THE UNCOORDINATED GIANT

Why U.S. Weather Research and Prediction Are Not Achieving Their Potential

BY CLIFFORD MASS

Although the U.S. meteorological community has made significant strides in weather prediction, more closely coordinated research and operations would accelerate progress.

There can be little doubt that weather prediction in the United States has improved considerably over the past several decades. Synoptic-scale numerical prediction models, such as the National Centers for Environmental Prediction's (NCEP's) Global Forecast System (GFS), are producing far more accurate forecasts of major cyclones and other large-scale features. High-resolution mesoscale models, such as the fifth-generation Pennsylvania State University (PSU)–National Center for Atmospheric Research (NCAR) Mesoscale Model (MM5), the Navy Coupled Ocean–Atmosphere Mesoscale Prediction System (COAMPS), and the Weather Research and Forecasting (WRF) model, often predict realistic mesoscale structures, a situation unheard of a decade ago. A national Doppler radar system [Weather Surveillance Radar-1988 Doppler (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. 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 community sentiment that weather prediction research and operations in the United States have significant problems, and that progress is far less than our discipline's potential. Many believe that the large American weather prediction enterprise has worked with insufficient coordination and cooperation, resulting in inadequate resources for key tasks, inefficient duplication of effort, slow progress in developing essential technologies, inadequate interactions with user communities, and unproductive or inappropriate use of limited manpower. Pielke and Carbone (2002), for example, noted that the goals of the weather prediction enterprise "are unlikely to be

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reached if the community proceeds in a balkanized fashion that has characterized it in the past" and that progress "requires strong and balanced leadership with a greater breadth of interaction than is presently associated with institutions, agencies, and sectors of the community in the United States." This opinion has been repeated at a number of recent meetings sponsored by the American Meteorological Society (AMS), the Weather Coalition, and others.

This paper examines the changes occurring in the weather prediction enterprise, reviews some warning signs, studies the issues of community cooperation and organization, and offers some suggestions on how the weather enterprise might proceed.

THE CHANGING WEATHER PREDICTION COMMUNITY. During the past decades the weather prediction community has changed greatly, both in its increased size and relative composition. The private sector has grown most rapidly, now standing as an equal to the government and academic sectors in its number of members, resources, and range of activities (Zevin and Seitter 1994; NRC 2003). In contrast, the National Oceanic and Atmospheric Administration (NOAA), and particularly the National Weather Service (NWS), now encompass a smaller proportion of the weather prediction community, but still provide critical observing, modeling, and warning infrastructure.

As the weather prediction community has evolved, the boundaries between the sectors have grown 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. Many university departments maintain Web sites with extensive weather resources, and private sector firms provide current forecasts and data over the Web or through cell phones and other wireless devices. While in the past weather data collection was monopolized by federal agencies such as NOAA and the Federal Aviation Administration (FAA), today all sectors of the community have active roles in collecting weather information. Some universities [e.g., University of Oklahoma (UOK)] maintain extensive regional networks, while others, such the University of Utah (MesoWest), and the University of Washington, collect, archive, and distribute the observations from a wide range of regional networks. Private sector firms are also involved in real-time data collection, 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 (online at www.wunderground.com).

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 traditional domains (NRC 2003), or can result in duplication of effort that wastes limited resources. Some tensions have become evident in the community (most acutely between some private sector forecasting firms and the NWS), but, as noted below, improved cooperation and dialog among members of the government, private sector, and research communities could go far in mitigating these problems.

The increasingly diverse and less centralized weather enterprise provides a challenge in the quest for leadership, something that is profoundly lacking today in the weather prediction community. As the NWS increasingly loses dominance, its ability to lead the community is reduced, and strategic planning becomes more difficult as the community becomes more heterogeneous. New coordination mechanisms and organizational approaches are required for the expanding weather enterprise, an issue discussed later in this paper.

SOME WARNING SIGNS. There are a number of warning signs that the U.S. weather prediction enterprise is not fulfilling its potential to provide the best possible weather information to the public and other users. As suggested below, lack of effective coordination and cooperation underlies nearly all of these problems.

The U.S. has lost leadership in global weather prediction. For a number of years the skill of the NWS NCEP global weather prediction model (the GFS) has been less than that of the European Centre for Medium-Range Weather Forecasts (ECMWF) global model, with the GFS lagging by approximately one day of useful skill. [Comparative prediction information for various modeling centers' global models is available from a number of sources, including NCEP's own verification site (online at 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 than that of the NWS GFS model.] Over the Northern Hemisphere, the skill of NCEP's global model is roughly equivalent to that of the global models used by the Met Office and the Canadian Meteorological Centre. This second-place status is in contrast to that of the U.S. meteorological establishment, which in size, breadth, and depth is far greater than that of the European community.

There are a number of reasons for the lesser performance of NCEP's Environmental Modeling Center (EMC). First, ECMWF enjoys nearly twice the scientific staff compared to EMC and has lesser responsibilities, for example, not having to deal with mesoscale atmospheric and real-time ocean prediction. EMC is not only underfunded, but over half of its support is from "soft money" that is not only transient, but brings with it other demands. ECMWF uses a more advanced data assimilation approach [four-dimensional variational data assimilation (4DVAR)] than that of NCEP [three-dimensional variational data assimilation (3DVAR)] and is more effective in using satellite data. With more computer resources and fewer responsibilities, ECMWF has been able to run its global model at roughly twice the horizontal resolution as NCEP.

But there are other factors that have allowed ECMWF to surpass the United States: a greater willingness to interact with the research community, the pooling of experts and resources from the entire European community, and clear strategies for effective model development. Unlike NCEP, ECMWF hosts numerous workshops during the year, has an annual seminar-reviewing progress, and facilitates a very active visitors program. In contrast to other facilities such as the Canadian Meteorological Centre and the Met Office, NCEP has also been slow to develop a unified model applicable to all scales, an approach that allows a greater concentration of resources and personnel on critical modeling issues. In short, a lack of resources and intellectual isolation have undermined NCEP's ability to take advantage of the substantial resources of the U.S. meteorological community in global prediction, and similar problems extend to mesoscale forecasting.[1]

Ineffective mechanisms for coordinating weather research. This section provides three examples of how U.S. weather prediction research is not properly coordinated with the operational and user needs of the nation and documents continuing problems with the transition of research to operations.

The decline and "reset" of the U.S. Weather Research Program (USWRP). Initiated in the early 1990s, the USWRP had the goal of funding and coordinating weather research that could be transferred to operational application. Although the USWRP has made substantial contributions, it has generally failed to bridge the gap between the research and operational communities. Recent discussions of "resetting" the USWRP have been fruitless, and the USWRP today is without a chief scientist, its community conference calls and newsletter have been suspended, and its program office has been disbanded.

An early direction of the USWRP was to form prospectus development teams (PDTs) that reviewed and made recommendations on a wide range of topics, including heavy precipitation, hurricane forecasting, hydrometeorology, and societal impacts.[2] Although a good starting place, there has been little follow-up to the PDT reports, which have become increasingly out of date. Later, the USWRP identified a triad of key topics (data assimilation, precipitation, hurricane landfall) for which it held several workshops. The USWRP never received sufficient financial support from federal agencies and its ability to fund university research or technology transfer projects was extremely limited, provoking widespread community frustration.

Perhaps the greatest success of the USWRP has been the Joint Hurricane Testbed (JHT), which funded research to accelerate technology infusion focused on hurricane analysis and prediction. Over the past four years, JHT research projects have resulted in innovations that have been transferred into operations. Unlike many of the other USWRP efforts, the JHT has enjoyed focus, larger funding, and a clear path to implementation.

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 little sense of a community working together toward specific and important goals, other than "weatherproofing the nation." A

[1] Similar conclusions were reached in the "valley of death" National Academies report (NRC 2000).

[2] Many of the PDTs have been published in *BAMS* or can be accessed on the USWRP Web site (online at http://box.mmm.ucar.edu/uswrp/PDT.html).

profound deficiency has been the lack of a USWRP oversight group representing the meteorological and user communities as a whole. Rather, a narrow collection of federal agencies [the Interagency Working Group (IWG)] provided sporadic direction, 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.

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 evaluating the ongoing priorities of the research and operational communities, and then coordinating the necessary research and development. Without such an active connection between research and application, 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. The USWRP has also been ineffective in public relations, failing to connect the inadequacies of current weather prediction with solutions, which, with sufficient resources and cooperation, could greatly serve the nation both in saving lives and enhancing the country's economic infrastructure. In addition, the USWRP did not clearly document the large societal impacts of weather, which is essential ammunition for securing necessary resources.

A LARGE NUMBER OF U.S. MESOSCALE MODELING SYSTEMS AND INSUFFICIENT COOPERATION HAVE RESULTED IN A LACK OF CRITICAL MASS FOR SOLVING KEY PROBLEMS. The history of mesoscale model development in the United States is characterized by too 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., the NCEP Eta Model, NCEP Nonhydrostatic Mesoscale Model (NMM), MM5, Colorado State University (CSU) Regional Atmospheric Modeling System (RAMS), UOK Advanced Regional Prediction System (ARPS), Navy COAMPS, NCAR Advanced Research WRF (ARN), and NCEP Regional Spectral Model (RSM)]. Although the United States is endowed with substantial depth in its weather modeling community, the existence of so many platforms has ensured that sufficient resources for attacking key problems have not always been available. For example, it is well known that there are major problems in physics parameterizations for virtually all modeling systems, particularly for grid spacings of 1–10 km.[3] Even major operational centers such as NCEP's EMC have only a handful of individuals working on each of the key physics parameterizations. Although modelers and physics specialists from the various groups do meet on occasion at scientific conferences and workshops, the level of active cooperation and coordination between groups has been inadequate, and academic research has not flowed effectively into the operational models. Most acutely, poor technology transfer between the university community and NOAA has been a major roadblock for the improvement of NWS forecasting models.

A recent attempt to develop a true community mesoscale mode (WRF) has met with some success, but has suffered from a lack of coordination and consensus. 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 Model. The goal was to end previous divisions within the modeling community, in which the universities used one set of modeling systems (MM5, RAMS, ARPS), while the operational communities used others (Eta Model, COAMPS). With limited funding, a general model infrastructure and a dynamical model core (ARW) have been developed at NCAR, with some assistance from NOAA's Forecast Systems Laboratory in the development of preprocessing software. The National Weather Service, nominally a participant of the WRF effort, has developed its own next-generation model (the NMM) to work either within or outside of the WRF infrastructure. Thus, instead of having one community model there is essentially two dynamical models under a single infrastructure "wrapper." The hope of having "plug compatible" physics that could move between multiple dynamical cores has not proven to be viable. Furthermore, this is little objective evidence to show that supporting two cores is worthwhile for either deterministic or probabilistic forecasts. However, it is clear that dual cores will continue the unnecessary separation of the research and academic communities, with all of the attendant problems. With limited and divided personnel and

[3] 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. 2003), and major questions exist regarding nesting and cumulus parameterizations (Colle et al. 2003).

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 Model, and neither NCAR, NCEP, nor the university community appear to have the resources to make significant progress in developing improved parameterizations. Although a number of development teams were established to oversee WRF model improvements, many of these groups have been inactive.

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 on the decision-making oversight board. The WRF Science Board, which was tasked to supply scientific oversight, met infrequently and has recently been terminated. Recently, a Research Applications Board has been established to secure more input from the research community on model development, but decision making is still in the hands of a limited collection of federal agencies and NCAR. Without broad representation of the groups that develop and use the model, nonoptimal decisions are inevitable and the lack of ownership and involvement lessens the probability of garnering additional resources.

INEFFICIENT AND POORLY ORGANIZED RESEARCH STRUCTURE IN NOAA. The National Weather Service has only a limited research capacity within its own organization. Rather, the government research laboratories that are tasked to provide new scientific and technical advances for the NWS are *outside* of the organization under NOAA's Office of Oceanic and Atmospheric Research. Such laboratories and research centers include the Geophysical Fluid Dynamics Laboratory (GFDL), the Hurricane Research Division (HRD), the National Severe Storms Laboratory (NSSL), the Earth System Research Laboratory [ESRL; formerly Forecast Systems Laboratory (FSL)], the Climate Diagnostic Center (CDC), the Pacific Marine Environmental Laboratory (PMEL), and the Atlantic Oceanographic and Meteorological Laboratory (AOML), among others. The result of this structure is that the director of the NWS has little control over the research that supports the mission of the Weather Service. Without direct management by the "user" agency and with research tasks balkanized over many laboratories, the research agenda has been inefficient, developing technologies that are unneeded or redundant, and often do not provide the research and development required by the NWS. Examples of such problems are numerous, including redundant mesoscale analysis systems [ETA Data Assimilation System (EDAS), rapid uptake cycle (RUC), Local Analysis and Prediction System (LAPS)], and the prototyping of expensive and impractical stationary balloon dropsonde systems [Global Air–Ocean In Situ Sensor (GAINS)]. Profound underfunding of NCEP science has undermined research there and an unwillingness to fund significant extramural research and recent suspensions of new extramural funding for the Cooperative Program for Operational Meteorology, Education, and Training (COMET) and Collaborative Science, Technology, and Applied Research (CSTAR) programs have isolated the NWS from potentially valuable research in the academic community.

Problems with the dissemination of weather information. The effective dissemination of weather data and forecasts demands close coordination between the meteorological and user communities—cooperation that has often been lacking. A recent example of the dangers of the lack of communication is the Interactive Forecast Preparation System (IFPS), the new National Weather Service system for forecast preparation and dissemination. Designed with minimal input from forecasters, users, or the weather research community, IFPS [also known as the National Digital Forecast Database (NDFD)] 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 as well as being automatically translated into text. As noted by Mass (2003) and others, this system has a number of serious problems, including a lack of bias correction, inadequate access to full model resolution for the three-dimensional model grids, coordination problems with adjacent offices, a lack of analyses of record for verification, a completely deterministic perspective, and problems with the text translation, to name only a few.

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 forecast dissemination problem is that model forecast grids produced by the National Weather Service are not readily available to the private sector because of a lack of bandwidth and server capacity. Ironically, National Weather Service offices themselves share in this inability to secure the full-resolution model grids.

Dissemination problems associated with a lack of coordination/cooperation extend to observational data. During the past few years there has been an explosion of surface weather stations owned by groups and individuals, aircraft observations from commercial aircraft [Aeronautical Radio, Inc. (ARING), Communications Addressing and Reporting System (ACARS)], and weather radars owned by the media and others. Unfortunately, the surface data networks are generally uncoordinated, often with multiple observations in close proximity, and without effective national organization for their collection, quality control, archival, and dissemination. The power of centralized, cooperative collection of surface networks has been demonstrated regionally (western United States) by MesoWest (Horel et al. 2002) and the Northwestern States Network (NWNet) (Mass et al. 2003). Recent meetings such as the AMS "Community Summit on Developing a National Mesoscale Observing Network" held in Dallas, Texas, on 27–28 July 2004 and the USWRP Mesoscale Observing Networks Workshop held in Boulder, Colorado, on 8–9 December 2003 have brought together a wide-ranging group to discuss this important issue. Access to the exponentially growing ACARS flight-level data, which provide thousands of ascent and descent soundings into U.S. airports each day, is highly restricted, making it difficult, if not impossible, for private sector, research, and state/local users to gain operational access to this highly valuable data source. Private weather radars have been installed throughout the country, but there is no organized attempt to collect and combine their information. 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.

But, there is a deeper communication problem, one considered in some depth by Hooke and Pielke (2000), namely, that many of the improvements in prediction and observing capabilities have not been transferred into enhanced products for decision makers and users. It is clear that even the current level of weather information could be far more effectively applied by society. A major issue is that the weather community often does not understand how users interpret or understand weather information or how it could be "packaged" to be of greater value. New icons and displays are developed by the weather community with little understanding of whether they are effective or useful. Clearly, the community as a whole needs to invest resources in the expert personnel and user evaluations that will provide solid insight into the optimal ways to communicate our rapidly increasing knowledge. Furthermore, new types of applications, designed to facilitate decision making in transportation, aviation, and other industries could be developed. Probabilistic and uncertainty information now produced by operational ensemble systems could be made available in a useful form for energy and other applications. In short, the forecast process needs to be seen as an end-to-end endeavor from observation and modeling to user application in order for it to be most effective, and such an approach demands active cooperation and coordination between the scientific and user communities—a process that has been generally lacking.

Developing tensions in the community, particularly between the private sector and the National Weather Service. During the past decade, increasing tensions have developed between some in private sector meteorology, particularly members of the Commercial Weather Services Association (CWSA), and the National Weather Service. A major stimulant to such tensions came in December 2004 when the NWS repealed its 1991 noncompetition and nonduplication policy in response to the recommendations of the NRC Fair Weather report. Subsequently, in 2005, Senator Rick Santorum (R-PA) introduced CWSA-supported legislation (S-786) that limits the National Weather Service to producing products that private sector weather companies cannot or are unwilling to offer, unless the information is related to "severe weather forecasts and warnings designed for the protection of life and property" or required under international accords or congressional mandates. Furthermore, this act calls for the NWS to issue all data, information, guidance, forecasts, and warnings without delay to ensure that all members of the public have the opportunity for simultaneous and equal access to the information. The first clause is in response to the CWSA perception that the NWS is unfairly competing with the private sector, and the second reflects experiences in which the NWS has provided tailored predictions, more timely information, or enhanced services to specific industries and users. The ill feelings and arguments attendant with this conflict have undermined the ability of the weather community to work together on common goals, such as improved national numerical weather prediction and increased support for weather research.

Insufficient funding for research and operations. Although weather prediction is critically important for the U.S. economy[4] and for the protection of life and safety, funding for related research and development is inadequate and lags that of climate and related disciplines, such as oceanography and astronomy. To a significant degree, this lack of funding is the byproduct of insufficient community cooperation.

Overall funding for weather prediction–related research is now in decline. NSF weather research support is steady state at best (particularly when inflation is considered); meteorology-related research at the Office of Naval Research (ONR), both basic and applied, has declined about 40% since 2001, and will probably decline another 10%–15% [Source: R. Ferck, Team Leader, Marine Meteorology Program, ONR). Total military funding for meteorological research has declined by 46% between 2001 and 2005 (information from the Office of the Federal Coordinator for Meteorology, available online at www.ofcm.org). NOAA has cancelled the latest request for proposals of the COMET cooperative program for joint NWS–university local weather research and will cut the other major cooperative research program (CSTAR) at least in half. At NCEP's Environmental Modeling Center, staffing is half that enjoyed at ECMWF and over half the budget is from "soft money," a major impediment for an operational center that must plan for the future (NRC 2000).

Climate research consistently receives more support than weather prediction research. In fiscal year (FY) 2003, total National Science Foundation funding in support of the U.S. Weather Research Program was $8.8 million (J. Gaynor, USWRP Project Office 2005, personal communication), while NSF support for the U.S. Global Change Research Program (USGCRP) was $187 million (information from the Office of the Federal Coordinator for Meteorology, online at www.ofcm.gov/). In NOAA's Office of Oceanic and Atmospheric Research, under which the various NOAA laboratories reside, $166 million was directed at climate research, but only $57 million was spent on weather and air quality research. Why is funding for weather prediction research and development in decline when the quality of weather forecasts influences the immediate safety and economic well being of most Americans? Why is climate favored over weather prediction in federal research support? When the hurricanes of the summer of 2005 struck the southeast United States, why were the media buzzing with stories on global warming, rather than problematic intensity forecasts and what were needed to fix them? As will be described below, one factor is certainly the inability of the weather prediction community to reach consensus, to effectively lobby together for adequate support, and to communicate the potential of the science.

[4] The National Research Council (NRC 1998) estimated that more than $1 trillion of the nation's 7 trillion dollar economy is directly weather sensitive.

Lack of strategic planning and leadership. A major issue for the weather prediction community is that it lacks a process for strategic planning that prioritizes research and development or provides an overall vision of the direction of the community. Pielke and Carbone (2002), after suggesting that the weather enterprise is analogous to an orchestra without a conductor, noted, "No organization or entity has embraced the collective measure of responsibility for improving forecast processes." Echoing the Pielke and Carbone perspective, an NRC study of the future of atmospheric sciences in the twenty-first 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 . . . all partners in the atmospheric enterprise . . . must join together as an effective team focused on the future.

A more recent NRC report (NRC 2005) observed that NSF's Atmospheric Sciences Program and other agencies dealing with atmospheric research work on an ad hoc basis without sufficient strategic planning. The NRC report notes that the Office of the Federal Coordinator for Meteorology (OFCM) does produce annual summaries of federal weather-cited activities and research as well as organizing occasional workshops, but additional mechanisms for joint planning are required.

At the July 2005 weather enterprise meeting in Boulder, staffers from the U.S. Congress as well as individuals involved in lobbying for weather research provided a stark analysis of the U.S. weather prediction community's attempts to organize its priorities and to garner additional support. Joel Widder, a government relations consultant for the University Corporation for Atmospheric Research (UCAR), noted that successful advocacy requires a united community that has reached consensus on its priorities. In addition, the community must be able to communicate "a single central message that can be understood and appreciated by federal decision makers and an informed influential public." The atmospheric sciences community has achieved neither.

He noted the example of astronomy in which decadal meetings organized by a NRC Board on Atmospheric Sciences and Climate (BASC) committee include all relevant players who prepare a consensus-planning document that is then supported by the entire community. Oceanography has an analogous mechanism in the U.S. Commission on Ocean Policy. Historically, the U.S. weather prediction enterprise has had no representative body setting overall goals and plans and no one group or entity supplies overall leadership. Narrow planning groups (e.g., often a subset of federal agencies), the lack of community consensus, and tensions between the various sectors have led to balkanized and uncoordinated attempts to move science forward and have been ineffective in securing federal and other resources. There are some encouraging signs, however. As noted below, recent enterprise-wide meetings and the recent establishment of the AMS Commission on the Weather and Climate Enterprise have provided new venues for community discussion and prioritization. But these steps are just the beginning for a community acutely lacking in consensus, overall goals, and, most importantly, leadership.

COMMUNITY INITIATIVES TO FOSTER BETTER COOPERATION AND COORDINATION. There has been increasing interest within the weather prediction community in enhancing communal decision making as well as facilitating enterprise-wide approaches to major problems. 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). Partially in response, 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 and other venues for the discussion of important enterprise-wide issues (information online at www.ametsoc.org/stacpjes/cwce/). 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 in Dallas (July 2004) on "Developing a National Mesoscale Network." Another new community organization, the Weather Coalition (available online at www.ucar.edu/oga/wx-coalition), has brought together the private sector, academia, and others to advance weather research. More recently (July 2005), the AMS Commission on the Weather and Climate Enterprise and the Weather Coalition organized a large three-day "Community Meetings on the Future of the U.S. Weather Prediction Enterprise" in which a representative cross section of the weather community examined the strengths and weaknesses of the U.S. weather prediction enterprise, discussed how community decisions should be made, and considered the need for a more cooperative and coordinated approach to weather prediction operations and research (information available online at www.ametsoc.org/boardpges/cwce/metcolorado.html). The key message from all of 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.

DECISION MAKING AND COORDINATION FOR THE U.S. WEATHER PREDICTION ENTERPRISE. The underlying cause of many of the problems noted above is the way in which 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 the Department of Defense (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.[5] This pattern of relatively circumscribed governance 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, because agency decisions re-

[5] NCAR sometimes suggests it also represents the university community, but in reality this is not the case. NCAR is a huge institution that has grown far beyond a support organization for university needs in computing and observation. More frequently, NCAR is actually a competitor with the universities in securing grant support from non-NSF agencies.

garding major national capabilities and infrastructure have a profound influence on the operations and viability of other portions of the weather enterprise, extensive community consultation and interactions are needed. Wise decisions often cannot be made without nonagency 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, much of the effort by the academic community on the MM5 and other community mesoscale models is not federally funded, but is provided by academic institutional support of salaries and infrastructure. The private sector provides a huge and expensive infrastructure for disseminating weather information and represents an essential communication tool for the National Weather Service and other government agencies.

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) should be coordinated 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 thereby 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 are available to the agencies alone. The traditional model has viewed a limited "pie"—one that is 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 becomes 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, mesoscale ensembles, and applications, such as road weather support and air quality forecasting (Mass et al. 2003). In the Northwest consortium, resources are pooled and major decisions are made by the group. It has been the Northwest experience that nontraditional sources of funding for weather prediction research and operations are available if others are allowed a place at the leadership table. Joint decision making, prioritization, and support encourages research to be directed toward the most acute needs and fosters innovation by suggesting new applications of weather information. 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 may prove to be uncomfortable to those accustomed to unfettered control of resources and manpower, but it is a 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 compel 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.

SOME CONCRETE SUGGESTIONS FOR MOVING FORWARD. This section provides a description of some steps whereby the weather prediction enterprise might more effectively advance the discipline, coordinate its efforts, and better fulfill the needs of its users. The most acute requirement of the community is to initiate a more cooperative and representative form of decision making and to fill the "leadership gap" from which we acutely suffer.

Step 1: Reduce the tensions among sectors of the community. The tensions among sectors of the weather prediction enterprise, and most acutely between the private sector and the NWS, is substantially weakening the enterprise's ability to move forward. Certainly, the fact that private-sector firms feel that their only remedy to perceived NWS intrusions is through legislation is a warning sign that something is very wrong. Some potential approaches for dealing with these tensions include the following.

(a) The National Weather Service should establish an advisory committee that is widely representative of the weather prediction community and users. The establishment of such a committee was a major recommendation of the NRC Fair Weather report and received overwhelming support at the July 2005 weather enterprise meeting in Boulder. This advisory committee will provide the NWS with advice on interface issues between the NWS and other sectors of the community, and will serve as an advisor on proposed new NWS products and initiatives.

(b) NOAA/NWS should amend its "Policy on Partnerships in the Provision of Environmental Information" to state that the NWS will not supply forecasts or products for specific industries, companies, or individuals unless required by law. Furthermore, the NWS should make more of an effort to ensure that its forecast offices are not providing industry-specific forecasts, a practice for which there are a number of examples.

(c) The NWS should put more effort into providing the full, high-resolution data stream of observations and forecasts to the entire community in a timely fashion. Currently, private sector access through NWS servers is often slow and inadequate.

(d) The private sector should accept the fact that the NWS will be using all modern technologies (e.g., wireless communication) to provide its products and that some overlap between the private sector products and NWS information is inevitable.

(e) The lack of representation of major sectors of the weather prediction community on important planning and management committees (e.g., WRF) has been a significant, and unnecessary, source of tension. Such committees should be widely representative, including members of the academic, private sector, and user communities.

(f) The AMS Commission on the Weather and Climate Enterprise should vigorously expand its role to provide venues for the discussion of weather enterprise issues, both at the AMS annual meeting and at other gatherings during the year. Furthermore, the AMS Commission itself, with wide-ranging representation of the community, should meet regularly and increasingly take on a leadership role in issues of importance to the entire weather enterprise.

Step 2: Community-wide long-term strategic planning should be initiated. An enterprise-planning committee should be established, either through the AMS Enterprise Commissioner or a NRC BASC committee, that will meet periodically to establish community priorities for the next several years. This committee would include wide representation from the weather enterprise and user communities and would serve a similar function as the astronomy decadal BASC reviews.

Step 3: The community must establish better mechanisms for organizing and coordinating development and research to serve operational and user needs. A critical deficiency in the current weather prediction establishment is a lack of coordination and planning capabilities for research and development. No weather enterprise group is asking the critical questions: What are the deficiencies of the current observing, modeling and data assimilation systems and how will the resources, both financial and personnel, be found to deal with them? How can duplication of effort be reduced? As noted above, the USWRP failed to provide such community organization and no other entity has filled the void.

A potential approach is to expand upon the newly initiated Developmental Testbed Center (DTC) in Boulder. The Developmental Testbed Center is a facility where the numerical weather prediction research and operational communities will interact to accelerate the testing and evaluation of new models and techniques both to improve the technology and for operational implementation. This center, marginally funded at this time, is currently involved in testing/supporting both the ARW (NCAR) and NMM (NWS) dynamical cores of WRF, the new national mesoscale modeling system. The DTC should expand its role to coordinate and support the nation's model development and testing. There should be several components to this approach.

(a) A DTC Oversight Board that is broadly representative of the weather prediction and user community should be established. This group would include individuals from the operational, academic, and private sectors, as well as user representatives. It would help coordinate research and development, coordinate resources, and would hold regular fora and workshops to secure community input and guidance on important modeling issues. The DTC would expand its purview to include global as well as mesoscale numerical prediction.

(b) Standing, active DTC working groups will be established for guiding the development of key aspects of the weather prediction enterprise. Possible working groups include

- model physical parameterizations,
- observations and assimilation,
- model development,

- ensembles, statistical postprocessing, and probabilistic prediction,
- forecast and model verification, and
- weather applications.

Each of the working groups would have subgroups in major areas that require coordination (e.g., a microphysics subcommittee).

(c) In addition to the oversight and working group meetings, there should be topic workshops (e.g. on improving PBL parameterizations), and annual or biennial plenary meetings that would be wide ranging.

An example of how this structure might work would be as follows. The model physics working group and its subcommittee on the PBL concludes that inadequate PBL parameterizations are a major roadblock for further forecast progress (quite true). With the support of the oversight committee, a workshop is held at DTC to examine this problem and make recommendations. Based on the results of this workshop, the boundary layer subcommittee puts together a plan for a research program with an active field phase to gather critical data. The plan goes to the oversight committee, which after approving the effort, coordinates funding for the effort from a collection of agencies and groups. The model physics working group and its subcommittee actively tracks and coordinates the project as it unfolds. New parameterizations developed by the effort are tested at the DTC, NCEP, and at regional prediction centers.

Close cooperation between these new entities, and particularly among the AMS Commission, the DTC Oversight Board, and the strategic planning committee, will be essential. Each has a role to play: the AMS Commission providing overall continuous leadership, the DTC Oversight Board taking responsibility for the nuts and bolts technology development and transition, and the strategic planning committee taking a long view of the needs and prioritization of the weather prediction enterprise.

SUMMARY AND CONCLUSIONS. The U.S. weather prediction effort has accomplished a great deal, but its potential has been hampered by a lack of coordination and cooperation. Furthermore, the nature of the U.S. 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.

Weather prediction is an extraordinarily complex enterprise. The computer forecast models at its core, along with the associated data assimilation, data collection, and postprocessing 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. The use and communication of this weather information is equally as complex, requiring a detailed understanding of the user community and its requirements as well as a profound knowledge of how humans interpret and perceive information. Weather prediction is not a mature technology. There is an enormous amount of work yet to be done, particularly regarding physical parameterizations and data assimilation, hurricane intensification, probabilistic prediction, and effective communication of weather information. Significant progress will demand extensive observational, personnel, and computing resources that only the coordinated application of the entire enterprise's capabilities can provide.

This paper suggests a multifaceted approach to dealing with the lack of enterprise-wide coordination. First, steps must be taken to reduce tensions within the enterprise, including the establishment of a National Weather Service advisory committee, the agreement by the NWS to refrain from producing products for specific industries or groups, the widening of membership on important management committees, and the aggressive expansion of the new AMS Commission on the Weather and Climate Enterprise, both in holding fora and acting as an interlocutor between sectors of the weather prediction enterprise. Second, community-wide strategic planning must be initiated. Finally, through the Developmental Test Center in Boulder the community must build a system for cooperatively improving the underlying technology of weather prediction and its application. These innovations and others are required if the U.S.

weather enterprise is to regain its stature as a world leader in both research and operational meteorology, and will allow it to far better serve the nation.

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