move in that direction. The communiqué issued after the Paris meeting of the "Group of Six" (*10*) on 22 February 1987 seemed to generalize that agreement to cover all the participants, although it failed to include the firm commitments to complementary changes in fiscal policy (covering both tax cuts in Germany and Japan and tax increases in the United States) that would have been called for by the guidelines laid out in this paper. In other words, there is still a long way to go from the ad hoc agreements that are back in fashion to the sort of articulated, comprehensive arrangements embodying agreed principles of policy adjustment when variables deviate from published target values that would constitute a new exchange-rate regime. The U.S.–Japan agreement will be significant if, but only if, it can in retrospect be seen as a milestone on the road to a comprehensive reform of the international monetary system.

REFERENCES AND NOTES

1. An "effective" exchange rate is a weighted average of the exchange rates against other currencies, where the weights may reflect bilateral trade flows or other measures of the strength of bilateral competition. A "real" exchange rate is one that is corrected for differential inflation. The index used in the figure is a composite of indices based on unit labor costs and wholesale prices.
2. P. B. Kenen and J. Williamson, in *World Economic Problems*, J. Williamson, Ed. (Institute for International Economics, Washington, DC, in press).
3. R. Baldwin and P. Krugman, "Persistent trade effects of large exchange rate shocks," National Bureau of Economic Research Working Paper no. 2017, 1986.
4. J. Williamson, *The Exchange Rate System* (Institute for International Economics, Washington, DC, ed. 2, 1985).
5. The indicators named in the communiqué issued at the conclusion of the Tokyo summit meeting on 6 May 1986 were the "growth rates of gross national product, interest rates, inflation rates, unemployment rates, ratios of fiscal deficits to GNP, current account and trade balances, international reserve holdings, and exchange rates."
6. H. J. Edison, M. Miller, J. Williamson, *J. Policy Modeling*, in press.
7. R. Dornbusch, *J. Polit. Econ.* **84**, 1161 (1976).
8. H. H. Rosenbrock and P. D. McMorran, *IEEE Trans. Autom. Control*, **AC16**, 552 (1971).
9. F. Kydland and E. Prescott, *J. Polit. Econ.* **85**, 473 (1977).
10. The six signatories were Canada, France, West Germany, Japan, the United Kingdom, and the United States; Italy absented itself from what would have been a meeting of the Group of Seven.

11. The author gratefully acknowledges comments on a previous draft by C. F. Bergsten, S. Islam, M. Miller, M. Noland, R. Solow, and two anonymous referees.

Scientific Basis of Modern Weather Prediction

JOSEPH J. TRIBBIA AND RICHARD A. ANTHES

A review of the scientific principles and computational methods used in modern weather prediction is presented. The history of research in this area shows that researchers attempting to improve weather prediction have advanced all of meteorology. The numerical models developed for weather prediction are today an integral component of meteorological data analysis and are used in simulating past and present climates and in assessing the potential for future climate changes. Related disciplines, such as oceanography, computational fluid dynamics, and mathematics, have also reaped benefits from this effort, which is currently being extended to studies at smaller spatial and longer temporal scales.

THE FOUNDATIONS OF QUANTITATIVE WEATHER PREDICtion, as currently practiced at a number of centers around the world, are the same fundamental laws by which modern science predicts nearly every event within the realm of everyday experience: the tides of the sea, the motions of the planets, or the flight of a rocket. These are the Newtonian laws of motion, the conservation of mass, the laws of classical thermodynamics, and the laws of transfer of electromagnetic radiation and its interaction with matter. The formulation of the problem of weather forecasting in such a manner is a direct outgrowth of the 19th-century deterministic philosophy that led Laplace to believe that the future of the cosmos could be determined from complete specification of the present state of the universe and the laws of Newtonian mechanics. The history of the successes and failures of the deterministic method in meteorology has led to the interaction of this science, already broadly interdisciplinary, with numerous other disciplines to their mutual benefit, including computational mathematics, oceanography, astronomy, biology, and chemistry. Even the philosophy of determinism has been affected by scientists grappling with the problems of weather prediction.

Historical Development

The present method of weather prediction has its origin in the scientific vision of three men: Vilhelm Bjerknes (1862–1951), Lewis Fry Richardson (1881–1953), and John von Neumann (1903–1957). Bjerknes's contributions to the atmospheric sciences and the dynamics of rotating, stratified fluids are manifold, including an extension of Lord Kelvin's circulation theorem and the polar front theory of cyclone development. In a seminal paper, published in 1904 (*1*), Bjerknes made two major contributions to modern weather prediction. First, he mathematically stated the problem of weather forecasting as a proper initial-value problem, pulling together the Newtonian dynamical equations for an ideal compressible gas in the form given by Navier and Stokes, the equation for the continuity of mass, the ideal gas law, and the first law of thermodynamics as stated by Helmholtz. Thus he demonstrated the principle that future values of the three-dimensional wind field, the temperature, the pressure, and the density of the atmosphere could be determined from the current values of these variables. Bjerknes's second contribution was his statement, influenced by the deterministic scientific philosophy of Heinrich Hertz (1857–1894), that the central problem of the science of meteorology is the prediction of future weather (*1*).

The system of equations set down by Bjerknes included only the barest representation of the complexity of atmospheric processes

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and yet was nonetheless analytically intractable. Even today there exists no general closed-form solution to this system. Bjerknes suggested that solutions could be obtained by graphical methods, but these proved to be too difficult, inaccurate, and time consuming to be of practical utility. A young British weather observer, who had been directed to familiarize himself with Bjerknes's methods, had a different and, as history has shown, better idea for the solution of the system of equations for forecasting the weather. Lewis Fry Richardson, who had studied physics and mathematics at Cambridge University, was interested in discrete, finite-difference approximations to differential equations, having used these methods to solve the heat diffusion equation. He proposed applying these techniques to the set of equations laid out by Bjerknes. In addition, Richardson boldly posed a grand elaboration of this system. He described his advanced ideas of weather prediction in a book published in 1922 entitled *Weather Prediction by Numerical Process* (*2*). This volume contains equations for the prediction of rainfall, heating, and cooling due to solar and terrestrial radiation, and the transfer of heat and moisture from the earth's surface to the atmosphere and into the solid earth, in addition to the fundamental system of equations posed by Bjerknes.

Richardson, a Quaker, served during World War I as an ambulance driver and, during this period, managed to write his revolutionary book while at the same time calculating by hand a trial forecast using the methods he proposed. Unfortunately, the resulting 6-hour forecast, initialized at 0700 GMT on 20 May 1910, for a region encompassing Central Europe was a total failure, predicting an enormous (145 mbar) surface pressure rise, more than 100 times the observed magnitude of change. The primary reasons for this failure were the paucity of observations in the atmosphere at levels above the surface and the lengthy 6-hour extrapolation. Apart from the observational problems, Richardson's method was not practical owing to the tremendous volume of the computations. He estimated that to have a forecast that kept ahead of current weather, 64,000 human calculators, working in concert, would be needed.

Two technological developments occurred during the next 25 years, both of which were spurred by the outbreak of World War II, that eventually made Richardson's methods feasible. The first was an enhancement of the upper-air meteorological observation network necessitated by military aviation requirements, which effectively relieved most of the observational problems that had doomed Richardson's first attempt at a numerical forecast to failure. The second, the advent of the electronic computer shortly after World War II, the development of which benefited from the work of von Neumann, alleviated the computational burden. Von Neumann's role in modern numerical weather prediction, however, goes beyond his participation in the development of the modern computer. A brilliant mathematician and physicist, von Neumann envisaged in his computing machine the capability of addressing the most stubborn problems of physics and mathematics—those with significant nonlinearities. Hydrodynamic problems were among those he felt were ripe for fresh attack with the computer, and he suggested addressing the numerical computation of shock waves, turbulence, and weather prediction. His interest in weather forecasting was encouraged by the most influential atmospheric scientist of the day, Carl-Gustav Rossby (1898–1957), who had worked under Bjerknes and who immediately recognized the import for meteorology of the new electronic computing machine. Von Neumann wasted little time in setting up a research team to study numerical weather prediction within the Institute for Advanced Study at Princeton.

Among those involved in the formative years of computational weather prediction were scientists who would oversee the developments in this area for the coming quarter century: Jule Charney (1917–1981), Arnt Eliassen, Ragnar Fjörtoft, Norman Phillips, George Platzman, Joseph Smagorinsky, and Philip Thompson. The contributions of these men, and others, led to the first experimental 24-hour weather predictions with an electronic computer for a region encompassing North America in April 1950. These first predictions were not only physically reasonable but moderately successful. The forecast model was, however, far more limited in scope than that designed by Richardson, in that the sole forecast variable was the pressure at a level approximately 5 km above the surface. The major limiting factor that necessitated the forecast of a single variable was the speed and memory size of the available computer, called the ENIAC (Electronic Numerical Integrator and Calculator), which was less powerful than today's personal computer.

The success of the feasibility studies of the research group at the Institute for Advanced Studies spurred research worldwide in the new field of numerical weather prediction. With the rapid advances in computer technology over the next three decades, the scope of numerical forecasting expanded commensurately. The spatial domain, the length of the forecast interval, the number of variables, the

Table 1. Number of meteorological data processed at the European Center for Medium-Range Weather Forecasts for 0000 GMT, 7 February 1979, during the World Weather Experiments (*3*).

Measurement platform	Number of data
Surface (land) observations	2,345
Ship (ocean) observations	1,225
Satellite winds (low level)	991
Satellite winds (high level)	1,276
Aircraft	1,373
Ocean buoys	379
Dropsondes, constant-level balloons	97
Radiosonde temperatures	770
Pilot balloon winds	506
Satellite temperatures	1,976
Total	10,938

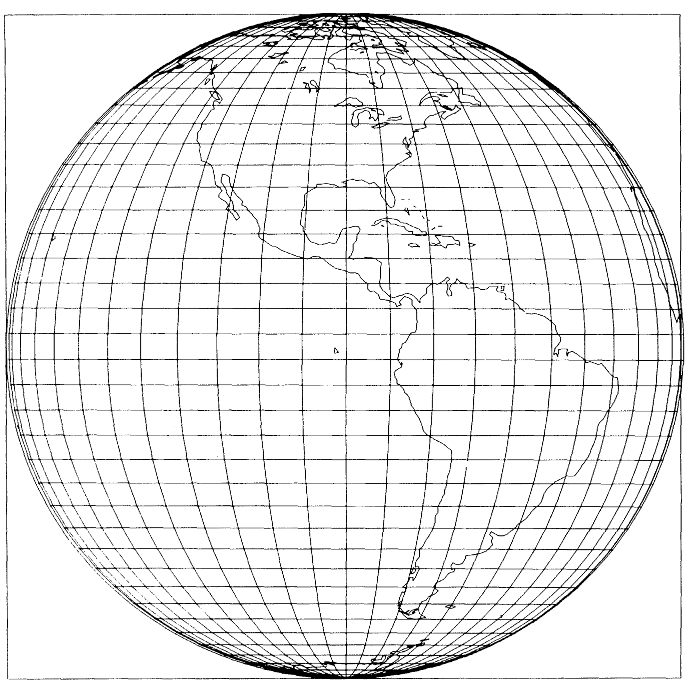

Fig. 1. Example of lattice covering the earth. This grid consists of 40 nodes in the latitude direction and 48 nodes in the longitude direction, for a total of 1920 nodes.

complexity of the included physical processes, and included interactions among the different processes have increased dramatically. In fact, the methods currently in use are remarkably similar to those originally presented by Richardson.

Fundamental Equations

To explore more fully the methods used in present-day numerical forecasting, we will first be more explicit about the physical laws and computational methods alluded to above. The prognostic equations governing atmospheric motions are presented below; for simplicity, we neglect the effects of moisture.

Newton's second law can be expressed in the Eulerian form of the Navier-Stokes equations for an ideal, compressible gas on a Cartesian plane tangent to and rotating with the earth's surface. These equations determine the time rate of change of the three components of the wind as a function of the forces that accelerate a unit mass of air.

$$\frac{\partial u}{\partial t} = -\mathbf{V} \cdot \nabla u + fv - \ell w - \frac{1}{\rho}\frac{\partial p}{\partial x} + F_x \tag{1}$$

$$\frac{\partial v}{\partial t} = -\mathbf{V} \cdot \nabla v - fu - \frac{1}{\rho}\frac{\partial p}{\partial y} + F_y \tag{2}$$

$$\frac{\partial w}{\partial t} = -\mathbf{V} \cdot \nabla w + \ell u - \frac{1}{\rho}\frac{\partial p}{\partial z} - g + F_z \tag{3}$$

where $\mathbf{V}$ is the three-dimensional wind vector composed of the eastward component, u; the northward component, v; and the vertical component, w; ρ is density, p is the pressure, g is acceleration of gravity; and F_x, F_y, and F_z represent frictional forces in the x, y, and z directions, respectively. The terms on the left side represent the temporal rate of change of the velocity components at a fixed point in space. On the right-hand side are various forces per unit mass. The first terms represent advection of the wind components by the wind itself; these advective terms arise in the Eulerian framework in the calculation of local (fixed in space) time tendencies. The nonlinearity of these terms is the fundamental property that makes the solution of the system of equations impossible by analytic methods. The Coriolis forces per unit mass, represented by fv, ℓw, fu, and ℓu, are fictitious forces due to the rotation of the reference frame, the earth. The parameters f and ℓ are functions of the earth's angular velocity, Ω, and latitude, ϕ

$$f = 2\Omega \sin \phi$$
$$\ell = 2\Omega \cos \phi \tag{4}$$

The gravitational and frictional forces, and the pressure gradient, are familiar body forces and stresses.

The continuity-of-mass equation, expressing the principle that mass is conserved, relates the temporal rate of change of density to the advection of density and the divergence of the wind field:

$$\frac{\partial \rho}{\partial t} = -\mathbf{V} \cdot \nabla \rho - \rho \nabla \cdot \mathbf{V} \tag{5}$$

The ideal gas law relates pressure, density, and temperature:

$$p = \rho R T \tag{6}$$

where R is the gas constant.

The first law of thermodynamics expresses the conservation of energy:

$$\frac{\partial T}{\partial t} = -\mathbf{V} \cdot \nabla T + \frac{1}{c_p \rho}\frac{dp}{dt} + \frac{Q}{c_p} \tag{7}$$

where c_p is the specific heat at constant pressure for dry air and Q is the diabatic heating rate per unit mass. Q takes into account radiative heating and cooling and frictional and diffusive heating.

The above system of equations describes the behavior of a hypothetical dry atmosphere. In the more general case, the effects of moisture are included by adding conservation equations for water vapor, liquid water, and frozen water, and adding the latent heat due to phase changes of water to the diabatic heating term Q. Kasahara (*3*) provides a review of a more complete system of equations for a spherical coordinate system.

This system of equations, with boundary conditions to determine the transport of heat, moisture, and momentum at the earth's surface, can, in principle, be solved in order to predict the temperature, pressure, and wind fields. Owing to the nonlinearity and magnitude of the computational task, however, the solution must be numerical, and requires approximating derivatives in the continuous equations above with finite differences in space and time. The field variables are then predicted at the nodes of a lattice, as illustrated in Fig. 1. The values of the fields at the lattice nodes, or grid points, represent averages over discrete volumes of space and finite intervals of time.

If one formally performs a space-time average of the prognostic equations, the appropriate equations for the temporal rate of change of the averaged variables can be derived. However, as noted by Osborne Reynolds (1842–1912), the nonlinear advective terms involve the average of the products of variables, which is generally not identical to the product of the averaged variables. This corresponds to the physical property that within any discrete lattice volume, there will in general be variations in the fields on scales smaller than the size of the lattice, and these small-scale variations in the momentum and thermodynamic fields can induce changes in the averaged variables. If, for example, the computational lattice has a horizontal scale of 100 km, which is typical of today's high-resolution models, a thunderstorm with a horizontal scale of 10 km will not be resolved by the lattice; and yet the average values of temperature and humidity over the 100-km grid volume will be affected by the presence of the storm.

In order to account for the effects of unresolved scales, the average effects of the small-scale features are related to the variables on the resolved scales by what is termed a closure relation. The problem of the determination of such a closure is not unlike the problem of deriving the laws of thermodynamics from the statistical mechanics of molecular motions, with the important exception that there is no generally clear scale separation between the parameterized subgrid scales and the resolved scales. This lack of separation between the temporal and spatial scales of the resolved and subgrid motions

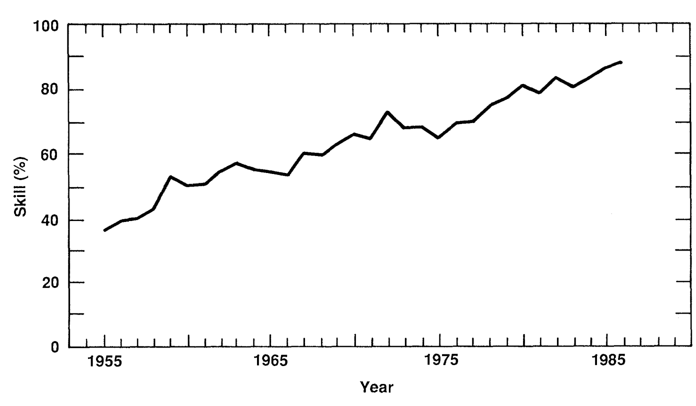

Fig. 2. Record of skill, averaged annually, of predictions of the 500-mbar geopotential height over North America 36 hours ahead, made at the U.S. National Meteorological Center. Skill = 100% is a perfect forecast and skill = 0% represents the average skill of a forecast of climatology (*22*).

makes this a difficult, ill-posed problem, although recent attempts with powerful renormalization group techniques used in statistical physics look promising (*4*). Nonetheless, the approximation of the continuous equations describing atmospheric behavior by finite differences, and the representation of the continuous atmospheric variables by averages over discrete intervals in space and time, represent a serious compromise.

Other compromises are also made in the name of computational efficiency. These are generally related to those aspects of a numerical forecast model that deal with the radiation and cloud fields, the three phases of water, and trace gas constituents. The details of the physics associated with these variables are extremely complex and are phenomena fundamentally on the micrometer scale or smaller. In fact, the exact quantum-mechanical calculation of the radiation-absorption spectra of a typical radiatively active atmospheric constituent is limited by a lack of precise knowledge of the intermolecular potential field. Even a precise treatment of the condensation of water vapor and the growth of a single droplet to precipitation size is beyond the capability of available computers. Thus, approximations must be made to the physical laws governing both the formation of clouds and the interaction of radiation with clouds and with radiatively active gases.

Modern Numerical Weather Prediction Models

The current level of sophistication and accuracy in numerical weather prediction can be elucidated by describing typical operational models used for predictions for both the short range (0 to 3 days) and medium range (1 to 10 days). It is useful to make such a distinction between short- and medium-range forecasts because of a difference in modeling practice for these two time scales.

For the problem of medium-range weather forecasting, the model lattice must cover the entire globe, as shown in Fig. 1, since remote influences may affect local weather on this time scale. With the current generation of supercomputers, the effective limit on the number of lattice points is about 8×10^5; these are distributed typically in the form of 16 concentric layers of 5×10^4 lattice points covering each spherical surface. This leads to a horizontal separation between lattice points of approximately 100 to 200 km and a vertical separation of about 1 km between layers.

The physical processes that are represented in most models include the latent heating of condensation in clouds; absorption and emission of radiation by the radiatively active constituents CO_2, H_2O, and O_3; absorption and scattering of radiation by clouds and aerosols; and addition of heat and moisture and frictional forces at the earth's surface. Subgrid-scale mixing of heat, moisture, and momentum is represented by eddy diffusion processes.

As discussed earlier, a critical component of numerical weather prediction models is the preparation of an analysis of the prognostic variables at the initial time of the forecast. This phase involves analysis of huge numbers of diverse data from land-surface stations, ships, ocean buoys, satellites, aircraft, and balloons (Table 1). These data are observed from different geographic locations around the world, at different times, and with varying accuracies. They must be combined to obtain analyses at a single time on the regular lattice nodes of the model—as shown in Fig. 1.

After the completion of the analysis phase, the necessary data are defined on the model lattice. However, if a forecast is initiated with these data, spurious, high-amplitude gravity-wave solutions will develop in the model. These solutions, which obscure the physically realistic evolution of the model atmosphere, arise from dynamic imbalances between the wind, pressure, and temperature fields in the analyses. To eliminate these spurious solutions, the mass and momentum fields are mutually adjusted to a balanced state, a process termed initialization. Great progress has been made in recent years, both in the understanding of atmospheric balances and in developing mathematical methods to make the small adjustments to the pressure, temperature, and wind analyses necessary to achieve this balance.

The combination of higher resolution models, made possible by larger and faster computers, increased understanding of atmospheric physical processes and their better treatment in models, increased number of observational data, and improved analysis and initialization techniques, have all contributed to a steady improvement in the skill of numerical weather prediction models since the 1950s (Fig. 2). The average level of skill for the model currently in operational use at the National Weather Service (NWS) is illustrated in Fig. 3, which shows the average pointwise correlation between the forecasted and observed sea-level pressure over North America for the month of December 1985. The correlation of the climatological value of this field is also shown to gauge the level of skill in such predictions. Figure 3 shows that present-day forecast models exhibit skill to about day 7 of the forecast during winter and are reasonably accurate for the first 3 days of the forecast.

Figure 4 shows the average of this correlation between the forecast and observed North American sea-level pressures averaged over the calendar year along with the time history of its improvement over the past decade. Note that averaging over all seasons leads to a correlation score of 45% for forecasts of climatology. Thus, since 1980 both 4- and 5-day forecasts have shown skill. The measures of skill shown in Figs. 3 and 4 serve to demonstrate that tremendous progress has been made in forecasting in the past decade.

A modification of the above global technique is used for producing more accurate short-range predictions over regions of special interest (*5, 6*). This method uses a higher horizontal resolution (typically 50 km) over the limited area of interest. The rationale for such a technique is that important local weather events often occur as a result of surface inhomogeneities, including mountains, and warm and cold frontal structures with spatial scales below that resolved by current global models. Regional models can resolve and predict these features more accurately. They also generally contain more realistic parameterizations of boundary-layer and precipitation processes, which are more influential on this scale (mesoscale). However, because such models are not global, they require specification of the forecast variables on the lateral boundaries of the model domain. The equations on the high-resolution, limited-area grid must be integrated in conjunction with a global model, which provides the regional model with lateral boundary conditions. Eventually, the solution over the fine mesh is dominated by the forecast variables from the global model, which deteriorates in skill as shown in Fig. 3. Thus regional models produce a superior

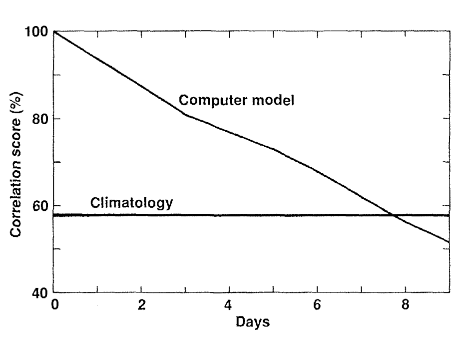

Fig. 3. Average correlation between forecast and observed sea-level pressure over North America for the month of December 1985 as a function of the forecast day. The average skill of a climatological forecast for this month is also shown. The Medium Range Forecast Model of the National Weather Service is on the average more accurate than climatology for 7.5 days (*23*).

forecast in the fine-mesh domain for a short period—typically 72 hours.

Why Forecasts Are Inaccurate

A striking aspect of Fig. 3 is the rather rapid deterioration of forecast skill. Because predictions of orbital motions and oceanic tides can be made many years in advance with only slight error, one might wonder why the weather can be predicted only several days in advance with useful accuracy. In the 1950s the inaccuracies of numerical weather forecasts were perceived to be due to the limitations imposed upon the resolution of models and the physical approximations by the power of the available computers. However, even in these early days at least two investigators, P. D. Thompson and E. N. Lorenz, suspected that there were some fundamental reasons for the decay of accuracy with time. By the late 1960s, Thompson and Lorenz had built a convincing case for the proposition that the atmosphere was not indefinitely predictable, even with very high-resolution models with greatly improved treatment of physical processes (*7*).

Thompson and Lorenz's early experiences in attempting to make numerical predictions led them both to note that numerical forecasts were sensitive to minor changes in their initial data. Thompson observed that the quality of the numerical forecasts depended significantly on the availability of upper-level reports at each individual observing station. If data were missing at even a single station and interpolation was needed, the forecasts were not as successful. Lorenz's experience was similar. While rerunning some experimental long-range numerical forecasts, Lorenz rounded off the initial data inserted into the computer. At the termination of the forecast, the forecasts initiated with the slightly modified data differed considerably from the original forecasts. Thompson pursued the reasons for the fundamental limits to atmospheric predictability by means of the statistical theory of homogeneous turbulence in two dimensions (*8*), whereas Lorenz attempted to understand his experimental results by designing a paradigm of the phenomenon of predictability of nonlinear systems (*9*).

Lorenz's 1963 study has attracted a great deal of attention outside the science of meteorology. His paradigm was a system of three ordinary differential equations that, although far simpler than the equations describing atmospheric behavior, was the first example of a nonlinear system exhibiting "chaotic" behavior, that is, possessing nonperiodic solutions with sensitive dependence on their initial conditions. The ramifications of Lorenz's work have had tremendous impact on the fields of applied and pure mathematics, theoretical physics, turbulence theory, mathematical biology, and the philosophy of determinism. Lorenz's study showed that some simple deterministic systems are only predictable for a finite time, which is dependent on the accuracy with which the initial conditions are specified.

Lorenz's result for the simplified set of equations has been duplicated with sophisticated atmospheric models that show that two solutions differing only slightly in the initial conditions will diverge with time and eventually become statistically uncorrelated. Current estimates for atmospheric models suggest that the doubling time of small errors is between 2 and 2.5 days.

Studies of homogeneous turbulence have shown that even with error-free initial conditions the predictability of atmospheric motions is limited. The presence of subgrid scales that must be parameterized in the model will produce the same effect as errors in the initial data. This is caused by what is termed an inverse cascade of error, through which errors in the small scales, containing only a small fraction of the energy, induce errors in slightly larger scales. These in turn amplify and induce errors on still larger scales, until eventually all scales are contaminated.

Because of the sensitivity of the forecast to errors in the initial data and treatment of the subgrid-scale processes, it makes little sense to treat any process in a forecast model with substantially more accuracy than the most inaccurate component of the forecasting system. Thus, a simple parameterization of infrared radiative heating, which has a rather long time scale of variation, will suffice for a short-range forecast, while frictional effects near the earth's surface, which have a shorter time scale and a larger local impact, must be treated with more care.

Numerical Weather Prediction and Related Disciplines

In spite of the problems of limited predictability, forecasts of the weather made today are better than those of the past and are continuing to improve (Figs. 2 to 4). These forecasts are useful to many sectors of society; in addition, the scientific effort in meeting the forecast challenge of Bjerknes has benefited other areas of meteorology and related disciplines.

One of the foremost benefits to the atmospheric sciences that has resulted from operational numerical weather prediction has been the accumulation of a large historical database through which we have discovered a great deal about the physics of the atmosphere. The daily analyses of winds, pressure, temperature, and moisture accumulated over the years of prediction—global since 1978 and hemispheric since 1966—have led to new discoveries on the role of orographically generated gravity waves, in the budgets of heat, water vapor, and angular momentum of the atmosphere, and a new understanding of the role of tropical circulation anomalies in producing intraseasonal circulation changes in mid-latitudes. Because of the relatively short history of hemispheric and global predictions (20 years), the historical data sets are only now of sufficient length that scientists can begin to look at the interseasonal variations in the atmosphere with statistical confidence. In the future, with the extension of the global analyses to longer time periods, the longer term climate variations will be accessible to diagnosis.

It is obvious that a numerical model requires a complete and

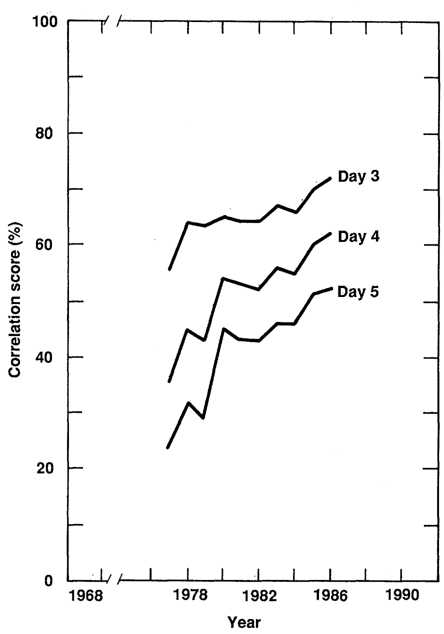

Fig. 4. Annual average correlation between forecast and observed sea-level pressure over North America for forecasts at days 3, 4, and 5, obtained with the National Meteorological Center's numerical weather prediction model. The value of this correlation is 45% for a climatological forecast (*22*).

accurate initial analysis of the atmosphere to produce a good forecast. In recent years, scientists have shown that the converse is also true; to produce the most comprehensive and accurate global analysis of the atmosphere requires a good numerical model. The reason for this is that the irregular observational network collecting the diverse meteorological data (Table 1) is not sufficiently dense in space or time to describe fully the atmosphere. The solution to this problem has been to use the information contained in the physical laws governing the atmosphere and treat the observations in four dimensions (space and time) with statistical interpolation in space and a numerical integration to interpolate in time. This technique is known as four-dimensional data assimilation and was first proposed by Charney in 1969 as a means of filling the large voids in the observational network (*10*). This method of analysis has resulted in a synergetic relation between observational meteorology and numerical prediction. Through analysis and interpretation of the observations, model deficiencies can be detected and corrected, thus improving not only the quality of the prediction but also the quality of subsequent analyses.

Another outgrowth of numerical forecasting that has had a substantial impact on meteorology has been the development and use of models for the simulation of the earth's past, present, and future climate. Because of the long time scales involved, more care must be taken in the parameterization of heat input and energy loss (radiative and latent heating, turbulent transport of heat, moisture, and momentum in the boundary layer, and cloud-radiation interactions) when simulating climate, but the general methodology is identical to that of medium-range forecasting. The scientific foresight to examine the climate of the earth in this manner is attributed to von Neumann, who envisioned the simulation of the equilibrium statistical behavior of the atmosphere as the next problem beyond short-range forecasts that the use of computational models could most easily address.

Early climate simulations were only partially successful in depicting the features of the general circulation. Within the last decade, however, global models have improved and now are sufficiently successful in their simulation of present climate that researchers have begun to examine the questions of climate change in the manner foreseen by von Neumann. Scientists today are investigating the sensitivity of the earth's climate to changes in the concentration of radiatively active trace gas constituents such as CO_2 and CH_4 (*11, 12*) and changes in the biosphere such as the effects of deforestation (*13*). Ice-age climates have been simulated in an effort to understand the mechanisms of these radical departures from the present climate (*14, 15*). In the future, models coupling the biosphere and the world oceans will be integrated with atmospheric models to gain fuller knowledge of the importance of these interactions on climate time scales.

A natural extension of meteorological modeling methods is that of modeling the oceans. Oceanographers, who also study a sparsely observed fluid system, are currently applying the methods used by atmospheric scientists to learn more about the fundamental dynamics of the oceans, through a judicious blending of observations and computation. One reason for the recent interest in such techniques is that, because of the small scale of energetic oceanic eddies as compared to their atmospheric counterparts, only with the current generation of supercomputers have realistic ocean models become a possibility.

Another discipline that has benefited from the experience of researchers in numerical weather prediction is computational fluid dynamics. The necessity of extended integration for the purpose of climate simulation uncovered an unsuspected nonlinear computational instability. This was first observed and analyzed by Phillips (*16*). The solution of the problem of nonlinear instability led atmospheric scientists such as Arakawa (*17*) to design conservative finite-difference methods for the integration of nonlinear equations and others to develop new spectral methods in which the forecast variables are approximated by continuous, spectral (wave-like) functions. Arakawa's methods are now widely used not only in the atmospheric and oceanic sciences but also in models of aeronautical and mechanical engineering flows. The efforts to make spectral methods computationally efficient have succeeded to the extent that these methods are now the technique of choice for global atmospheric modeling and engineering problems with simple geometries.

Future Prospects

As for the future of computational forecasting, the advent of the next generation of supercomputers in the 1990s and the development of new observing systems bode well for the continued steady improvement of numerical forecasting skill. However, there is also a perception that increased accuracy of forecasts will require more accurate parameterizations of physical processes and better initial analyses of the variables to which these parameterizations are sensitive, especially water vapor, clouds, and large-scale vertical motions. A symptom of these problems is seen in present-day medium-range forecast models, where systematically the precipitation in the tropics is about 50% less than the observed precipitation for this region during the first 1 to 2 days of the forecast. Researchers are addressing this problem by attempting to define better the initial water vapor and vertical velocity fields by means of satellite observations in order to circumvent this delay in the development of precipitation. This delay is also a major problem in short-range forecasting on the mesoscale, since latent heating and convective scale motions are appreciable energy sources for this scale.

The current frontiers of numerical weather prediction tend toward opposing ends of the spectrum of time and space scales: the extension of medium-range forecasting into long-range (beyond 10 days) forecasting of the large-scale features of the circulation and the extension of short-range forecasting to ever smaller scale atmospheric phenomena. Both of these time-space scales are influenced strongly by diabatic physical processes, of which the interactions among water vapor, clouds, precipitation, and radiation are the most uncertain at present. Progress on this problem is requisite if forecasting is to improve significantly beyond its current state. There is, however, an advantage to the fact that both the large and the small spatial scales that are currently being most studied are removed from the scales of maximum temporal variance and are therefore more susceptible to diabatic effects. In fact, the inhomogeneities induced by diabatic effects may render the predictability estimates made under the assumption of statistical homogeneity overly pessimistic. Some evidence supporting such notions may be seen in recent studies of extended-range and mesoscale forecasting (*18, 19*).

The dynamics of global weather regimes—the focus of extended-range forecasts—are affected not only by inhomogeneities in the earth's surface such as land-sea contrasts and mountains, but also by energetic eddies of the synoptic scale, which contain most of the energy and the temporal variance of the atmosphere and are not predictable at extended range. Similarly, mesoscale systems such as frontal rain bands and complexes of convective storms receive energy from both diabatic heating on the mesoscale and motions at larger scales that have limits to their predictability. Thus both extended-range forecasting and short-range mesoscale forecasting will be most successful if they combine probabilistic and dynamical methods. Such stochastic dynamic methods have not been operationally used for lack of adequate computer power, but the next-generation computers will allow such techniques in the near future.

The development of new ground- and space-based remote sensing observational systems (*20, 21*) has also encouraged researchers in global and mesoscale forecasting. Ground-based systems include the UHF (Ultra High Frequency) and VHF (Very High Frequency) Doppler-radar wind profilers, and microwave-radiometer temperature and water vapor profilers. The radar wind profiler is capable of measuring, with great accuracy, the vertical profile of winds over a particular location with a temporal resolution of about 30 minutes. The six-channel microwave radiometers provide high temporal resolution of temperatures and water vapor; however, the vertical resolution of these systems (typically 2 km) is lower than that of radiosonde systems (typically 500 m).

Current satellites provide useful information on the wind, temperature, water vapor, and cloud fields. Geostationary satellites, at an altitude of 36,000 km above a fixed point on the earth, provide high-resolution (in time and in the horizontal dimension) cloud-image data in visible and infrared wavelengths. Time-lapse pictures are used to infer cloud motions, which provide estimates of horizontal winds. They also provide similarly high-resolution temperature and moisture soundings using a 12-channel infrared radiometer; however, the vertical resolution of these soundings is about the same as that of the surface-based microwave profilers.

Polar orbiting weather satellites provide soundings of temperature and water vapor with greater vertical resolution than the geostationary satellites because of their lower orbits (about 850 km) and their use of higher resolution (20 channels) infrared sounders. However, in their sun-synchronous orbits, they sample only limited regions of the atmosphere at any one time.

Altogether, the above high-resolution (in either space or time) data, when used in a four-dimensional data assimilation scheme, are capable of resolving mesoscale atmospheric structures on a global basis to an extent never before possible. New instrumentation planned for future satellites scheduled for launch during the next decade will provide even more accurate data at higher resolutions, promising significantly more complete atmospheric data sets for initializing numerical models.

In summary, forecasting the weather by numerical models will continue to be an area of active research and an integral part of the science of meteorology and its interaction with other disciplines. Not only are improved forecasts an important operational goal, the new forecast models will serve the important role of providing stringent verifications of the parameterized physical processes in research models that couple atmospheric, oceanic, and land-surface processes. These are the facets of climate models that, because of their uncertainty, limit our ability to answer definitively questions concerning climate variability and change.

REFERENCES AND NOTES

1. V. Bjerknes, *Meteorol. Z.* (1904), pp. 1–7.
2. L. F. Richardson, *Weather Prediction by Numerical Process* (Cambridge Univ. Press, Cambridge, England, 1922).
3. A. Kasahara, *Encyclopedia of Physical Science and Technology* (Academic Press, New York, 1987), vol. 14, pp. 621–640.
4. V. Yakhot and S. Orszag, *J. Sci. Comput.* **1**, 3 (1986).
5. R. A. Anthes, *Mon. Weather Rev.* **111**, 1306 (1983).
6. R. A. Kerr, *Science* **228**, 40 (1985).
7. P. D. Thompson, *Bull. Am. Meteorol. Soc.* **64**, 755 (1983).
8. ——, *Tellus* **9**, 275 (1957).
9. E. N. Lorenz, *J. Atmos. Sci.* **20**, 130 (1963).
10. J. G. Charney, M. Halem, R. Jastrow, *ibid.* **26**, 1160 (1969).
11. S. Manabe and R. J. Stouffer, *J. Geophys. Res.* **85**, 5529 (1980).
12. W. M. Washington and G. A. Meehl, *ibid.* **88**, 6600 (1983).
13. R. E. Dickinson and A. Henderson-Sellers, in preparation.
14. J. B. Kutzbach and P. J. Guetten, *Ann. Glaciol.* **5**, 85 (1984).
15. S. Manabe and A. J. Broccoli, *J. Geophys. Res.* **90**, 2167 (1985).
16. N. A. Phillips, *The Atmosphere and the Sea in Motion*, B. Bolin, Ed. (Rockefeller Institute, New York, 1959), pp. 501–504.
17. A. Arakawa, *J. Comput. Phys.* **1**, 119 (1966).
18. J. Shukla, *Adv. Geophys.* **28B**, 87 (1985).
19. R. A. Anthes, Y.-H. Kuo, D. P. Baumhefner, R. M. Errico, T. W. Bettge, *ibid.*, p. 122.
20. D. C. Hogg *et al.*, in *Remote Sensing of Atmospheres and Oceans*, A. Deefak, Ed. (Academic Press, New York, 1980), pp. 313–364.
21. A. Schnapf, *Monitoring Earth's Ocean, Land, and Atmosphere from Space—Sensors, Systems and Applications* (American Institute of Aeronautics and Astronautics, New York, 1985).
22. Figure provided by J. Brown, National Meteorological Center.
23. F. D. Hughs, "Skill of medium range forecast group," *National Meteorological Center Office Note 303* (U.S. Department of Commerce, Washington, DC, 1985).

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