forecast discussions—often using cryptic acronyms—does the National Weather Service communicate its confidence in its forecasts. Most media outlets provide little information on forecast uncertainty, with the possible exception of expected temperature ranges.

The current deterministic approach not only denies valuable probabilistic information to the user community but also has the potential to undermine confidence in our products as the inevitable deterministic forecast failures occur. Clearly, the issue of relative resources provided for high-resolution and ensemble prediction should be a prime candidate for community discussion and prioritization.

5. Problems with the dissemination of weather information

The effective dissemination of weather data and forecasts demands close coordination and communication between the meteorological and user communities. Unfortunately, such cooperation has often been lacking. A prime recent example of the dangers of isolation is provided by the Interactive Forecast Preparation System (IFPS), the new National Weather Service system for forecast preparation and dissemination. Designed with minimal input from forecasters or users, IFPS represents a major paradigm shift in forecast preparation whereby NWS forecasters create graphic renditions of the weather out to seven days that are distributed digitally to users as well as being automatically translated into text. As noted in Mass (2003) and others, this system has a number of serious problems, including a lack of bias correction, inadequate access to full model resolution of the three-dimensional model grids, coordination problems with adjacent offices, lack of analyses of record for verification and climatological guidance, a completely deterministic perspective, and problems with the text translation, to name only a few. IFPS was not designed to facilitate nowcasting and short-term (0-12 h) forecasting, an area in which human forecasters can probably make their largest contribution.

It seems clear that in developing a system at the critical interface of the forecasting and user communities, wide-ranging discussion and joint planning would be required. One might reasonably hypothesize that if a representative segment of the meteorological and user communities had been gathered to discuss the proposed transition to a gridded forecast system, some of the current problems might have been avoided or mitigated.

Another serious issue concerns inaccurate or inadequate information being provided to the public by supposedly professional members of the meteorological community. Although many media meteorologists are well trained and provide state-of-the-art guidance, too many weathercasters lack the training/education to properly represent the science. As a result, miscommunication is widespread, ranging from suggesting that bird echoes on weather radar is precipitation and the provision of medium-range forecasts well beyond the period of skillful prediction (e.g., 7-14 days), to providing little information on forecast uncertainty. Major weather outlets on the web provide automated short and long-range forecasts that often possess extraordinary errors. National Weather Service forecasts, both on the internet and NOAA weather-radio, are not updated with sufficient frequency, often providing patently inaccurate weather information (e.g., predicting rain today when skies are clear).

The issue of miscommunication extends to the pronouncements of long-range forecasts. All too often, members of our community make long-range seasonal predictions, with little basis in science and inevitably poor skill. For example, last fall a local state climatologist predicted a wet and stormy season for the Northwest, a prediction that was widely publicized in the media and which was opposite of the observed weather (a drought with few storms). Even well-considered seasonal predictions by highly competent meteorologists are often obfuscated by confusing terminology and non-intuitive displays of forecast uncertainty.

The influence of such poor communication is to undermine the public's confidence in our forecasts and in the professionalism of the community, making the meteorological profession grist for humor and undercutting attempts to secure additional resources for research and development. To address this issue will take a comprehensive and unified approach, ranging from enhanced minimum training of media weathercasters to more careful monitoring by professional societies, such as the AMS, of the products distributed by the community.

6. Lack of emphasis on short-range prediction and nowcasting

One of the greatest weaknesses of the weather forecasting enterprise in the United States has been its inability to furnish the public with detailed current weather information (what is happening right now) and to provide a description (through a convenient medium) of how the local weather is expected to evolve during the next few hours. All too frequently one listens to a forecast on the radio or views a prediction on the web that is out of keeping with what is happening outside of the window. Meteorologists know a great deal about the short-term evolution of weather conditions that is never communicated to the public and other users of weather information. Thus, society has been denied the advantage of this highly useful information, with great implications for both public safety and the economy. As noted above, the discrepancy between the observed and forecast weather greatly undercuts the credibility of the discipline.

The origin of this problem is manifold: lack of resources for frequent (perhaps hourly) updates at the National Weather Service, inadequate delivery mechanisms for frequent nowcasts/short-range forecasts by the National Weather Service and the private sector, inadequate access to all mesoscale data sources by the forecasting community, and inadequate data assimilation technology for the shorter time and spatial scales. Only by a joint effort of the weather enterprise can this critical issue be properly addressed.

7. Climate and other earth sciences have been far more successful than the weather prediction in garnering research and development funding. Prediction research funding is declining.

Although diagnosing and predicting the weather is critically important for the

U.S. economy[6] and for the protection of life and safety, funding for related research and development greatly lags that of climate and related disciplines such as oceanography and astronomy. For example, in FY 2003 the total National Science Foundation funding in support of the U.S. Weather Research Program was $8.8 million[7] , while NSF support for the U.S. Global Change Research Program (USGCRP) was $187 million[8]. In NOAA's Office of Atmospheric Research, under which the various NOAA labs reside, $166 million was directed at climate research, but only $57 million was spent on weather and air quality research, including OAR funding to various research partners. Why is climate favored over weather prediction in the research budgets of virtually every federal agency? How can this be when weather prediction is the one scientific discipline with a representative on nearly every evening news broadcast, and which directly influences the immediate safety and economic well being of most Americans? One explanation is that U.S. administrations of both parties have generously supported climate research in lieu of taking potentially politically sensitive decisions that would significantly influence the economy and life-style. Thus, providing research funding provides an appearance of action, while finessing the difficult choices. Although this explanation is undoubtedly valid, an ancillary explanation is that the weather prediction community has failed to make a compelling case for the potential value of improved weather prediction—a case that should be relatively easy to demonstrate.

[6] The National Research Council (NRC 1998) estimated that approximately $1 trillion of the nation's $7 trillion dollar economy is weather sensitive.
[7] Personal communication, John Gaynor, USWRP Project Office.
[8] Information from the web site of the Office of the Federal Coordinator for Meteorology. (http://www.ofcm.gov/)

Research funding for weather prediction-related research is now in decline. NSF funding as a whole, and weather-related research in particular is steady state at best (particularly when inflation is considered), meteorology-related research at the Office of Naval Research (ONR), both basic and applied, for meteorology has declined about 40% since 2001, and will probably decline another 10-15%[9]. Total military funding for meteorological research has declined by 46% between 2001 and 2005[10]. NOAA has cancelled the latest Request for Proposals of the COMET cooperative program of joint NWS-University local weather research and will cut the other major cooperative research program (CSTAR) in half. In addition, an expanding the National Center for Atmospheric Research has created a large competitor to the university community for this shrinking pool of research funding.

8. Problems with data collection and distribution

Few aspects of the forecast process have suffered more from the lack of coordination than the gathering and distribution of weather observations and forecasts. During the past few years there has been an explosion of surface weather stations owned by groups and individuals, aircraft observations from commercial aircraft (ACARS), weather radars owned by the media and others, and satellite-based observations such as cloud track and scatterometer-derived winds, to name only a few. Unfortunately, the surface data networks are generally uncoordinated, often with multiple observations in close proximity, and without effective national organization for their collection, quality

[9] Source: Dr. Ron Ferek, Team Leader, Marine Meteorology Program, ONR.
[10] Information from the web site of the Office of the Federal Coordinator for Meteorology. (http://www.ofcm.gov/)

control, archival, and dissemination. The power of centralized collection of a wide range of observation sources has been demonstrated over the western U.S. by MesoWest (Horel et al. 200) and NWNet (Mass et al 2003). Recent meetings such as the AMS "Community Summit on Developing a National Mesoscale Observing Network" held in Dallas on 27-28 July 2004 and the USWRP Mesoscale Observing Networks Workshop held in Boulder on 8-9 December 2003 have brought together a wide-ranging group to discuss this important issue.

Even when observational and model data exist, there are often roadblocks to their distribution. Access to the exponentially growing ACARS flight-level data, which provides hundreds of ascent and descent soundings into U.S. airports each day is highly restricted, making it difficult for private sector and state/local users to gain operational access to this highly valuable data source. Gridded model data produced by the National Weather Service is now easily available to the academic community, but lack of bandwidth and server capacity makes it difficult for the private sector and others to gain useful access. Ironically, the worst access to model grids and large data sets is experienced by National Weather Service offices, most of which lack the bandwidth to acquire NCEP grids at full resolution. Finally, the U.S. observing network needs a careful community reevaluation based on changes in the observing assets and data assimilation technologies-- the assigned, but unfulfilled, task of the North American Observing System (NAOS) program.

3. A New Model of Decision Making and Coordination for the U.S. Weather Prediction Enterprise

The underlying cause of many of the problems noted above is the way the weather prediction community makes decisions, sets priorities, and coordinates its work. The classic approach on major projects is for Federal agencies such as NOAA, NSF, or DOD to dominate decision-making because they supply most of the financial resources. NCAR, because of its large infrastructure and substantial internal resources, often joins the leadership councils. This pattern of relatively circumscribed leadership has been repeated many times, including the oversight of both the USWRP and WRF. Other major efforts that are supported by a single agency (e.g., NOAA's IFPS forecast generation/distribution system) have generally kept decision making within that agency, even when such projects greatly influence the remainder of the community.

It can be argued that this agency-centric approach is fundamentally problematic and prone to produce poor decisions. First, since agency decisions regarding major national capabilities and infrastructure (e.g., forecast dissemination, model development) have a profound influence on the operations and viability of other portions of the weather enterprise, a wide range of guidance is needed. Wise decisions often cannot be made without non-agency representatives, who are privy to knowledge and experience outside the purview of well-meaning agency leadership. Second, there are many types of resources required for weather research and operations, and Federal agency support is only one of them. For example, work by the academic community on the MM5 and other mesoscale models, a critical and large resource, is generally not federally funded, but folded into local institutional support. The private sector provides a huge and expensive infrastructure for disseminating weather information to the public and other users, and represents an essential communication tool for the National Weather Service and other government agencies.

There has been increasing interest within the weather prediction community for more communal decision-making and enterprise-wide solutions. The Weather Coalition[11] has brought together the private sector, state and local governments, and academia to advance weather research. Stimulated by private sector complaints of perceived unfair competition by the Federal government, the NRC Fair Weather Committee examined the relationships among the various sectors of the weather enterprise, recommending that more communication could strengthen weather prediction and research (NRC 2003). An AMS Ad-hoc Committee on the Weather Enterprise brought together a representative sample of the weather prediction community to discuss how community interactions might be facilitated; their recommendations, which were approved by the AMS Council, included the creation of an AMS Commission on the Weather and Climate Enterprise, which will facilitate fora for discussion of important enterprise-wide issues[12]. Other community wide meetings included the December 2003 USWRP-sponsored meeting in Boulder (Design and Development of Multifunctional Mesoscale Observing Networks in Support of Integrated Forecasting Systems, Dabberdt et al 2004) and a recent "enterprise-wide" gathering sponsored by the AMS Ad-Hoc Committee on the Weather Enterprise on "Developing a National Mesoscale Network." The key message from all these activities is that many in the growing weather prediction community believe that more communication and joint decision-making is required for effective future progress.

[11] http://www.ucar.edu/oga/wx_coalition/
[12] http://www.ametsoc.org/stacpges/cwce/

The need for more community integration was discussed in some detail by Pielke and Carbone (2002), who noted that the goals of the weather prediction enterprise "are unlikely to be reached if the community proceeds in a balkanized fashion that has characterized it in the past—public versus private, research versus operations, satellite versus insitu, and other lines of division. Both the weather community and broader society of which it is a part would benefit from an overarching perspective on the weather prediction enterprise and the effectiveness of it's processes." Achieving this perspective "requires a fundamental shift in the structure of the community. It requires strong and balanced leadership with a greater breadth of interaction that is presently associated with institutions, agencies, and sectors of the community in the United States." Pielke and Carbone note that the weather prediction community is like an orchestra without a conductor. "No organization or entity has embraced the collective measure of responsibility for improving forecast processes." Echoing the Pielke/Carbone perspective, an NRC study of the future of atmospheric sciences in the 21st century (NRC 1998) commented: "Today, there is reason for considerable concern about planning for atmospheric research. No one sets the priorities; no one fashions the agenda. ... Thus, BASC believe that a national research environment requires a strong disciplinary planning mechanism. ... all partners in the atmospheric enterprise –in government, in universities, and in a variety of commercial undertakings– must join together as an effective team focused on the future."

In contrast to the agency-centric or "small-circle" decision-making that is the general rule today, another model is possible, one that is more open and inclusive. Major weather-related activities that affect a large proportion of the community (such as national numerical model development or an entity like the USWRP) should be directed by a representative collection of members of the weather community and major users. One would expect that such a group would possess the information and scope to make better decisions and could avoid some of the serious problems noted above.

A representative collection of enterprise members could also provide additional resources, both in funding and personnel, than available to the agencies alone. The traditional model has viewed a limited "pie," one that mainly constrained to the financial and other resources of the participating federal agencies. In contrast, by opening the door to the opinions, needs, and leadership of others in the weather enterprise, the potential for other sources of resources become possible, if not probable. A successful test of this concept on a regional level has taken place in the Pacific Northwest, in which a wide-ranging group of Federal, state and local agencies, academic institutions, and private sector entities –known as the Northwest modeling consortium-- have combined resources to build a regional weather prediction system, encompassing both high-resolution modeling (down to 4-km grid spacing) and mesoscale ensembles (Mass et al 2002). In the NW consortium, resources are pooled and major decisions are made by the group. It has been the Northwest experience that non-traditional sources of funding for weather prediction research and operations are available if others are allowed at the leadership table and a more inclusive integration of effort is fostered. Joint decision making, prioritization and support encourages research to be directed towards the most acute needs and fosters innovation by suggesting new applications of weather information. In the Northwest, joint decision making has resulted in the construction of a regional environment prediction system, in which meteorological observations and forecasts have been integrated with air quality, smoke dispersion, and hydrological models, as well as transportation-related applications. There is no apparent reason that the Northwest experience cannot serve as a model of cooperation and integration for the entire U.S. weather prediction community.

This new paradigm of community integration will prove uncomfortable to those accustomed to sole control of resources and manpower, but it is critical step if we wish to serve our users and our discipline effectively. Perhaps some of us have noted smugly the travails of the U.S. intelligence community and the apparent inability or unwillingness of multiple intelligence-related agencies to work together effectively for the common good. Unfortunately, an objective examination of our own discipline suggests that we suffer from many of the same problems, including a significant lack of leadership. For the intelligence community, exterior forces pushed for an "Intelligence Czar" with authority to push the various agencies and groups to work together. Hopefully, our discipline can find the wisdom and foresight to develop a more cooperative model of interaction.

4. A Concrete Vision of a Future Weather Prediction Enterprise

This section provides a description of how the weather prediction enterprise might be reformulated to more effectively advance the discipline and the needs of its users. The proposed effort might be called the U.S. Weather Prediction Program (USWPP), since the essential core of the project will be the coordinated application of research and operations towards weather prediction. The USWPP would have the following major elements:

a. An oversight group broadly representative of the weather prediction and user community should be established. This group, perhaps encompassing 10-20 members, would include individuals from the operational, academic, and private sector meteorological communities, as well as user representatives. Such a group would help coordinate the national research/development/operations efforts, coordinate resources, and would hold regular fora to secure community input and guidance. Its varied membership would insure that all major sectors of the community would have an opportunity to provide ideas and feedback, lessening the chances of myopic and uninformed decisions. The group would meet regularly, with physical meetings at least twice a year and monthly conference calls. An important component of each meeting would be to review concrete measures of progress towards improving weather prediction in the U.S., such as model verification scores and the performance of human forecasters.

b. Standing, active working groups will be established for guiding the development and application of key aspects of the weather prediction enterprise. The centerpiece of the USWPP will be a collection of active committees that will coordinate and manage the community's forecast model and weather application development efforts. These groups will report to the oversight committee. Possible working groups include:

<u>Model Physical Parameterizations</u>: This group will review the adequacy of the physical parameterizations used by the community and recommend/coordinate needed research, development, and field experiments.

<u>Data Availability and Assimilation</u>: This working group will be responsible for evaluating the current observational network and make recommendations to the USWPP regarding specific new observing systems, targeted observation programs, synoptic and mesoscale data assimilation, and relevant programs such as THORPEX.

Model Development: This working group will be responsible for actively coordinating synoptic and mesoscale model development, including the dynamic cores, physical parameterizations, infrastructure, and pre/post processing software.

Ensembles, statistical post-processing, and probabilistic prediction: This working group will examine the potential of ensemble systems and other approaches for producing calibrated probabilistic forecasts both on the synoptic and mesoscale and will appraise the adequacy of current efforts in the operational and research communities. The charge of this committee will extend to statistical post-processing, including MOS, neural nets, and model bias removal, and the communication of probabilistic information (including prediction of forecast skill) to users.

Forecast and Model Verification: This working group will take on the important (and underdeveloped) area of model and forecast verification, with particular emphasis on mesoscale verification. This group will supervise the USWPP regional and national testbed activities, develop standard verification approaches for use in national and regional forecasting efforts, and organize the collection of real-time verification statistics for major U.S. modeling systems that will be used for guidance in model development efforts.

Weather Applications: This working group will coordinate the USWPP's weather application activities (including air quality modeling and transportation weather). It will also provide advice on the relationship of the weather prediction community and users, including products and capabilities that require active community development. The communication and distribution of weather information will also be under this committee's purviewc.

Annual Plenary Meeting and Specialty Workshops

In addition to oversight and working group meetings, there should be topic workshops that would include one or several of the above committees, and annual or biennial plenary meetings that would be wide ranging. The latter gatherings, perhaps scheduled for the annual American Meteorological Society meeting and organized in concert with the AMS Commission on the Weather Enterprise, would be expected to include several hundred participants and would provide an excellent forum for determining the priorities and expectations of the larger community. In general, the AMS Commission would provide venues for airing general enterprise issues, while the USWPP would be heavily involved in active coordinate of enterprise efforts.

5. Summary and conclusions

Weather prediction is an extraordinarily complex enterprise. The computer forecast models at its core, along with the associated data assimilation, data collection, and post-processing systems, are some of mankind's most complex constructs, encompassing hundreds of thousands of lines of code, and phenomena ranging from the microscopic to planetary scales. Weather prediction is hardly a mature technology. There is an enormous amount of work yet to be done, particularly regarding physical parameterizations and data assimilation, and the development and application of probabilistic prediction is in its infancy. Significant progress will demand large amounts of observational, personnel, and computing resources that only a combination of the entire enterprise's resources and effective advocacy can provide. Since weather prediction involves a diverse group of researchers, operational centers, and users, this technology can only be developed effectively if all members of the enterprise have a voice and share the burdens.

The U.S. weather prediction effort has accomplished a great deal, but its potential has been hampered by a lack of coordination and cooperation. The nature of the weather prediction community has evolved considerably over the last few decades, and thus the modes of interaction of the past may no longer be appropriate. This paper calls upon the community to initiate a new paradigm of cooperative research, development, and operations that will benefit all sectors of the discipline. The U.S. weather enterprise has a great deal going for it: the world's largest meteorological academic community, leadership in remote sensing technologies, the largest and most successful private sector, the largest governmental research community, and demonstrated great creativity. It is time these strengths are brought together in a synergistic and coordinated whole that will provide for substantial improvement in the quality, availability, and usefulness of weather information.

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References

Stoelinga M. T., P. V. Hobbs, C. F. Mass, J. D. Locatelli, B. A. Colle, R. A. Houze, Jr., A. L. Rangno, N. A. Bond, B. F. Smull, R. M. Rasmussen, G. Thompson, and B. R. Colman, 2003: Improvement of Microphysical Parameterizations through Observational Verification Experiment (IMPROVE). *Bulletin. Amer. Meteor. Soc.*, **12**, 1807–1826

Brian A. Colle, Joseph B. Olson and Jeffrey S. Tongue. 2003: Multiseason Verification of the MM5. Part II: Evaluation of High-Resolution Precipitation Forecasts over the Northeastern United States. Weather and Forecasting, **18**, 458–480.

Walter F. Dabberdt, Mary Anne Carroll, Darrel Baumgardner, Gregory Carmichael, Ronald Cohen, Tim Dye, James Ellis, Georg Grell, Sue Grimmond, Steven Hanna, John Irwin, Brian Lamb, Sasha Madronich, Jeff McQueen, James Meagher, Talat Odman, Jonathan Pleim, Hans Peter Schmid and Douglas L. Westphal. 2004: Meteorological Research Needs for Improved Air Quality Forecasting: Report of the 11th Prospectus Development Team of the U.S. Weather Research Program*. Bulletin of the American Meteorological Society: **85**, 563–586.

Mass, C., 1996: Are we graduating too many atmospheric scientists? *Bull. Amer. Meteor. Soc.,* **77***,* 1255-1267

NRC, 2003: Fair Weather: Effective Partnerships in Weather and Climate Services. Washington, D.C.: The National Academies Press

Pielke, R. Jr. and E. R. Carbone, 2002: Weather impacts, forecasts, and policy. An integrated perspective. Bull. Amer. Meteor. Soc., 83, No. 3, pp. 393–403

Zevin, S. F, and K. L. Seitter, 1994: Results of Survey of Society Membership: Demographics. *Bull. Amer. Meteor. Soc.*, **75**, 1855-1866.