1

Weather prediction

JOSEPH J. TRIBBIA

1. History and introduction

The public tends to have certain misconceptions about the nature of research on weather prediction. It is not that the general populace is of the opinion that weather prediction is a field so developed and accurate that research is not necessary. Nor is it surprising to most that modern weather prediction makes heavy use of the most advanced computers available. Rather, it is the technique of prediction that is most unexpected to the nonspecialist. Most often it is supposed that a large, powerful computer is used to store an archive of past weather from which the most similar analog of the current weather is utilized to form a prediction of the future weather. While variants of such statistical techniques of prediction are still in use today for so-called extended-range predictions, the most accurate forecasts of short-range weather are based in large part on a deterministic application of the laws of physics. In this application, the computer is used to manipulate that vast amount of information needed to effect the solution of the equations corresponding to these physical laws with sufficient accuracy to be useful.

The recognition that the physical laws embodied in Newton's laws of motion and the first and second laws of thermodynamics could be applied to the problem of weather prediction has been attributed to Bjerknes (1904). It was only at the end of the nineteenth century that the application of Newton's laws to a compressible fluid with friction and the application of the empirical laws of the thermodynamics of an ideal gas could be joined to form a closed set of predictive equations with the same number of equations as unknowns. V. Bjerknes, a physicist interested in meteorology, recognized the relevance of these developments to the problem of weather forecasting. He laid out the prospect for weather prediction using the principal laws of science. Bjerknes and his collaborators embarked upon this path of prediction by using the following set of equations and variables:

(i) The Newtonian equations of motion relating the change of velocity of air parcels to the forces acting on such parcels; the gradient of pressure, gravity, frictional forces, and the fictitious Coriolis force, which is necessary when describing motion relative to a rotating reference frame such as the Earth:

$$\frac{d\mathbf{V}}{dt} + 2\boldsymbol{\Omega} \times \mathbf{V} = -\alpha\nabla p + \mathbf{g} + \mathbf{F}. \tag{1.1}$$

(ii) The equation of mass conservation or continuity equation, which reflects the impossibility of the spontaneous appearance of a vacuum in the atmosphere:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho\mathbf{V}) = 0. \tag{1.2}$$

(iii) The equation of state for an ideal gas relating pressure, temperature, and density:

$$p\alpha = RT. \tag{1.3}$$

(iv) The first law of thermodynamics, reflecting the conservation of energy, including internal thermal energy of a gas:

$$C_v\frac{dT}{dt} + p\frac{d\alpha}{dt} = Q. \tag{1.4}$$

In equations (1.1) through (1.4), $\mathbf{V}$ is the three-dimensional velocity vector of the air; $\boldsymbol{\Omega}$ is the vector of the Earth's rotation pointing in the direction perpendicular to the surface at the North Pole; ∇ is the gradient operator; $\mathbf{g}$ is the vector acceleration due to gravity; $\mathbf{F}$ is the vector of frictional forces per unit mass; p is the atmospheric pressure; T is the atmospheric temperature; ρ is the atmospheric density; α is its inverse, specific volume; Q is the heating rate per unit mass of air; C_v is the specific heat at constant volume; R is the gas constant for dry air; and t is time. (For a fuller explanation and derivation of the above, see Petterssen, 1969.)

With the above predictive equations, Bjerknes stated that one could determine the future velocity, temperature, pressure, and density of the atmosphere from the present values of these quantities. That is to say, one could forecast the weather for indefinitely long periods of time. There was one difficulty, however, of which Bjerknes was aware, which is hidden in the forms of equations (1.1) through (1.4): When expanded for use in a geographically fixed reference frame (a so-called Eulerian perspective), these are nonlinear equations, which precludes their solution in a closed form. Bjerknes intended to circumvent this difficulty by seeking graphical solutions.

The solution via graphical methods proved to be too cumbersome and inaccurate for Bjerknes to convince anyone of its utility. However, the theoretical concepts that Bjerknes brought to bear on the prediction problem did attract the interest of groups working on weather forecasting in Europe. In particular, the British took an interest in Bjerknes' scientific approach and sent a young weather observer, L. F. Richardson, to Bergen, Norway, to learn more about Bjerknes' ideas. Richardson was a former mathematics student of renown at Cambridge. He knew, through his own personal research, of a more accurate, more elegant, and simpler technique of solving systems of equations such as those above. This technique, which was ideally suited to the task of weather prediction, is called the finite difference method. Richardson began designing a grand test of the overall method of prediction and performing calculations in his spare time. World War I had begun and Richardson, a conscientious objector, found time to design his test during respites from his duties as an ambulance driver on the Western Front.

The story of Richardson's first grand test, which contains several twists of fate detailed in the account by Ashford (1985), would be impressive if the ensuing forecast had been successful. However, it was a complete disaster. Richardson predicted enormously large surface pressure changes in a six-hour forecast for one locale over Germany — the only location for which he computed a forecast. (A recent reconstruction of Richardson's calculation by Lynch [1994], using only slight modifications of Richardson's original method [which are obvious, given the perspective of modern-day knowledge], gave a very reasonable forecast.) Additionally, Richardson estimated that in order to produce computer-generated weather forecasts faster than the weather was changing, a group of 64,000 people working continuously with mechanical calculators and exchanging information was needed. Absorbed by his other interests, such as a mathematical theory on the development of international hostilities, Richardson never returned to the weather prediction problem. Despite the fact that his attempt was published in 1922 in a book entitled *Weather Prediction by Numerical Methods* (Richardson, 1922), the field lay dormant until the end of World War II.

Richardson's wildly inaccurate prediction highlighted the need for both scientific and technological advances to make weather prediction from scientific principles a useful endeavor. Both of these were forthcoming as indirect results of the war. The development of the electronic computer and the cooperative efforts in atmospheric observation, necessitated by military aviation, were precisely the advancements needed to bring to fruition scientifically based weather prediction using the governing physical laws. These advances were, of course, greatly buttressed by scientists' growing understanding of the atmosphere and its motions, knowledge gained over the twenty years during which research into physically based prediction was dormant. During that period, scientists including C. G. Rossby, J. G. Charney, E. T. Eady, R. C. Sutcliffe, J. Bjerknes, G. Holmboe, and A. Eliassen contributed their insights on how the atmosphere behaves, and they developed an understanding of its motions through the application of the physical laws enumerated above. Thus, when J. von Neumann envisioned scientific problems that the new electronic computer could address, weather prediction was a candidate for exploration.

In the mid 1940s, von Neumann met with the leading scientific lights of the time in meteorology to discuss the prospects for computer-produced weather prediction. The enthusiasm of Rossby, the most influential meteorologist in the world at that time, encouraged von Neumann to devote a portion of the scientific research at Princeton's Institute for Advanced Study to the numerical weather prediction project. A group of scientists — Charney and Eliassen, along with P. D. Thompson, R. Fjortoft, G. W. Platzman, N. A. Phillips, and J. Smagorinsky — set forth to produce a successful weather prediction from scientific laws and the Electronic Numerical Integrator and Computer (ENIAC).

In order to avoid the difficulty that thwarted Richardson's effort and to make the time necessary to produce a forecast as small as possible, the set of equations used to define the forecast was limited to a single equation that predicted the pressure at a single level approximately three miles up in the atmosphere. Even with this major simplification and limiting the domain of the forecast to the continental United States, the 24-hour forecast required 6 days of continuous computation to complete. This forecast was not only reasonable but also similar in accuracy to the subjective forecasts at the time. Thus the field now known as numerical weather prediction was reborn.

2. The modern era

From these beginnings, one might dare to predict a degree of success once the speed and power of computers caught up with the new understanding of atmospheric science. Indeed, an examination of the improvement of computer-produced weather forecasts since the mid 1950s, when such forecasts were operationally introduced, indicates that significant increases in skill occurred immediately following the availability of a new generation of computers and new numerical models.

Because of the rapid rise of computer power, the models used to predict the weather today are in many respects similar to the computational scheme developed by Richardson, with some elaborations. Richardson's forecast equations were in fact quite sophisticated, and many of the physical processes that Richardson included in his "model" of the atmosphere have only recently been incorporated into modern weather prediction models. For example, Richardson was the first to note the potential advantage of replacing the Newtonian relation between force and acceleration in the vertical direction with a diagnostic relationship between the force of gravity and the rate of change of pressure in the vertical. Thus Richardson replaced, and all modern (large-scale) weather prediction models replace, equation (1.1) above with:

$$\frac{d\mathbf{V}_h}{dt} + f\mathbf{k} \times \mathbf{V}_h = -\alpha\nabla_h p + \mathbf{F}_h, \tag{1.1a}$$

$$\frac{\partial p}{\partial z} = -\rho\, g. \tag{1.1b}$$

In equations (1.1a) and (1.1b), the subscript h denotes the horizontal component, f is the Coriolis parameter (i.e., the projection of the Earth's rotation in the direction perpendicular to the mean surface), $\mathbf{k}$ is a unit vector normal to the mean surface of the Earth, z is the coordinate in the vertical direction, and g is the scalar gravitational constant.

Richardson also included a prognostic equation for water vapor in the atmosphere, which is a necessary component of present-day forecast models:

$$\frac{\partial q}{\partial t} + \nabla \cdot (q\mathbf{V}) = S, \tag{1.5}$$

where q is the specific humidity (fractional mass of water vapor in a unit mass of air) and S represents the sources and sinks of water vapor such as evaporation and precipitation. The above set of relationships (equations 1.1a, 1.1b, and 1.2–1.5) forms the basis of most weather prediction models in existence today.

To delve further into the production of numerical weather predictions, it is necessary to explain in more detail the basic underlying concepts in the transformation of the physical laws described above into the arithmetic manipulations that Richardson envisioned of 64,000 employees and now performed at high speed by computer. The equations above are formulated with regard to a conceptual model of the atmosphere as a continuous, compressible fluid. For the purpose of solving these equations in approximate form on a computer, the continuous atmosphere must be subdivided into manageable volumes that can be stored in a computer's memory. Such a process is called "discretization"; one of the most common ways of discretizing the atmospheric equations is the finite difference technique used by Richardson. In this discretization technique, the atmosphere is subdivided into a three-dimensional mesh of points. The averaged velocity, temperature, pressure, and humidity for the volume of atmosphere surrounding each node on this mesh are predicted using the physical equations (see Figure 1.1). Because the equations contain terms that require the derivative of the predicted quantities with respect to the spatial variables (i.e., longitude, latitude, and height), these derivatives are approximated by the difference of the quantity between neighboring grid nodes divided by the distance between the nodes. Note that the true derivative is simply the limit of this difference as the distance between nodes approaches zero.

For current numerical weather prediction models, the distance between grid nodes is between one and two degrees of longitude or latitude (between 110 and 220 km at the equator) in the horizontal and between 500 m and 1 km in the vertical. The above figures are for the models used for global operational prediction at

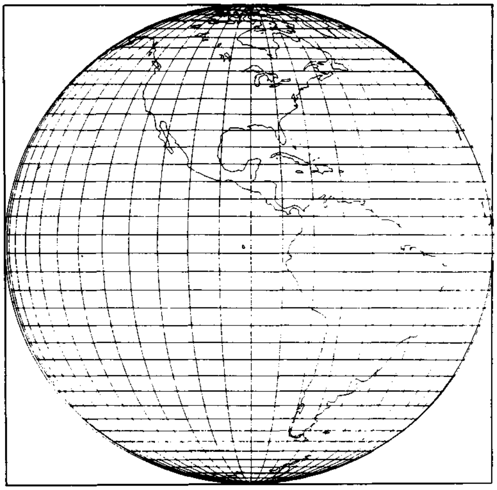


Figure 1.1. Example of grid lattice covering the earth. This grid consists of 40 nodes in the latitudinal direction and 48 nodes in the longitudinal direction. Many such lattices (10–30) cover the globe in a stacked fashion to give a three-dimensional coverage of the atmosphere.

the U.S. National Meteorological Center (NMC), recently renamed the National Centers for Environmental Prediction (NCEP), and are also valid for the global prediction model at the European Centre for Medium Range Weather Forecasts (ECMWF). Note that distances between nodes can be a quarter of those quoted above for models of less than global extent used for short-range (0- to 3-day) forecasting.

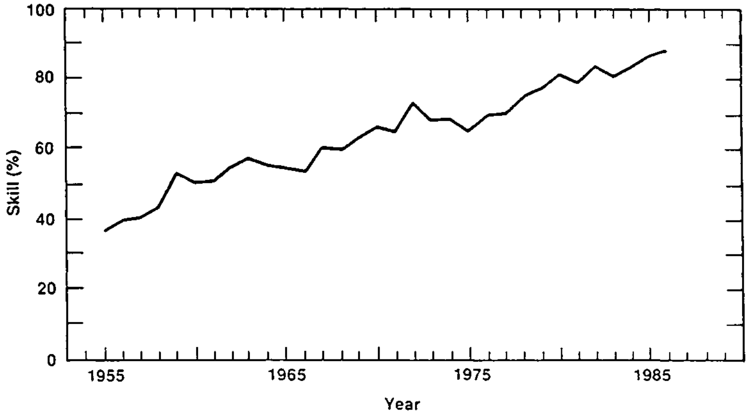
From the values of the predicted quantities and the estimates of their spatial derivatives, all the terms in equations (1.1a), (1.1b), and (1.2–1.5) can be evaluated to determine the (local) time derivative of the forecasted quantities at the grid nodes. These (approximate) time derivatives are then used in a finite difference method to determine the prognostic quantities a short time in advance, typically about 15 minutes. Since such a short-range forecast is not of general use, the process is continued using the new values of the predicted quantities at the nodes to make a second forecast of 15 minutes' duration, then a third forecast, and so on until a potentially useful (12-hour to 10-day) forecast is arrived at.

The dramatic increase in computing power over the past 40 years has greatly influenced the accuracy of numerical predictions. This progress is illustrated in Figure 1.2 (top), which depicts the skill of 36-hour forecasts as a function of time since the inception of operational numerical weather prediction though 1986. Figure 1.2 (bottom) shows a recent skill record during winter for lead times ranging from 0 to 10 days. A significant reason for this improvement is the fact that with faster computers and larger storage capacity, models can be integrated with much finer mesh spacing than was previously possible. Thus major improvements in forecast skill mirror the major advances in computing technology.

3. Finite predictability

Despite this impressive progress in increasing skill, computer-produced weather forecasts are far from perfect. Imperfections are partially due to the fact that even with today's supercomputer technology, the distance between nodes is not sufficiently small to resolve (i.e., capture) the scale of phenomena responsible for thunderstorms and other weather features. Figure 1.2 represents a scientist's bias in that it depicts the improvement in forecast skill of upper-level flow patterns, approximately 5 km above the surface, which are associated with the high- and low-pressure patterns the media weather forecasters often show and which are resolved by current forecast models. Precipitation events associated with such phenomena are oftentimes one or two orders of magnitude smaller in horizontal extent, being structurally linked to the warm and cold fronts. Yet, for most people, precipitation is the single most important discriminator between a correct and incorrect forecast. Thus, the improvement in forecasts of surface weather, while still substantial, is not necessarily as impressive as Figure 1.2 implies. As will be explained below, both in the forecast equations and in the actual forecast issuance, a statistical procedure is used to incorporate the effects of phenomena too small in spatial scale to be resolved by the computer representation of the forecast equations (as well as to remove any systematic bias of the numerical model).

Hidden within the terms representing sources and sinks of heat, moisture, and momentum are representations of physical processes too small in scale and sometimes too complex to be completely included in a numerical forecast model. As mentioned previously,



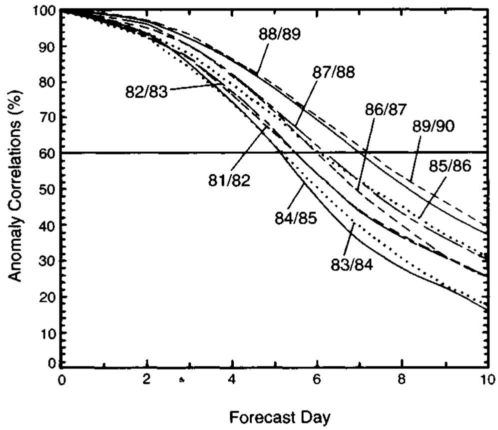


Figure 1.2. Record of forecast skill of 500 mb height over North America: (top) annual average skill of 36-hour forecasts (i.e., forecasts of 36-hour lead time) (Courtesy of U.S. National Meteorological Center); (bottom) recent skill for winter as a function of lead time (shown is the anomaly correlation, with separate curve for each winter season; horizontal line represents limit for synoptically useful forecasts). (From Kalnay, Kanamitsu, and Baker, 1990).

convective storms and their associated precipitation are an example of one such process. Other examples include clouds and their solar and infrared radiative interactions; turbulent exchanges of heat, moisture, and momentum resulting from the interaction of the atmosphere and earth's surface; and the momentum sink associated with gravity (buoyancy) waves induced by the small-scale topography of the earth. All these processes are primarily or exclusively active on spatial scales too small to be resolved in present-day models of the atmosphere. They are called "subgrid scale," for they represent processes occurring on scales that would fit within a volume surrounding a grid point in Figure 1.1.

If such processes influenced only the motion, temperature, and moisture fields on spatial scales characteristic of these processes, they could be neglected within the context of the prediction model. (The prediction of a thunderstorm would be statistically related to the prediction of the larger-scale model but would have no influence on the larger-scale model's prediction.) This is not the case, however. Thunderstorms, turbulent motions in the lowest kilometer of the atmosphere, and cloud radiation interactions all influence the larger scales through their averaged effects (transports of moisture, heat, and momentum for storms and turbulent gusts and mean correlations for radiation and clouds). Thus the statistical relationships must be incorporated in the physical model and used continuously to produce a large-scale forecast. This statistical empirical relation is called a "parameterization." The "art" of numerical weather prediction, as opposed to the science, is intimately tied to the parameterization of subgrid scale processes.

The second reason for imperfect weather forecasts is related to a fundamental aspect of the governing equations: their nonlinearity. The sole reason that thunderstorms and turbulent subgrid scale motions can influence their large-scale environments is that the prediction equations written out in a Eulerian frame contain product terms — such as the vertical transport of temperature, wT, and moisture, wq, by the atmosphere. These product terms have large-scale influence, even if individually each variable has only small-scale structure. This, in turn, necessitates the parameterization noted above, and leads to yet another difficulty: any small-scale errors, for example, on the scale of two or three grid volumes, will cause errors in the terms used to forecast all larger scales of the forecast model — even the global scale. This would not be disastrous to the large-scale forecast were it not for the fact that the equations governing the atmosphere are subject to a now commonly recognized, inherent difficulty: Their predictions are extremely sensitive to small changes in the predicted variables. This is the hallmark of a chaotic system with limited predictability.

The recognition of the unstable nature of the equations governing atmospheric evolution can be traced back to the ideas set forth in studies by P. D. Thompson and E. N. Lorenz in the late 1950s and early 1960s. Thompson's work (Thompson, 1957) was motivated by his early operational experience with numerical weather predictions, while Lorenz's efforts were related to his research in extended-range (monthly) prediction. Lorenz distilled the essence of the predictability problem in a seminal paper (Lorenz, 1963), in which he demonstrated that a system of only three nonlinear differential equations can have solutions that are sensitively dependent on their initial conditions. That a simple system of such low dimensionality (note that a typical computational model of the atmosphere requires the solution of several million such equations) could exhibit this behavior came as a surprise not only to the meteorological community, but also to the mathematics and mathematical physics communities. Although these latter groups began to recognize the ubiquity of this type of chaotic behavior a decade after Lorenz's publication, this system remains one of the prototypical examples of a deterministic system with limited predictability.

Other researchers in the field have followed Thompson's lead and applied the tools of the statistical theory of turbulence to the problem of predictability. The studies of D. K. Lilly, C. E. Leith, and R. H. Kraichnan in the early 1970s elucidated the nature of the loss of predictability inherent in the necessity of limiting the range of scales explicitly predicted and of parameterizing the subgrid scales (Kraichnan, 1970; Leith, 1971; Lilly, 1972). Such studies helped place upper bounds on the time interval over which weather forecasts have any skill. These early estimates suggested a two-week limit on forecast range, while more recent, more conservative estimates (cf. Lorenz, 1982; or Tribbia and Baumhefner, 1988) suggest about 10 days. Lorenz's 1982 work shows a comparison between actual and theoretically attainable forecast skill (Figure 1.3).

The output of a numerical forecast model predicts directly the following meteorological variables: three-dimensional variation in pressure, temperature, horizontal winds, and relative humidity; two-dimensional fields of surface pressure, temperature, and precipitation. These fields are available in time increments of approximately 20 minutes and have been listed in decreasing order

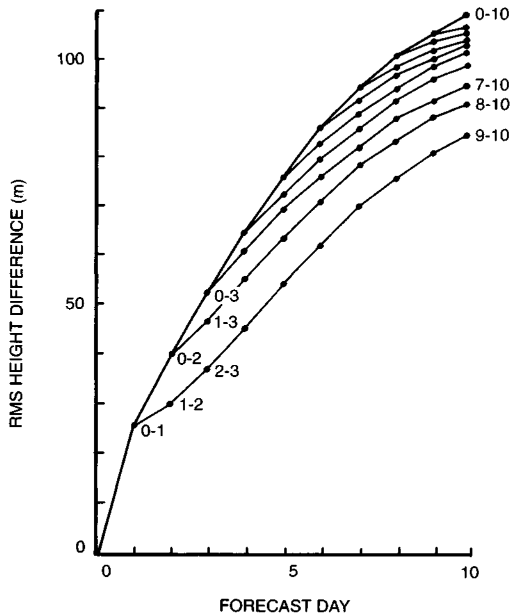


Figure 1.3. Global root-mean-square 500 mb height differences $E(j,k)$, in meters, between j-day and k-day forecasts made by the European Centre for Medium Range Weather Forecasts operational model for the same day, for $j < k$, plotted against k. A j-day forecast is one with a lead time of j days. Values of (j,k) are shown beside some of the points (e.g., "0–1" indicates $j = 0$ days and $k = 1$ days). Uppermost curve connects values of $E(0,k)$, $k = 1, 2, \ldots, 10$ days. Remaining curves connect values of $E(j,k)$ for constant $k - j$. (From Lorenz, 1982)

of accuracy at any given time within a forecast. Thus, pressure and temperature are the most accurate fields forecast, while moisture and precipitation are the most difficult for a numerical model to predict (Figure 1.4 shows trends in the accuracy of forecasts for temperature and precipitation).

4. The future

Figure 1.3 illustrates that the difference between what is being achieved and what can be achieved is not large, but its elimination would effectively double the range of useful predictive skill. The current research aimed at reducing this difference focuses on two goals: (i) to improve the numerical models so that they more accurately represent the physical processes in the atmosphere; and

(ii) to describe more accurately the initial state of the atmosphere as input to the computational iterations that result in the forecast. With respect to model improvements, it is clear that with increasing computer power, model resolution will increase, easing the need for parameterization of the current range of subgrid scales. Nevertheless, some processes are likely to remain beyond resolution for the foreseeable future (e.g., cloud formation, which occurs through droplet growth on the scale of microns), and subgrid scale parameterizations must be used and refined if models are to improve. However, increased resolution carries with it the need to observe the atmosphere on the spatial scale that the model resolves, so that accurate predictions of these small scales can be produced and evaluated. Thus, improving the accuracy of the initial input state of a computational model requires a more accurate specification of the currently resolved scales and an accurate specification of the smaller scales to be resolved in the future.

Fortunately, the resolution of scales of motion and the inclusion of such scales in a prediction model are linked by the manner in which atmospheric analyses used as initial states are produced. Because of the irregular manner in which the atmosphere is observed both temporally and spatially, interpolation in space to the grid nodes and in time to forecast initiation times is needed. Sophisticated statistical interpolation methods are currently used to interpolate in space, while the forecast model itself is used to interpolate in time. Current research at NCEP and most other operational centers in the world is focusing on making a completely consistent four-dimensional analysis system using the principles of optimal control theory (cf. Daley, 1991). This focus makes the inclusion of smaller scales in the initial state a natural consequence of current and planned higher-resolution forecast models.

The accuracy of any initial input state is limited, however, by the quantity and accuracy of the observations used in the interpolation method. In order to obtain more accurate large- and small-scale analyses, more detailed information is necessary. Currently, the backbone of the analysis system used for initial state construction is the land-based, upper-air radiosonde network developed as an outgrowth of World War II. Over the oceans, weather satellites afford coverage, but primarily they observe infrared radiation indicative of atmospheric temperature and humidity, requiring winds to be estimated from cloud tracks in the visible satellite channels.

An estimate of the accuracy of the current analysis system on the large scales included in present-day models can be obtained by extrapolating the forecast error curve in Figure 1.3 to day 0. New space-based and land-based sensors, such as lidar and radar wind profilers, are currently being developed and incorporated into the observing network. Wind, temperature, and moisture fields with high resolution in both space and time are needed to provide accurate small-scale and more accurate large-scale information to the analysis system used in numerical weather prediction.

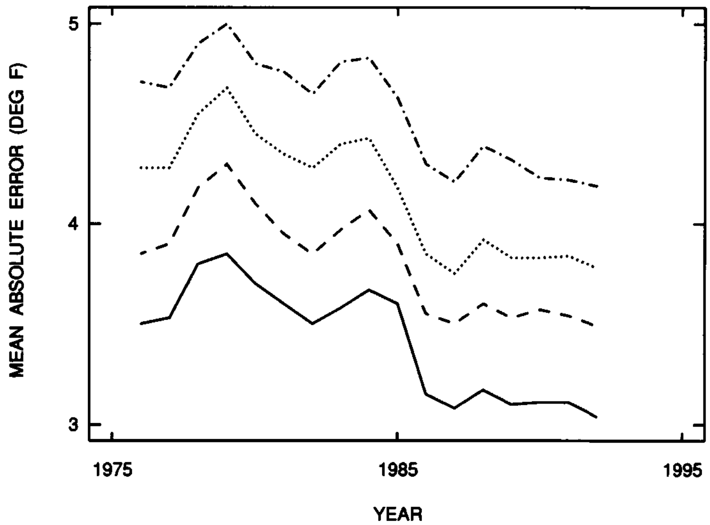
Last, it has become increasingly clear that even if detailed accuracy is unachievable because of the inevitable growth of small initial errors, some useful information may be gained from numerical weather forecasts if the forecast system recognizes the statistical nature of the problem. This is already being done to a certain degree in precipitation forecasts (as well as other variables) where, as noted above, convective precipitation is a result of a parameterized physical process. A model forecast of the occurrence of convective precipitation should actually be regarded as indicative of a higher likelihood than normal of this type of precipitation within the grid volume. To optimize skill in forecasting precipitation locally, operational forecast centers have developed and utilized statistical relationships between the output of numerical models and forecasts of precipitation and other weather variables for individual forecast locales. Such use of model output statistics (MOS) and other statistical approaches is discussed at length in Wilks (1995, chap. 6); also Chapters 2 through 5 in the present volume include consideration of forecasts produced by this technique.

For the purpose of completeness, here it is sufficient to note that the various approximations made in producing a numerical forecast for a given locale, both physical and computational in origin, can lead to systematic errors in forecasts of grid cell–averaged weather. This error can be corrected, in the mean, through the use of MOS, which interprets the forecast of grid cell–averaged weather in the cell containing the specific locale of interest — not as the weather to be expected, but as predictors of the weather to be input into a statistical forecast model. This statistical model can be used to correct the systematic bias of the numerical forecast model and to downscale, or refine, the forecast to the locale of interest. Additionally, quantities that can be forecast sensibly only in terms of probabilities are relatively easily handled by specifying the probability of occurrence as the predictand in the MOS formulation. Improvements in the accuracy of MOS predictions in recent years are shown for maximum/minimum temperature and probability of precipitation (Figure 1.4).

Another quantitative result from the statistical turbulence studies of the early 1970s was that smaller scales lose predictive skill first and errors progress up scale, until the largest scales are finally contaminated with error and the forecast is totally devoid of skill (Lorenz, 1969). Thus precipitation, which can occur on very small scales of the order of a kilometer, can be accurately predicted only for a short period of time on the order of a few hours, while a large-scale low-pressure disturbance in midlatitudes can be accurately forecast for up to a week or more. In both cases, a completely accurate forecast requires the exact determination of the location and timing of the event. Nevertheless, forecasts with less than perfect skill, as reflected by probability forecasts produced using model predictions, should still be societally valuable.

Weather services are currently researching the possibility of meeting these needs by experimentally producing ensembles or multiple realizations of numerical predictions (Toth and Kalnay, 1993). This approach allows a forecaster to consider the relative likelihood of a particular weather event's occurrence by examining its frequency of occurrence in the forecast ensemble.

The theoretical roots of such methods were first discussed by E. S. Epstein and C. E. Leith in the early 1970s (Epstein, 1969; Leith, 1974). After two decades of gradual improvement in computer power, the advantages of increasing the resolution of forecast models can now be weighed against the advantages of probabilistic ensemble predictions. As stated above, this trade-off is a function of the spatial and temporal scale of the phenomenon to be predicted. For convective precipitation, ensemble forecasts should be of use in determining rainfall risks in forecasts of one day or longer, while for global-scale weather, ensembles should be of use for forecasts longer than one week. Because the predictability error growth studies (noted above) have shown that small-scale features inevitably are the first to lose skill in a forecast, high-resolution information is of little use beyond these phenomena-dependent time ranges. Thus, computational effort and expense is more wisely



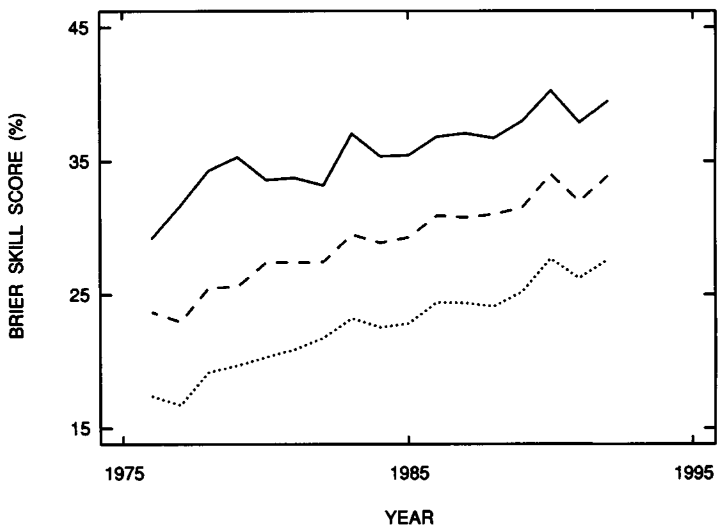


Figure 1.4. Verification of MOS forecasts for approximately 90 National Weather Service reporting stations (solid line represents 12- to 24-hour forecast, dashed line represents 24- to 36-hour forecast, dotted line represents 36- to 48-hour forecast, and dot-dashed line represents 48- to 60-hour forecast: (top) mean absolute error for maximum/minimum temperature; (bottom) Brier skill score (see Chapter 2 of this volume) for probability of precipitation. (From Vislocky and Fritsch, 1995)

utilized in the production of multiple forecasts. Such methods allow the numerical model to determine which forecast features are robust in the presence of the noise of predictability error. They also have obvious applicability in forecasting the atmospheric response to anomalous atmospheric forcing, for example, the equatorial sea surface temperature anomalies associated with El Niño, which form the basis for current operational monthly and seasonal outlooks.

Acknowledgments

The author wishes to thank the late P. D. Thompson, whose accounts of the historical developments in the field of numerical weather prediction form much of the content of this chapter. Of course, any misstatements of fact are the author's responsibility.

References

Ashford, O.M. (1985). *Prophet – or Professor? The Life and Work of Lewis Fry Richardson.* Bristol: Adam Hilger.

Bjerknes, V. (1904). The problem of weather forecasting considered from the point of view of mathematics and mechanics. *Meteorologische Zeitschrift*, **21**, 1–7.

Daley, R. (1991). *Atmospheric Data Analysis.* Cambridge: Cambridge University Press.

Epstein, E.S. (1969). Stochastic dynamic prediction. *Tellus*, **11**, 739–759.

Kalnay, E., Kanamitsu, M. & Baker, W.E. (1990). Global numerical weather prediction at the National Meteorological Center. *Bulletin of the American Meteorological Society*, **71**, 1410–1428.

Kraichnan, R.H. (1970). Instability of fully developed turbulence. *Physics of Fluids*, **13**, 569–575.

Leith, C.E. (1971). Atmospheric predictability and two dimensional turbulence. *Journal of the Atmospheric Sciences*, **28**, 145–161.

Leith, C.E. (1974). Theoretical skill of Monte-Carlo forecasts. *Monthly Weather Review*, **102**, 409–418.

Lilly, D.K. (1972). Numerical simulation studies of two-dimensional turbulence II. *Geophysical Fluid Dynamics*, **4**, 1–28.

Lorenz, E.N. (1963). Deterministic nonperiodic flow. *Journal of the Atmospheric Sciences*, **20**, 130–141.

Lorenz, E.N. (1969). The predictability of a flow which possesses many scales of motion. *Tellus*, **21**, 289–307.

Lorenz, E.N. (1982). Atmospheric predictability experiments with a large numerical model. *Tellus*, **34**, 505–513.

Lynch, P. (1994). Richardson's marvellous forecast. *Proceedings, International Symposium on the Life Cycles of Extratropical Cyclones*, 38–48. Bergen, Norway.

Petterssen, S. (1969). *Introduction to Meteorology* (third edition). New York: McGraw-Hill.

Richardson, L.F. (1922). *Weather Prediction by Numerical Process.* London: Cambridge University Press.

Thompson, P.D. (1957). Uncertainty of initial state as a factor in the predictability of large scale atmospheric flow pattern. *Tellus*, **9**, 275–295.

Toth, Z. & Kalnay, E. (1993). Ensemble forecasting at NMC: the generation of perturbations. *Bulletin of the American Meteorological Society*, **74**, 2317–2330.

Tribbia, J.J. & Baumhefner, D.P. (1988). Estimates of predictability of low-frequency variability with a spectral general circulation model. *Journal of the Atmospheric Sciences*, **45**, 2306–2317.

Vislocky, R.L. & Fritsch, J.M. (1995). Improved model output statistics forecasts through model consensus. *Bulletin of the American Meteorological Society*, **76**, 1157–1164.

Wilks, D.S. (1995). *Statistical Methods in the Atmospheric Sciences.* San Diego: Academic Press.