50TH ANNIVERSARY OF OPERATIONAL NUMERICAL WEATHER PREDICTION

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Editorial Note: A Meeting to Remember. The past few years have marked several important anniversaries of landmark events in the history of numerical weather prediction (NWP). This past August was the 60th anniversary of the founding of the Meteorology Project at the Institute for Advanced Study in Princeton, New Jersey, the progenitor of modern weather prediction modeling. Similarly, 2004 was the 50th anniversary year of operational numerical weather prediction. To celebrate that anniversary and the vast changes NWP has spawned in weather forecasting, the National Centers for Environmental Prediction (NCEP), the Air Force Weather Agency (AFWA), the Fleet Numerical Meteorology and Oceanography Center (FNMOC), the National Weather Association, and the American Meteorological Society (AMS) cosponsored the “Symposium on the 50th Anniversary of Operational Numerical Weather Prediction,” held on 14–17 June 2004 at the University of Maryland in College Park, Maryland. For three full days, participants shared their recollections, examined the state of the art, and discussed the future of numerical weather prediction. For more details, the symposium agenda, a compilation of many of the most important historic NWP papers (available as a CD-ROM), and PowerPoint presentations are available online at www.ncep.noaa.gov/nwp50. This essay was inspired by the major themes of that meeting.

The Joint Numerical Weather Prediction Unit (JNWPU), a financial, administrative, and personnel collaboration of the U.S. Weather Bureau, Navy, and Air Force, opened its doors on 1 July 1954. The operational unit was the culmination of research by the Meteorology Project at the Institute for Advanced Study in Princeton, New Jersey; the Numerical Prediction Project at the Air Force Cambridge Research Laboratory’s Geophysical Research Directorate; and the International Meteorological Institute in Stockholm, Sweden. Directed by George Cressman, the JNWPU issued its first operational forecast on 6 May 1955—the day of its dedication. Operational numerical weather prediction had stirred to life only a few months earlier, in late September 1954, when Carl-Gustav Rossby’s Stockholm-based team produced the first real-time barotropic forecasts on the Binary Electronic Sequence Calculator (BESK).

The JNWPU’s first operational forecast maps were 36-h 400-, 700-, and 900-mb prognoses. The forecast charts were meteorological in nature and surpassed expectations, but did not include sensible weather elements and were far from good enough to replace subjective human-based forecasts. However, the operational efforts on both sides of the Atlantic provided the means for operational forecasters, theoreticians, and
Fred Shuman (left) and Otha Fuller circa 1955 at the IBM 701. The 701 was the first computer used by the JNWPU to produce operational numerical weather prediction.

Atmospheric modelers to combine forces to push NWP from the fringes of theoretical and applied meteorology to mainstream atmospheric science within a decade.

Although far from obvious at the time, real-time numerical weather prediction is now seen as the greatest intellectual achievement and scientific advancement in twentieth-century atmospheric science. Like most advances in the atmospheric sciences, NWP was an international achievement dependent upon close cooperation among all facets of the meteorology community—academic and governmental, theoretical and applied, research and operational, and military and civilian. Meteorology’s successful research and operational attack on NWP depended on exploiting conditions produced by the spoils of World War II: the availability of vast amounts of surface and upper-air data, a 20-fold increase in meteorologists, and the introduction of the new electronic digital computer.

Atmospheric scientists continued to exploit advances in all of these areas throughout the remainder of the century. Data sources increased with the development of remote sensing. High-speed communication links delivered observational information quickly. Computer designers created and produced machines with more memory and faster processing capabilities. Moreover, some of the brightest minds in the world, fascinated with atmospheric processes, pursued advanced degrees in newly established academic programs. The interplay between technological advancement, intradisciplinary cooperation, and educational opportunities, coupled with a determination to understand the Earth–atmosphere system and apply that knowledge for the benefit of both science and society, has been the driving force behind numerical weather prediction. We see this same force at work as the twenty-first century unfolds, creating great promise for the future of numerical weather prediction.

REFLECTIONS ON THE EARLY DAYS OF OPERATIONAL NUMERICAL WEATHER PREDICTION

The 50th Anniversary Symposium was a special occasion for a number of reasons, not least because it gathered a number of the pioneers of numerical weather prediction. Several of them shared their thoughts about the leading personalities and principal concerns of the early days of computers in forecasting. We quote from their presentations:

ON RICHARDSON
Bo Doos: It was a remarkable piece of work. Nevertheless, I do not think his contribution had very much of an impact on operational NWP. He was too far ahead of his contemporaries in his vision of what might be possible. There was no Lorenz in these days to inform him that it is not always true that the more equations you add to describe a system, the more accurate will be the eventual forecast.

George Platzmann: At the time operational NWP was being developed, in the mid-1950s, I believe
A 1000-mb prog from grid-point “contouring” program written by Air Force Lt. Col. Art Bedient. Early model resolution was determined by the characters that could be printed per inch by the JNWPU’s computer printers. A “bedient” was set as the geographic distance between NWP grid points of one-half-inch separation on a polar stereographic map projection true at 60° with a 1/30,000,000 scale. The resolution of the first NWP models were set at one bedient (381 km). Future models had resolutions set at ½ bedient and ¼ bedient.

Richardson’s contributions were viewed mainly in terms of his failed multilevel primitive-equation model. Paradoxically, his approach may have been more influential than at first sight appears, because it provided both a goal to strive toward and a lesson in how not to begin. I should add that although Richardson came to understand the underlying reason for his failure, it took about 25 years for a simple remedy to appear, the barotropic vorticity equation, which if I’m not mistaken, was the starting point for operational prediction.

ON ROSSBY
Bo Doos: Rossby had the ability to concentrate on the important processes. He did not attempt to take into account for example the evaporation of falling leaves!

ON CHARNEY
Bo Doos: My first reaction [to Charney’s forecast]: Not much! The reason for this answer is that the first time I read this paper I had little knowledge of meteorology and no experience in weather prediction. Maybe my comment was: “Well, not bad at all.” It was only later I recognized its importance.

political and social events, scientific and academic efforts within government laboratories and university departments, and technological developments in computer and communication systems. Despite the theoretical work of the nineteenth century, early twentieth-century weather prediction was still more art than science. Its practitioners were often looked down upon by their mathematically rigorous scientific brethren. One scientist who decided to provide a mathematical and physical basis for meteorology was Norwegian physicist Vilhelm Bjerknes. His participation in this endeavor was a product of broader trends. As historian of science Robert Marc Friedman argued in his book on the Bergen School, Appropriating the Weather, Bjerknes applied his circulation theorem to the atmosphere and oceans because there was no funding for his theoretical physics field in Norway. Having committed himself to a new career path, Bjerknes focused on applying physical principles that could be solved with mathematical techniques and argued that meteorologists needed to calculate the weather. Because the hydrodynamical equations were never going to be analytically solvable, Bjerknes proposed graphical techniques.

It is impossible to know how much traction Bjerknes’s ideas would have gained had World War I and the rapid rise of aeronautics not intervened. Twentieth-century wars were extremely advantageous for advancing meteorological theory and applications. Military leaders on the ground, at sea, and in the air needed significantly more meteorological support than in past conflicts. Pilots needed weather support, and they greatly increased the amount of upper-air data available to forecasters. Observational
First JNWPU Director George Cressman and Air Force Lt. Col. Art Bedient preparing to mount a data tape for computer-microwave linking (c. 1960).

Norm Phillips: I believe that the largest breakthrough in the early stages of NWP was made by Jule Charney. First, he carried out a scale analysis of large-scale motion, in which he derived the quasigeostrophic system of prediction equations. This was in his 1948 paper "On the scale of atmospheric motions." He wrote this in Norway, where he spent about 8 months in Oslo, with Eliassen and Fjortoft. He was stimulated in this analysis by his visit of 6 months with Rossby in Chicago, and attendance at a meeting in Princeton called by von Neumann in August 1947. Charney then joined von Neumann in Princeton and laid out a plan for implementing NWP. In his next paper ("On a Physical Basis for Numerical Prediction of Large-Scale Motions in the Atmosphere"), Charney examined the volume of the atmosphere that should be considered to make a one-day forecast, and also derived a method to define an equivalent barotropic atmosphere. This was the first time that a logical method had been used to focus on the 500-mb level as the most realistic level at which a barotropic model could be applied. But his deduction of the horizontal area that should be considered was more optimistic than justified, primarily because he ignored to some extent the behavior of very long waves.

Research based on instruments carried by tethered kites and balloons, free-floating balloons, and, later, radiosondes added to the data pool. Yet, forecasting still remained an art form even as its scientific underpinnings improved.

One who pursued a frontal attack on the hydrodynamical equations was British meteorologist Lewis Fry Richardson. Carrying out voluminous calculations between ambulance runs in his makeshift office, Richardson's famous unsuccessful wartime attempt to forecast the weather by solving primitive equations attracted short-lived attention. In addition to producing flawed forecast maps, the work was completely impractical in the 1920s. Richardson estimated 64,000 human computers would be required just to keep pace with the unfolding weather. Theoretical work continued, but nascent numerical weather prediction died.

World War II provided the necessary conditions for NWP to reemerge and flourish: expanded data, a 20-fold increase in professional meteorologists, and the development of electronic digital computers. World War II was fought in the air and in all corners of the globe. Tens of thousands of pilots needed accurate, timely forecasts no matter where their mission, either at high latitudes, or in the Tropics or oceanic areas. Forecasts depend on data and, to fulfill this need, surface and upper-air stations spread over the globe, providing coverage to areas that had long been meteorological "black holes." Forecasts also depend on forecasters, and thousands of young mathematics- and physics-savvy men and women received intensive, graduate-level educations in meteorology so they could support military forces. The large increase in observations coupled with a large new population of scientifically trained meteorologists met the first two necessary conditions for a new assault on NWP. The third condition—an electronic digital computer—was also an outcome of the war. When brilliant Hungarian-born mathematician John von Neumann proposed using the computer on his drawing board to forecast the weather, the U.S. operational meteorology community was ready to take him up on the offer. Weather Bureau Chief Francis W. Reichelderfer drew in U.S. Navy and Army Air Force meteorologists who concurred with his assessment that NWP was an opportunity worth pursuing. With the Office of Naval Research (later joined by the air force) providing the funds, The University of Chicago's Carl-Gustav Rossby rounding up potential personnel, and Rechelderfer working to keep the effort alive, the Meteorology Project was born at the Institute for Advanced Study in Princeton, New Jersey.
Jersey, in August 1946. Then, just as today, cooperation across agencies and sectors was critical for the advancement of numerical weather prediction. Military, civilian, and academic meteorologists all contributed from their strengths to further theoretical and applied atmospheric science. The history of operational NWP provides many salient lessons on how interdisciplinary cooperation produces outstanding success.

The Meteorology Project’s first two years were difficult due to a serious lack of personnel. In the summer of 1948 help arrived in the form of Jule Charney, fresh from a fellowship year in Norway where he developed a set of predictive equations solvable by von Neumann’s computer and a filtering technique to keep the solution under control, and Norwegian meteorologist Arnt Eliassen. While they and an ever-changing team of theoretical meteorologists worked on barotropic and baroclinic models in Princeton, former project member Philip D. Thompson developed models at the Air Force Cambridge Research Laboratory. In Stockholm, Rossby’s international team, including U.S. meteorologists, launched its own modeling effort.

Early runs on Army Ordnance’s Electronic Numerical Integrator and Computer (ENIAC) gave hope to all of the modeling efforts. Later successes on von Neumann’s new computer, and at the Stockholm and Cambridge venues, led all concerned to realize that numerical weather prediction needed to “go operational” if it were to become acceptable to both theoretical and operational meteorologists. With the vast majority of their colleagues doubting the viability of their techniques, the NWP pioneers knew they had to demonstrate the predictive capability of numerical methods.

Selling numerical weather prediction was not easy. As Lennart Bengtsson recalled, his mentor Tor Bergeron agreed that the idea behind NWP was interesting—he just did not see how it could be useful for prediction. Operational meteorologists were equally skeptical that a machine could create a forecast based on data and equations. However, Cold War-era military leaders were very interested in objectively produced maps that could be transmitted worldwide and provide a uniform basis for operational decisions. The perennially cash-strapped

The two-dimensional mechanical curve-following plotter, developed expressly for NWP, used to draw hemispheric upper-air contour charts for monitoring data entering the numerical models. In use since the early 1960s, it took 4 minutes to draw the contours and isotherms and label the centers for a hemispheric 500-mb chart on the 1:30 million stereographic projection used at the National Meteorological Center (NMC). This picture was taken in 1967 and shows NMC staff members Bill Drewes and Joe Ships standing in the rear.

ON OBSTACLES

NORM PHILIPS: I cannot now recall any impressions from the early days as to what the biggest obstacle was at that time. Looking back on matters, I see that computer and graphics limitations were very significant. At the time I and others seem not to have realized the importance of experimentation, that is, computer time to test out new formulations before going operational with them. It was also very confining to be unable to do something as simple as to compare different forecasts by computer construction of difference maps. In other words, archiving of readily available forecasts and data played a crucial part in the way NWP took off in the mid-1970s.

HARRY NICHOLSON: While I always believed that research would lead to improved models, I was dubious about the prospects for obtaining enough observational data to define the initial state adequately. This was especially true over the oceans which were my main focus. The development of satellite remote sensing has done much to solve this problem. I was also surprised at the magnitude of the increase in forecast skill when we were able to increase the spatial resolution of the models, even without a corresponding increase in observational density.
Weather Bureau was similarly tantalized by the possibility of successful NWP to improve their forecasts, reduce labor requirements, and thereby reduce costs. With numerous adjustments as they adapted to a swelling stream of model guidance. The relationship between computers, model output, and forecasters has also continually evolved since the JNWP opened its doors. From the beginning, a major component of successful operational NWP was the handling of data—getting it to the operational center, processing it, analyzing it, and using it to make predictions. As remote sensors became more sophisticated, a flood of data threatened to overwhelm the atmospheric scientists’ ability to make sense of it. Data assimilation is just as much a problem today as it was for NWP pioneers.

Likewise, determining which model would provide the best guidance has been an issue since forecasters were first presented with more than one model-predicted atmosphere. Operational forecasters became the ultimate subjective ensemble forecaster. Since the 1990s, the availability of objective methods for analyzing the range of forecast outcomes has made ensemble forecasting one of the most important innovations in NWP. Forecast periods have also increased. Far surpassing the dream of 14-day forecasts, seasonal forecasts and climate projects have become increasingly viable with the past few years. More sensors, more data, different computing environments, new mathematical approaches, and a multitude of products are on the horizon. Where is NWP going? How will it fit into “Earth system” prediction? Several themes show how the field can realize a future of continued, unimaginable gains.
THE CONSISTENT GAP BETWEEN COMPUTERS AND COMPUTING NEEDS. By today’s standards, the ENIAC, the first computer used to run the Meteorology Project’s trial models, possessed minuscule computing power. The JNWPU’s first operational machine, the IBM 701 “Defense Calculator,” represented significant improvements in architecture, memory, and input/output devices. Yet it too represented only a minute fraction of today’s supercomputing capabilities. Early atmospheric modelers were required to work around such limitations and simultaneously pursue advanced models in anticipation of the next-generation computer. Today’s sophisticated weather and climate models have all benefited from rapid increases in computer power, architecture, and mathematical algorithms.

Each new computer generation was greeted as the “supercomputer” of its time, and looking back at NWP model development and capability it is clear that a “lockstep relation,” as Tom Rosmond of Monterey’s Naval Research Laboratory puts it, has always existed between computer and model sophistication. Modelers always greeted the latest computer with enthusiasm only to watch it fall from favor within a few years as data assimilation and “crunching” requirements overwhelmed the system. Working within budget constraints, numerical centers would obtain the next-greatest computer, and models would leap ahead, exploiting the extra computing power. As computer power grew, model complexity and product accuracy grew with it, as shown in Fig. 1.

While the lockstep relationship exists, Tony Hollingsworth of the European Centre for Medium-Range Weather Forecasts (ECMWF) argues that there has always been, and will continue to be, a gap between atmospheric modelers’ needed computing power and the availability of that power at an affordable price. The question then becomes the following: how do numerical centers address the gap? There are several possibilities. A possibility proposed by Bengtsson is to make the transition to parallel computer systems that will not be science application specific. Furthermore, he argues, software development needs to show continued improvement. Making modeling an integral part of meteorological education will be critical to producing improved software.

Hollingsworth proffers three suggestions for addressing the gap. First, atmospheric scientists must make the case to funding authorities that the benefits of increased accuracy far outweigh the cost of investing in NWP resources—an idea not always apparent to government leaders or the public. Second, modelers must write code to run efficiently on the full spectrum of current and emerging computer architectures. If software can run on a variety of platforms, costs will drop as competing hardware providers scramble to fill the need. Third, we need more efficient numerical algorithms for data and forecast models, and developing modern digital techniques for distributing digital data to navy units around the world. Seeing that the navy had problems in oceanography which were similar to those which he was addressing in the atmosphere he moved into that area and initiated work on a comprehensive analysis/forecast system extending from the bottom of the ocean to the top of the atmosphere. He later led the National Ocean Service after his retirement from the navy.

NORM PHILLIPS: Professor George Platzman at the University of Chicago was the person who had the greatest influence on me. He taught courses on atmospheric dynamics, he introduced me to editorial work for the Journal of Meteorology, he was one of the faculty members who talked me into staying for a Ph.D., he was the supervisor of my thesis, he arranged that I participated in the second ENIAC expedition, and he was instrumental in arranging that Charney invite me to work with him at Princeton. He has always been a role model for me in my career, and still acts as a mentor on many occasions. His greatest impact has been his faithfulness to accuracy in reasoning and writing.
assimilation and model integration. As examples, Hollingsworth points to the four-dimensional variational data assimilation (4DVAR) system and semi-implicit integration schemes that have led to efficiency gains. Cost savings from efficiency increases can be applied to further improvements, including those providing better severe-weather predictions and climate outlooks, which will yield significant payoffs in future risk management.

**BROADENING AND DIVERSIFYING NUMERICAL WEATHER PREDICTION.** The JNWPU’s founding agencies disbanded after just a few years because their unique missions required them to focus on particular model enhancements and related applications. Their missions and modeling approaches have been evolving for 50 years. In the early years, modelers were heavily focused on “going global.” Today they are just as likely to focus on going local to provide more specific and higher-resolution model forecasts for a variety of customers.

For example, for their high-flying customers, the U.S. Air Force required the following special products: contrail and high-altitude wind forecasts. Today U.S. Air Force forecasters provide mission support to hot spots around the globe. They need to focus on extremely flexible, mission-appropriate, limited area models. When a field unit submits a request, AFWA can create the product, transmit it via the Internet, and deliver it to the operational commander in a few hours. NWP has definitely moved far beyond a one-size-fits-all product suite.

JNWPU’s original product line of once-daily 36-hour forecasts for three levels would not constitute even a tiny sliver of an operational NWP center’s model output today. At NCEP, 6-hourly Global Forecast System (GFS) runs produce a plethora of predictive maps, and special models predict wave height and frequency, sea ice, climate, hurricane, and fire weather forecasts with 99.9% “on time” delivery. These weather and climate models include critical ocean, cryosphere, and land processes missing from their simple barotropic and baroclinic predecessors. Modelers added relatively basic ocean heat fluxes first. Radiation physics, the diurnal cycle, nonzero latent and sensible heat fluxes over land, and moisture factors made their first operational appearances in the 1980s. Land-based data have become increasingly detailed in the last 10–15 years. Multilayer soil models routinely contain vertical profiles of soil moisture and temperature, as well as vegetation and snowpack cover, accounting for seasonal changes. As NCEP/Environmental Modeling Center’s Ken Mitchell points out, as data assimilation techniques improve, so too will land data assimilation. Including these new data points will provide better initial conditions for NWP models and lead to improved forecasts.

**PEOPLE ADAPTING TO TECHNOLOGY.** Theoreticians and modelers were not the only ones whose professions were changed by NWP. Operational forecasters often received the new products with the dictum, “use it!” Compelled to change, they had to be sufficiently adaptable to deal with model updates supposedly (but rarely) “transparent” to the user and ready to adjust their understanding of model strengths and weaknesses accordingly.

As the forecasting floor gradually made the transition from making all subjective to all objective analyses and prognoses, the physical handling of these products took place at a more glacial pace. The paper maps, which were first hand drawn, then main frame produced, and then workstation created, invariably ended up posted on the wall so the forecast team could make its own assimilation of the atmospheric state. Scientific culture and practice are often slower to advance than the scientific discoveries and developments that spur them forward.

However, while the culture slowly changed, the technology and its associated models seemed to ad-
vance in discontinuous leaps. New sensors provided massive amounts of data used by the physics-based routines being added as computer capacity grew. With each change, operational forecasters modified their approach to increase their value in the man–machine mix.

Forecasters are a critical part of the man–machine mix that produces carefully tailored forecasts for diverse customers. For instance, NCEP/Hydrometeorological Prediction Center (HPC) forecasters still add significant skill over the models, especially for quantitative precipitation forecasts (QPFs). Figure 2 shows the model skill over time compared to the greater skill of HPC forecasts over time.

A decisive human “sanity check” on numerical predictions is provided through forecaster knowledge of model biases, understanding of problems typically encountered with particular weather regimes, and interpretation of ensemble output. Operational forecasters also provide atmospheric modelers with the information they need to increase both the accuracy and temporal range of weather predictions through a feedback process that depends on theoretical modeling and operational expertise. Forecasters remain at the forefront of statistically based products (“perfect prog” and model output statistics (MOS)) and ensemble forecast usage as they deliver timely and useful weather information to the public.

THE CONTINUING NEED FOR DATA ASSIMILATION TO EVOLVE. Receiving, processing, and preparing North American data often seemed overwhelming tasks to the first JNWPU members. Automated data processing was a new concept. Data were often transferred from one medium to the next before finally being loaded for the model run. Yet the data assimilation challenge did not disappear with better technology. It grew rapidly as data sources expanded to include additional surface and radiosonde observations, pilot reports, and data from radar systems, satellite-borne instruments, vertical profilers, and other remote sensors. The early NWP pioneers realized they needed a method to judge which data points to keep and which (suspect) ones to eliminate before the model run. As we face a flood of information, data assimilation systems will continue to be critical to NWP’s success.

The nature of data assimilation has evolved, particularly in the last two decades, from a simple data management system to a complex mathematical approach for extracting critical information from the observations used to initialize the models. Analysis schemes shifted from an empirical to a theoretical basis in the 1980s. The introduction of variational assimilation techniques allowed all observations to be used at once and eliminated failure-prone approximations. The direct use of satellite-obtained radiances within the variational-based data assimilation systems produced significant improvements in forecast skill for both Northern and Southern Hemispheres. Modeling advances require data variables well beyond wind, temperature, and surface pressure. Today’s models need information on clouds, ozone and other gases, aerosols, and surface variables, such as soil moisture and snow cover. By 2010, new observation platforms will deliver 100,000 times as many daily upper-air observations as were available in 1990, from 4.5 times as many satellite sensors. Data assimilation has advanced from being a “necessary evil” to an essential, scientifically based component of NWP.

The challenge of the future will be to garner the computer power and technique enhancements required to successfully assimilate all of these new data without significantly increasing run times. Improved data assimilation techniques, such as 4DVAR or ensemble Kalman filters (EnKFs), hold the promise of reducing error sources and increasing model accuracy. They will allow models to use extremely large amounts of high-

it is not influential. For example, I believe V. Bjerknes’s program of 1903 was an intellectual milestone, but not as influential as it might have been, possibly because he did not apply it in a practical way. The converse might be the ENIAC calculations of 1950. It could be reasonably argued that they were not a significant intellectual milestone, but they were inarguably a highly influential one. In terms of intellectual milestones of that era that could be viewed as precursors to NWP, I would cite Rossby’s “Rossby-wave” paper of 1939 and Charney’s “scale” paper of 1948.

ON FORECASTERS
Bo Doos: What did the forecasters feel? Yes, I had plenty of opportunities to get to know their reactions. Some (often, the most experienced forecasters), were very positive. However, some other had obvious difficulties accepting that the behavior of the atmosphere had anything to do with the horizontal motion of a noncompressible and homogeneous fluid confined between two plates.

I remember the reactions of Professor Tor Bergeron. He seemed to have no problem in accepting NWP. But, to let the computer do the weather map analysis. No way could he accept that. For him, the weather map analysis was a fine art.”
were threatened by it. The navy established an excellent forecasting and failed to consider other aspects, which could compute a product and tried to improve on it, many forecasters (circa 1970), I observed first hand that more were handled well, and those the models handled poorly. Even so, many forecasters would perceive a problem in one aspect of a model analysis or forecast and fail to consider other aspects, which could have been of great benefit to their understanding of the synoptic situation.

During a period when I was leading a group of forecasters (circa 1970), I observed first hand that more often than not, when a forecaster disregarded the model output his forecast suffered. In most cases it was the more experienced forecasters who would make the mistake of ignoring what the model was telling him.

A frustrating effort was the attempt to eliminate the vast clutter of paper covering the walls of the typical forecast office. With the installation of the first...

**Ensemble Forecasting: Few Certainties, More Synergies.** Operational ensemble forecasting based on global “medium range” prediction debuted in December 1992. Until that time, operational NWP centers calculated a single control forecast that started with the best estimate of initial conditions. Ensemble forecasts, however, start from slightly perturbed initial conditions to produce a set of model forecasts within an envelope of predictions from which a more confident forecast package can be delivered and applied. The solutions’ mean is generally more accurate than a single deterministic forecast and shows more run-to-run consistency, and the solution spread provides information about forecast errors and uncertainty. Ensemble forecasts provide operational forecasters with an objective method for considering a variety of atmospheric scenarios that complements extant subjective methods.

Early research ensemble forecasting methods (Monte Carlo, lagged average forecasting) have given way to several operational methods, for example, singular vectors, breeding, and multisystems, used by several NWP centers. However, the Office of Naval Research’s Steve Tracton reminds us “there will always be varying degrees of uncertainties in forecasts!” Ensemble forecasts, therefore, have come to be recognized as indispensable for operational forecasters and have fostered a break with purely deterministic thinking in NWP. The University of Reading’s Lennart Bengtsson, who has been observing the advance of NWP since his student days in Uppsala almost 50 years ago, argues that all weather and climate integrations need to be treated in the ensemble mode, although he is uncertain just how these ensemble runs would be optimized. For example, forecasters can visually weigh the range of solutions with graphical clustering (e.g., “spaghetti charts”) and decide which way to lean in their predictions.

Like the history of data assimilation, ensemble forecasting is another instance of increased objective components of forecasting not anticipated in the early days of NWP. Data assimilation and ensemble forecasting are mutually beneficial because of the requirement to generate the slightly perturbed initial conditions before making the forecast. NCEP/Environmental Modeling Center’s Zoltan Toth emphasizes the synergy between NWP model development and ensemble techniques. The simulation of different types of model-related uncertainty can substantially enhance ensemble forecasting, while the resulting ensemble forecasts can be useful in NWP model development. By using ensemble forecasts to evaluate model-related uncertainty, it might be possible to facilitate model component/parameter selection based on the most recent verification statistics. Therefore, interaction between ensemble forecasting and data assimilation may extend to an equally satisfying interaction between NWP modeling and ensemble forecasting.

Operational forecasting will continue to build from the base first established by ensemble techniques in the 1990s. Not only will forecasts be more accurate, they also will set a quantifiable level of certainty and thus build confidence in the minds of forecasters and their myriad of customers.

**The Persisting Goal of Long-Range Forecasting.** Long-range forecasting (weeks, months, seasons, and years) has been the desire of agriculture interests, military planners, manufacturers, and utility companies since the beginning of the twentieth century, if not before. Meteorologists coping with limited data, sometimes spotty communications, and rudimentary theories once considered themselves fortunate to get out a reasonable forecast for the next day. While those deficiencies may have
stopped the Weather Bureau from making long-range forecasts, they did not stop astronomers, economists, physicists, chemists, sociologists, and charlatans from selling their view of the meteorological future based on sunspots; the positions of the stars, the moon, or planets; or the bushiness of a squirrel’s tail.

Serious work on long-range forecasting, funded by the Bankhead–Jones Act of 1935 in the aftermath of the massive drought-induced Dust Bowl, got underway in the late 1930s at the Massachusetts Institute of Technology (MIT). When John von Neumann proposed the Meteorology Project for developing numerical weather prediction in 1946, the possibility of long-range forecasting was one of the top factors supporting the undertaking. In reality, creating long-range forecasts was a lot tougher than von Neumann had imagined, or at least admitted. However, the last 50 years have seen tremendous gains in advancing forecasting length.

Early NWP efforts only affected the 5-day “extended” forecast product, based on the synoptic techniques developed under Jerome Namais’s leadership, according to former NCEP Long-Range Forecast Branch head Don Gilman. Because 5-day forecasts depended upon a 5-day average of 700-mb heights, NWP helped to improve these forecasts as well. The forecast interval gradually increased from 3 to 5 days, and then from 6–10 to 7–14 days during the 1990s. The first 90-day seasonal product appeared in 1972, but it remained unaided by NWP until the 1990s. Numerical methods for seasonal forecasts still need much work. They tend to be more accurate in the Tropics and for global sea surface temperatures; they remain modestly successful for most of the United States.

The effectiveness of extended predictions will not only vary by region, but will also depend on the increased incorporation of land surface processes, sea ice, and upper-ocean data. In addition, the numbers of these forecasts available for verification has limited advances in the effectiveness of seasonal forecasts. Over 500,000 daily forecast maps are verified each year, which is 100 times the number of mean seasonal predictions. One possible way around this problem, according to George Mason University’s Jagadish Shukla, would be to reanalyze and reforecast the seasonal variations for the past 50 years every year, verify them against observations, and use the resulting data to reduce the errors.

EXTENDING NWP BEYOND WEATHER.

Just as an ensemble forecast offers a range of solutions, atmospheric scientists have a wide range of thought on where NWP should be headed and why. The diversity of opinions is apt, considering that advances will likely also depend on a diversity of modeling approaches and a growing comprehensiveness as NWP becomes more focused on the Earth system than on atmospheric modeling.

By forging an interdisciplinary approach, linkages between climate, weather, water, land, cryosphere, space weather, and chemistry will become a routine part of the scientific landscape. An Earth system model binding together these advancements will provide a seamless approach to climate and weather, fostering the expansion of model prediction systems as a basis for environmental prediction, including air and water quality and ecological processes, not just weather. Weather predictions will be enhanced by a spectrum of coupled forecasts, including meteorological–hydrological and combinations of ocean, land, and atmospheric forecasts. The new model systems will examine the effects of solar activity on the economy and climate. Ozone forecasts will improve through the combined efforts of air chemistry and operational models.

Whether the forecast is for the onset, duration, and end of an ENSO event, or the weekend’s golfing weather, lead times will increase. The reliability and accuracy of forecasts for dangerous weather will also

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significantly improve, expanding the evacuation window during hurricanes, and advancing notification of snowstorms, floods, and conditions favoring forest fires. Seasonal forecasts could become as reliable as today’s weather predictions, allowing farmers, utility managers, and others to deal with reduced water flow. Whereas in the past operational meteorology meant forecasting the temperature and precipitation for tomorrow, in the future operational prediction will embrace ocean conditions, ecosystems, the carbon cycle, solar flares, and more. Through coupled forecasts, the broader atmospheric science–related community will expand its tremendous social importance.

**COOPERATION CONTINUED, 50 YEARS LATER.** The future is bound only by the limits of our imaginations. Our scientific mission must be to continue to provide the fertile environment for the seamless extension of numerical Earth system prediction from the sun to the sea. A critical aspect of that environment will be a bridge over the spatial and temporal distance between research and operations, what is often called the “Valley of Death.” As with the joint research and application efforts that began in the late 1940s, once again interagency efforts are bringing together the resources of NOAA, the U.S. Navy, and the U.S. Air Force to do this. The successors of the JNWPU partners—NCEP, FNMOC, and AFWA—have once again joined forces and signed a national Weather Research and Forecast (WRF) model concept of operations framework. The WRF is an initiative of the U.S. Weather Research Program, which in turn was formed to establish partnerships between federal agencies, universities, and a variety of research institutions. WRF, like the JNWPU, is a collaborative effort among operational prediction agencies and the research community, with the goal of putting research results into immediate operational use. It once again provides a cooperative venue for civilian and military operational weather agencies.

The availability of new technology and the creation of new operational concepts will eliminate overlap, increase efficiency, and provide outstanding Earth system support for their users. Newly developed models will be evaluated at test beds under operational conditions without disrupting the day-to-day routines of forecast centers. Meanwhile, newly developed NWP products will allow operational forecasters to concentrate on being a scientific resource for consumers and decision makers, particularly in the days leading up to and during hazardous weather events.

Meteorology has always been an international science; NWP was an international development from its inception, and international collaboration will continue to advance the community’s ability to improve environmental forecasts to benefit the world’s societies and economies. The Hemispheric Observing System Research and Predictability Experiment (THORPEX), a successor to the Global Atmospheric Research Program, is the multiyear meteorological component of the upcoming International Polar Year (2007–08). This international field experiment centered over the Pacific Ocean will ultimately lead to improvements in 2–10-day forecasts in the United States. THORPEX will use the Global Earth Observation System of Systems—an international cooperative effort to ensure the compatibility of existing and future hardware and software needed for data acquisition and supply—to determine under what circumstances Earth observations contribute most to the improvement of forecasting skills that will lead to more accurate customer-specific products. Through these efforts, all nations will have access to the cutting-edge environmental data and predictions needed to provide improved quality of life for all people.

The excitement surrounding the introduction of operational numerical weather prediction by the JNWPU 50 years ago was largely confined to the meteorological pioneers who believed in its ultimate purpose. Within a few years, however, their vision spread throughout the community as both research and operational sectors recognized its possibilities. The handful of initial forecast products expanded to meet the operational requirements of Weather Bureau, air force, and navy missions, and researchers adopted numerical techniques to increase understanding of the Earth–atmosphere system.

Today the excitement about the next 50 years of NWP should be shared by a broad research, operations, and applications community as additional model development, computing capacity, and collaboration continues. The JNWPU’s opening was the culmination of the purely research-oriented development of NWP techniques as well as the beginning of operational numerical weather prediction. The advances of the past 50 years went well beyond the expectations of our pioneering predecessors. Today, in the early years of the twenty-first century, we anticipate another 50 years of significant enhancements. They will likely be far beyond our current expectations and seem just as amazing when our successors celebrate the 100th anniversary of operational numerical Earth system prediction.