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Numerical Weather Prediction in Daily Use

The tenth anniversary of calculations for daily weather forecasts finds forecasts more accurate and useful.

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The perennial object of praise or complaints from people in all walks of life, the weatherman, has been spending his efforts in producing new solutions each day to a physical and mathematical problem which has been called the second most difficult problem known to science (the first being that of human behavior). This daily problem is suitable for solution on a modern high-speed computer that can process large volumes of data rapidly and obtain numerical solutions to partial differential equations in large three-dimensional meshes.

The fact that useful solutions have been obtained for more than 50 years is attributable to a certain amount of regularity that exists in atmospheric motions. The deficiencies in the daily forecasts are there because of the many irregularities in the complex motions of the real atmosphere. The prediction of these irregularities is our challenge.

The general meteorological forecasting problem to be solved is the determination of the complete state and motion of the atmosphere in advance, including the presence or absence of clouds and precipitation, cold waves, heat waves, high altitude winds and temperatures, turbulence for aircraft operations, large and severe storms, and many other phenomena.

Scientifically, it is a problem in the field of fluid dynamics. The fluid motion at a given time in the forecast is a function not only of its initial motion but also of the distribution of its initial internal and potential energy. The energy transformations during the forecast period depend on the field of motion, on the exchange of heat by radiation, on heat conduction to and from the earth's surface, and on the heat exchange due to phase changes of water.

The differential equations applicable to these phenomena have been well known for many years. They are exceedingly general, describing a wide range of atmospheric phenomena ranging from sound waves to the largest scale of atmospheric motions. The great generality of these equations has prevented their analytical integration, except for a few greatly simplified types of patterns. The invention and improvement of large-scale electronic computers has given meteorologists a practical tool for numerical integration of these equations, at first in a relatively simple form, but later in an increasingly complex and complete form. This activity is known as numerical weather prediction. Data on atmospheric conditions obtained from an internationally coordinated world-wide network are assembled within a few hours after observation time and used to integrate the appropriate equations with respect to time and to predict the future state and motion of the atmosphere.

On 1 July 1954, the U.S. Weather Bureau, Air Force, and Navy jointly established a unit to capitalize on research done at the Institute for Advanced Study at Princeton, New Jersey (*1*), at the Air Force's Geophysical Research Directorate at Cambridge, Massachusetts (*2*), and under the late C. G. Rossby at Stockholm (*3*). Known as the Joint Numerical Weather Prediction Unit, its mission was to make, for use by the nation's weather and military services, daily forecasts of the future state of the atmosphere. These forecasts began in the spring of 1955. In 1961 the Weather Bureau assumed full support of the unit, integrating it into the National Meteorological Center at Suitland, Maryland.

The idea of numerical prediction goes back many years. The aforementioned equations were established before the end of the 19th century (1861–85). V. Bjerknes, suggesting the use of graphical methods (*4*) of solution, proposed their integration for purposes of prediction in 1911. In 1922, the English meteorologist L. F. Richardson (*5*) published a remarkable treatise setting forth a complete procedure for integrating the equations of state and motion to predict the future state and motion of the atmosphere. His first calculation of the rate of change of sea-level pressure was laboriously worked out by hand. The results of the calculation were completely unrealistic, and they helped to discourage a generation of meteorologists who might have thought that the problem of atmospheric prediction could be solved by a straightforward calculation with the physical equations.

Richardson was unable to go further primarily because the computational problem was so massive, and his whole concept lay dormant for over 30 years.

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Now one is inclined to believe that if Richardson had had access to a large electronic computer for the necessary numerical experiments he would have arrived at a practical and workable method of prediction. In fact, his writings contain a hint that he knew how to get around his second most difficult mathematical problem, the most difficult being how to add or multiply in a few microseconds.

As interest waned in Richardson's physical method, the art of forecasting by simpler means developed. These methods amounted to simple extrapolation of patterns on the weather map, modified by the experience of the forecaster (mental analogs). Some principles of physics were instituted through the years in the form of approximate integration techniques which could be accomplished graphically. By the middle of the 1940's, C. G. Rossby was promoting the idea of simplifying the basic meteorological equations in such a manner as to eliminate the sound waves and the rapidly moving gravity waves as possible solutions. This work was intended to yield a more computationally tractable set of equations. These simplified equations are now known as the "filtered equations." Charney's 1948 paper (*6*) is a landmark in this effort. Shortly afterward J. von Neumann was looking for a way to put the meteorological problem on his new computer at the Institute for Advanced Study at Princeton.

Two-Dimensional Modeling

The first numerical calculation was made in anticipation of von Neumann's computer, on the Eniac at Aberdeen, Maryland, by von Neumann, Charney, and Fjörtoft (*7*). The prediction equation was much simpler than Richardson's complete set, which never would have fit into the Eniac. It specified the changes in a "barotropic" atmosphere. This atmospheric "model" is a two-dimensional one without sources or sinks of kinetic energy. Existing circulation is redistributed, but circulation is not created or destroyed.

A physical analogy, described by the same equation, would be a rotating, homogeneous, incompressible fluid between frictionless plates at the top and bottom. The principal motions in a vertically integrated representation of the real atmosphere resemble very closely the motions in the analogy. Since the vertically averaged flow is fairly well represented by the flow at mid-atmosphere (500 millibars or about 5500 meters above sea level), we can use real atmospheric data from this level as initial data for the forecast.

The information required for the calculation is retained at the points of a rectangular mesh, and the partial differential equations describing the behavior of the model are represented by their finite difference analogs (finite difference equations). The initial rates of change, with time, of the fundamental parameters are computed, and an extrapolation for a short time ahead (such as 1 hour) is made. This process is iterated, new tendencies are computed, a new extrapolation is made, and so forth. Since an adequate representation of the initial atmospheric state requires data at more than a thousand gridpoints at the same time and altitude, and since 36 iterations are required for a 36-hour forecast with the simplest atmospheric model, a useful solution can be obtained only if an electronic computer is used to make the calculations.

The initial barotropic forecasts, while not especially accurate, proved correct enough to be encouraging in spite of the gross oversimplification of atmospheric structure and processes. One of the most interesting and difficult aspects of these early barotropic forecasts, a problem solved by much work and simple enough in hindsight, was the fact that the most unsatisfactory characteristics of the results were caused, not by the excessive simplifications in modeling the atmosphere, but by modeling inconsistencies and by inconsistent numerical approximations. We formerly thought that many of the largest errors were a consequence of the neglect of physical processes in the atmosphere and directed many of our early efforts toward generalizing our atmospheric models to include more vertical levels as well as the production and dissipation of kinetic energy, heat gain and loss from the surface of the earth and from condensation of water vapor, and other important physical factors. It is easy to recall the general sense of frustration as experiments of this type produced forecasts that were, on the whole, worse than the barotropic forecasts. It thus became evident that improvement of the mathematical and numerical solutions of the equations would be necessary before generalization of our atmospheric models would be worthwhile.

A first requirement was the formulation of the differential equations of the model in a way that errors of the destructive type would be avoided. In making approximations, one can consciously commit errors of some types. On the other hand, certain errors lead to results ranging from undesirable to catastrophic (*8*). Such errors arose from inconsistencies in formulation of the prognostic equations. These introduced small but cumulative errors during the course of the integrations. Since the problem is treated as a marching problem, with a new time step every 60 minutes or less, this type of error sometimes produced forecast values of the variables which were not even within meteorological range by 36 hours.

We also learned that the finite difference equations had to be carefully formulated to conserve exactly the same properties conserved by the differential equations, or similar errors would occur.

An early problem was the lateral boundary problem. The effects of a given atmospheric disturbance are soon felt at great distances, the fastest energy propagation occurring at the speed of sound. (The sound waves, however, are excluded from all existing models.) The bulk of the energy is propagated horizontally more slowly, at speeds ranging up to a few times the vertically averaged wind speed. But this means that in the course of a 48-hour forecast the effects of a given disturbance extend almost halfway around the hemisphere. Thus, a forecast made from initial data covering only North America will be rendered worthless after a few hours by influences from the real atmosphere propagating into this area across its boundaries from several directions. We surmounted this difficulty by expanding our grid to cover almost the whole Northern Hemisphere (Fig. 1). The propagation of influences across the equator seems to be relatively slow, and it is not so destructive to a 2- or 3-day forecast.

Before 1960 we (that is, the meteorologists of several nations) solved enough of these problems so that we were able to make barotropic forecasts of considerable value, covering the Northern Hemisphere, correctly predicting most of the large-scale changes, and giving valuable 3- and 4-day forecasts (*9*).

Three-Dimensional Models

Having solved the two-dimensional problem, we were able to return to the more general three-dimensional problem (known as the problem of baroclinic modeling) with fresh optimism. Two paths to this end seemed open. The first was through the use of a more general set of the filtered equations which included a representation of the transformations between kinetic, potential, and internal energy. The principal problem was that of including all necessary physical processes and maintaining the necessary consistency in the equations, which were becoming rather complicated. They were formulated as "jury" equations, in which the difference equations take the form of a set of simultaneous equations (about 8000 of these at a time in a model having 2000 grid points in the horizontal and four in the vertical).

Data from several levels above the surface of the earth are required; a minimum of two levels can represent some of the energy conversion processes, but data from more levels are desirable. There is, however, considerable redundancy in the data from the real atmosphere as far as vertical structure is concerned. For example, if we have data for five levels above a given point on the earth's surface, taken from the bottom 90 percent of the mass of the atmosphere, we can interpolate to obtain values for intermediate levels with sufficient accuracy for almost any practical purpose. Hence a five-level model should have enough vertical resolution for accurate prediction.

A modest but significant improvement over barotropic forecasting has

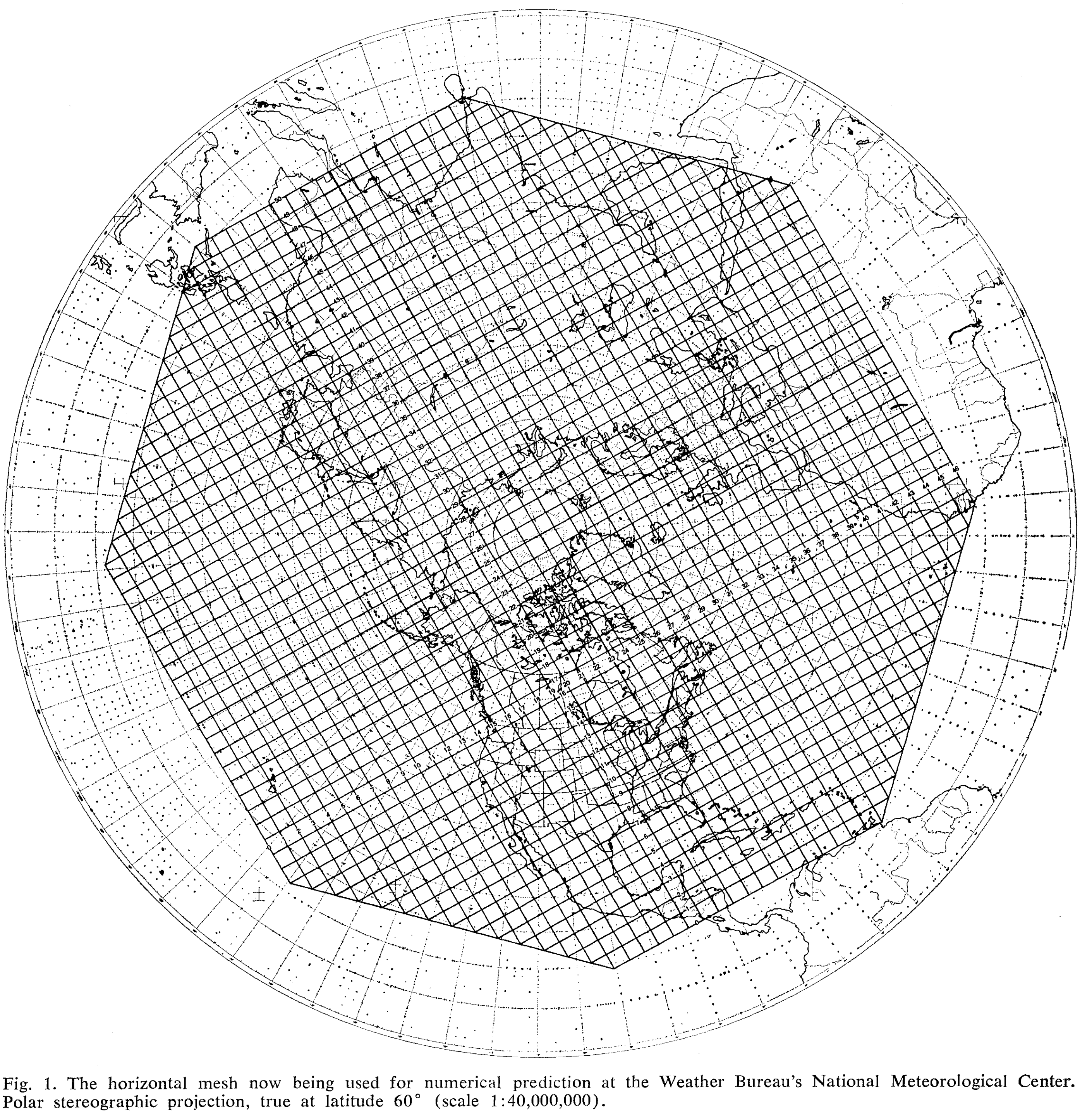

Fig. 1. The horizontal mesh now being used for numerical prediction at the Weather Bureau's National Meteorological Center. Polar stereographic projection, true at latitude 60° (scale 1:40,000,000).

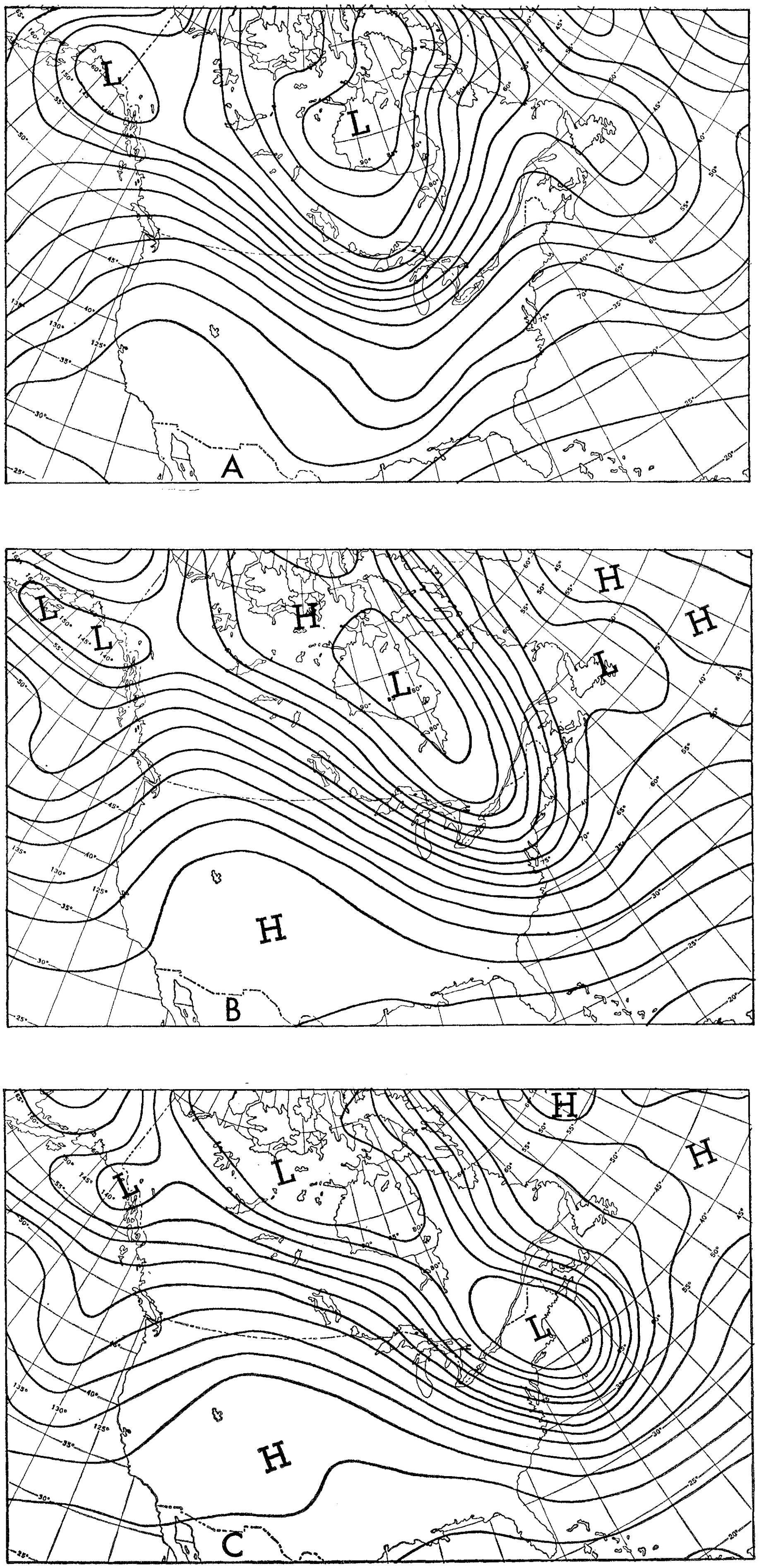

Fig. 2, parts *A–C*. *A*, Contours of the 500-millibar pressure surface for 7:00 a.m., EST, 29 December 1962; *B*, 500-millibar chart 24 hours after Fig. 2*A*; *C*, 500-millibar chart 36 hours after Fig. 2*A*.

been attained with baroclinic models and the filtered equations. At this writing, I know of several countries using such models for daily prediction—Japan, the United States, Great Britain, Norway, and the Soviet Union.

In the meantime, Richardson's more fundamental approach had not been entirely forgotten. Richardson's first difficulty was that his method of representing his initial conditions by atmospheric data introduced gravity waves of completely unrealistic amplitude. In 1954, J. Charney (*10*) demonstrated, by integration of a barotropic model, that if these were eliminated from the initial data by balancing the initial wind and pressure fields (altering them to eliminate the implied horizontal divergence at the initial time) the growth of these waves in the forecast was slow and could be controlled.

In the late 1950's some kind of breakthrough was achieved when workers on three separate projects—in Norway (*11*), the United States (*12*), and Germany (*13*)—achieved the successful integration with the primitive equations of multilevel atmospheric models. The term "primitive equations" has come to mean the original equations of motion and state; these equations contain all but the sound waves, which are excluded by a statement of hydrostatic equilibrium.

In principle, the main difference between the primitive equation model and the filtered equation model is that the former contains the gravity waves. This difference may be irrelevant to a practical solution of the forecasting problem because our observation network doesn't give us any knowledge of gravity waves at all. The only virtue in allowing these waves to occur in the calculations is that they may represent some kind of adjustment mechanism important to the changes in the atmospheric systems of larger scale. In any case, we don't know whether this is true. The main attraction of using the primitive equations is that, for a baroclinic model, the equations are simpler and the computer programming is easier. On the other hand, the appropriate formulation of the finite difference analogs of the primitive

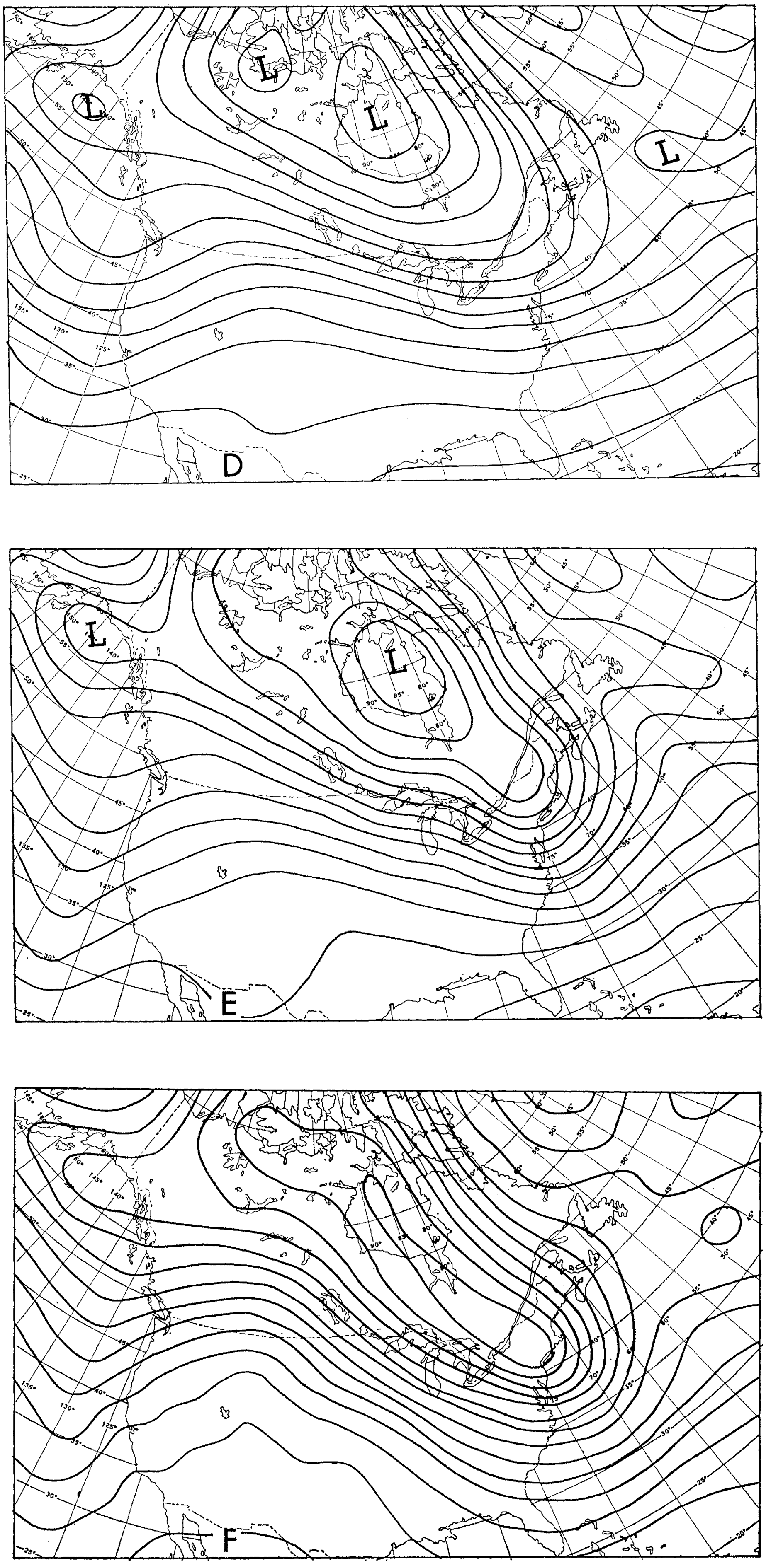

Fig. 2, parts *D–F*. *D*, 36-hour barotropic forecast from 7:00 a.m., 29 December 1962; *E*, 36-hour forecast from the operational three-level model; *F*, 36-hour forecast from a four-level primitive-equation model.

equations has been a real problem, with reasonably satisfactory forms available only recently (*14*). Furthermore, the Courant-Friedrichs-Lewy computational stability criterion (*15*) says that the ratio of time step to grid length must be such that the event forecast cannot move more than one mesh length during each time step. The existence of the fast-moving gravity waves thus limits the time step to 10 to 15 minutes; thus the whole forecast has to be repeated with that frequency, and the requirements for computer time are severe. On the other hand, the filtered equations, though more difficult to program, can be used with longer time steps (30 to 60 minutes), and they take less computer time.

Just now all the centers using numerical prediction for daily forecasting are using the filtered equations for their models. However, I think it only a question of time before the equations in their more general form will prevail (i) because they are simpler, making easier the more complete inclusion in the atmospheric models of the important physical effects, and (ii) because more people are working on them.

Those responsible for operational forecasting in the Weather Bureau considered that the first really acceptable baroclinic forecast model had to be successful in three respects. (i) It had to forecast correctly at least some of the conversions of potential to kinetic energy in the atmosphere. (ii) It had to show less overall error than the barotropic forecast model. (iii) It should make hardly any noticeably worse forecasts than the barotropic model. By 1962 we were able to put into operation, at the Weather Bureau's National Meteorological Center at Washington, the first model acceptable by these standards (*16*). It is still in use in essentially the same form today. The vertical structure of the atmosphere is represented in this model by data at three pressures: 850 millibars (about 1500 meters above sea level), 500 mb (about 5500 m), and 200 mb (about 13,000 m). The model is capable of representing the aforementioned energy conversions; and it contains, in addition, a good approximation of the effects of the mountains on the atmospheric flow and of the frictional drag of the earth's surface on the atmosphere. Its principle limitations are due to its lack of a better vertical resolution of the atmosphere and the omission of the effects of the latent heat of condensation. This last-mentioned effect appears to play an important role in the intensification of many storms, especially those that cause so much inconvenience to the residents of the east coast of the United States. It seems now that both of these factors (better vertical resolution and latent heat) must be taken into account before the result is really satisfactory.

Figure 2 illustrates the capabilities of models of increasing complexity in forecasting a complex process, new storm development. Parts *A*, *B*, and *C* show the events at the 500-millibar surface associated with the development of a storm over New England. There is a deep 500-mb cyclone in that area by 36 hours after the time

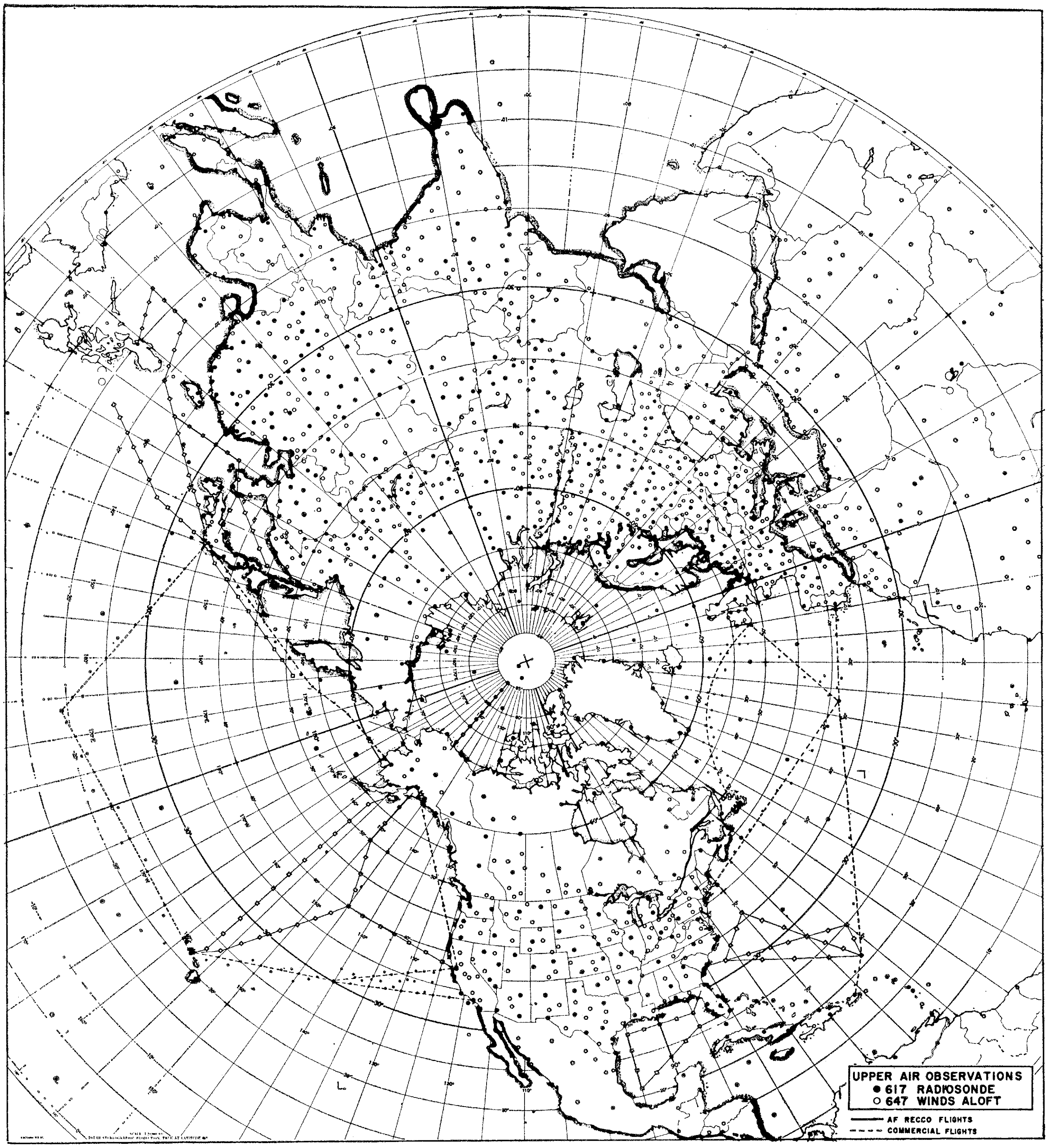

Fig. 3. The present upper-air observing network. Stations taking temperature and wind soundings are indicated by solid circles; stations taking wind soundings only, by open circles. Weather reconnaissance routes (USAF aircraft) are indicated by dashed lines and main commercial air routes by dotted lines. Dots along commercial air routes give positions of observations from commercial aircraft in a typical 6-hour interval.

shown in Fig. 2*A*. The barotropic forecast, which is usually so useful, failed completely to show this development (Fig. 2*D*). The three-level filtered-equation model (Fig. 2*E*) indicates the general pattern but fails to show the strength of the development. Figure 2*F* shows the forecast produced by an experimental four-level primitive equation model developed by F. Shuman, of the Weather Bureau. This forecast, while not at all perfect, is substantially better than the others.

Extensions to Different Scales of Motion

Several groups are working with numerical experiments to simulate the long-term aspects of atmospheric behavior. In these it is important to include in the numerical model the essential sources and sinks of energy both accurately and in the right amounts relative to each other. When this is done, the numerical calculations show the behavior of atmospheric models through periods of several months or more. This may require months of computer time for the largest models. However, aside from other purposes, when the necessary physical and computational problems of these projects are mastered, a new possibility exists for long-range forecasting. Starting the calculations from the data on a given day, the forecasts fail to give an accurate detailed picture of atmospheric systems after a few days, because of inadequacies in the initial data, if nothing else. However, the statistical characteristics of the forecast calculation may be useful much longer and could indicate areas favorable for storm development, favored cyclone and anticyclone tracks, and areas where the average temperature will be above or below normal.

Other problems of equal difficulty and interest concern motions on a much smaller horizontal scale. For example, E. Fisher of New York University (*17*) and M. Estoque of the University of Hawaii used the techniques of numerical prediction to compute the evolution of the sea breeze (*18*). J. Hovermale of the Weather Bureau has computed the details of flow over a single mountain range. An interesting application of this small-scale work is possible. Suppose, for example, that we consider an area such as the Los Angeles basin, bounded by mountains forming a natural wall on the east and by a relatively homogeneous ocean surface on the west. Suppose also that we could get adequate initial data on a small scale from this area. A numerical prediction of the development of the sea breeze cycle, together with the other orographically controlled circulations, could yield a valuable short-range forecast of the displacements of and the changes in concentration of smog.

The meteorological problem, including the automatic data processing and analysis to be described, requires a general-purpose digital computer for its effective solution. A quite small computer is adequate for barotropic forecasting, but as the complexity of the forecast model and the number of levels used increases, the demands on the computer grow. The requirements for early forecasts and the problems of distributing output to a large weather-service organization set a practical limit of about 1 hour of computer time to 1 day of forecast time. In our own group, in Washington, we began daily numerical forecasting early in 1955 with an IBM 701 computer. We are now using an IBM 7094 II.

The problem of computing a forecast is quite different from that of processing the initial data. The modern general-purpose digital computer is, however, the best available tool for both kinds of work.

A complete specification of the temperature, pressure, humidity, and horizontal motion of the atmosphere at any given time for the position of each point in the grid of Fig. 1 is beyond our capability. We take the observations where we can get them. Over the populous and economically developed areas of the world a good data-gathering network is found, both at the surface of the ground and aloft. Over the rest of the Northern Hemisphere the problem of gathering initial data is difficult. A reasonably good collection of surface observations is made from ships of all types; obtaining data on the upper air is more difficult. A few specially equipped ships take soundings of the upper air. In-flight reports of wind, pressure, and temperature from aircraft are useful for filling in between these ships on the regular air routes. However, essential data are scant for large areas in both the Atlantic and Pacific oceans. Figure 3 shows the observing network now in use.

The reports from the observing stations are encoded in standard code forms, organized into collective form, and distributed by telecommunications to the meteorological services of the world. This outstanding result of international cooperation attests to the effectiveness of the World Meteorological Organization at Geneva, Switzerland, which is the focal point of this collaboration.

At Washington, most of the reports are received within 5 hours of observation time. A typical collection consists of about 1500 surface reports, 400 complete upper-air soundings, and 150 in-flight reports from aircraft.

The first step in preparing these data for the prediction process is referred to as "input-data handling." This begins by the conversion, usually as data on magnetic tape, of the signals on the telecommunications lines to a form of data suitable for use on the computer. When all data are accumulated on the tape, the computer must recognize the beginning and end of each report, determine the format used in encoding the report, decode the report, perform all possible consistency checks on each report, compare duplicates, and finally sort the reports into a systematic order (*19*). This operation takes only about 10 minutes but requires an extensive computer program consisting mainly of tests and decisions, in contrast to the forecasting program, which is mostly arithmetic.

After the input-data handling, it is necessary to obtain information at the regularly spaced grid points from the data at the irregularly spaced observation sites. The most widely used method of achieving this end begins by carrying over all possible information from the last observation time, a previous forecast being used as a first guess. The guess is then corrected by the observed data in a series of approximations of gradually decreasing horizontal scale. Further detection and removal of any remaining erroneous data takes place by comparison of each observation with "expected" values obtained initially from the first guess and later by comparison with neighboring data. This comparison amounts to a test for excessive and unrealistic roughness (large values of high-order horizontal derivatives) in the combined values of the observed parameter and the derived values at the grid points. This whole process is known in meteorology as "objective analysis" (*20*).

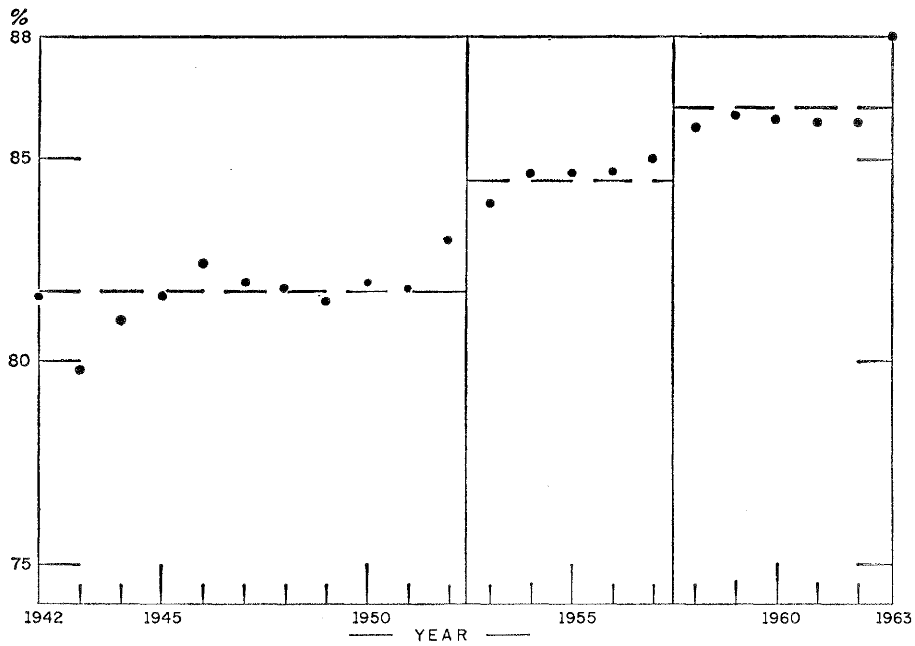

Fig. 4. Verifications of the public forecasts issued by the Chicago Office of the Weather Bureau. Horizontal dashed lines give average values of score for periods between vertical lines.

The problem of "output-data handling" has been solved by devices that represent the fields in mapped form from the data at the grid points (by digital to analog conversion). For this purpose we use commercial devices, with some modifications. We have been using electromechanical curve plotters which draw curved lines at the rate of 25 centimeters per second; these plotters operate by reading from magnetic tape the coordinates of successive points on the lines to be drawn (*21*). Facsimiles of these forecast maps are distributed to forecast offices of the Weather Bureau, Air Force, and Navy for use in aviation and local forecasting. We are now trying out a device which, operating from the same kind of information on tape, draws the lines on the face of a cathode ray tube. A photograph of the tube is suitable for rapid production of a large-scale map by Xerox process as well as for direct transmission of the image on the film by facsimile.

We are also filling a number of requirements for production and transmission of large amounts of data in digital form. Messages containing forecasts of wind and temperature, as well as completed flight plans, go out in considerable volume. These are produced automatically, being written on magnetic tape, converted to paper tape, and transmitted by Dataphone or teletype. The flight plans are produced by the Air Force for planes of the Military Air Transport Service. A fleet of several hundred imaginary planes is flown along a great number of routes at several altitudes in the wind environment described by the history tape of the numerical forecast. This contains the winds from each time step of the forecast. The history of these imaginary flights, containing the relevant navigational parameters, is then transmitted for use by real aircraft.

Impact on General Predictions

I have discussed some of the aspects of the impact of numerical prediction on forecasting. The centralized processing of hemispheric meteorological data is now done automatically, and forecasts of many elements are produced and distributed automatically. However, the important question is: "How much has the accuracy of forecasts improved?" The fact is that we can't give a simple answer to that simple question, partly because there are many kinds of forecasts. First, let us consider forecasts of winds at upper levels of the atmosphere which are essential to aviation. A continuous verification of forecasts issued by the Weather Bureau's National Meteorological Center has been prepared from 1954 to the present. This indicates a reduction of the error of the 36-hour forecasts of the wind at 500 millibars of about 25 percent. A perfect forecast method would not have resulted in the elimination of all the error, since the inadequacies of the existing data network over the oceanic areas adjacent to the United States would set a limit of roughly 60 percent to the attainable reduction of the degree of error in 1954. The present error in forecasting these winds 36 hours in advance is about twice the probable error of measurement, or about 8 meters per second.

It is not possible to give such a straightforward answer where the public forecast of rain or snow, cloudy or sunny, warmer or colder is concerned. For one thing, this type of forecast is not explicitly a part of a numerical prediction. The numerical prediction gives the horizontal flow pattern at several levels in the atmosphere and the vertical motion between them. Until explicit forecasts of water phase are made, the numerical predictions must be interpreted by forecasters before the general public forecast can be obtained. In doing this the forecaster naturally includes some of his own experience and ideas. Another problem is that there is no really meaningful measure of the accuracy of this type of forecast over a long period of years, and we are just now trying to establish a verification base line for future use. For example, comprehensive forecasts of the total amount of precipitation expected during a given period in advance have been verified closely for only 6 years. These show a threefold increase in "skill score" occurring between 1959 and 1962. An interpretation of the "skill score" can be obtained by considering that in 1959 a place for which 2½ centimeters (1 inch) or more of precipitation was forecast to fall during the succeeding 24 hours had only a 10 percent chance of getting that much. By 1962 the probability was up to about 33 percent.

A record of verification of the public forecasts issued by the Chicago office from 1942 to the present has been made available to me by L. Hughes. A plot of the yearly averages, slightly smoothed, is shown in Fig. 4. The verification numbers are the percentages of correct forecasts of weather and temperature. Significant improvement in scores is noted around 1953, and again around 1958. The 1963 score is spectacular, but several years will be required before we should try to interpret it.

Thus only minimum resources are required to obtain a substantial benefit from numerical prediction—an IBM 1401 being sufficient for the preparation of a barotropic forecast—and many countries have now become engaged in operational numerical prediction. At this time, the following countries can be named: Great Britain, Norway, Sweden, France, Belgium, Italy, Israel, Canada, Japan, the Soviet Union, and the United States. West Germany is scheduled to start, and India may follow. In the Southern Hemisphere, Australia, New Zealand, and South Africa are beginning experiments. Their problem is more difficult than that of the Northern Hemisphere countries, since in the Southern Hemisphere the supply of data is so scant that the initial conditions can't be described with even a marginally acceptable accuracy. The World Meteorological Organization has organized a monthly exchange of numerical predictions, made on the 15th of each month. These forecasts are exchanged among nearly all operating numerical centers, and they give all concerned a chance to evaluate and appreciate the work of their foreign colleagues as well as to evaluate their own work in comparison. International exchange of ideas, techniques, and methods in this field is extraordinarily free.

Priority Problems

Several problems are now confronting workers in numerical prediction:

First, there is the need to produce a short-range, multilevel prediction model which carries enough information at both high and low levels of the atmosphere to give the necessary detail required by users of the forecasts. For forecasting 2 to 3 days in advance, the physical effects of the large-scale flow over mountains, friction between the air and the surface of the earth, and heating or cooling of the atmosphere at the earth's surface will be needed. Models of this type have been under development for several years. The next year should see one of these models in operational use by the U.S. Weather Bureau and, before much longer, by one or two other countries.

The next problem is the inclusion in such a prediction model of the atmospheric sources and sinks of heat due to the changes of phase of water. Several existing experimental models include the production or absorption of latent heat, but with less than satisfactory results. A chief difficulty is that of avoiding the creation of instabilities in the model. The release of latent heat gives rise to high vertical velocities, and the numerical description of the process tends to get out of hand, with the growth of instabilities. One solution has been to suppress the instabilities with an artificially high internal viscosity, but this leads to other undesirable effects outside the condensation area. Obtaining the initial distribution of water in vapor and cloud forms is not very satisfactory. The meteorological satellites will help with this aspect of the problem. An adequate inclusion of the effects of latent heat of condensation is essential for solution of the short-range forecast problem and should lead to 5- or 6-day forecasts.

A basic problem, underlying many others, is that of obtaining the data necessary to describe the atmosphere at a given moment with enough completeness and accuracy to serve as an adequate start for numerical forecasts. The immediate problem is, of course, getting observations of upper-level wind pressure, temperature, and humidity from the oceanic areas of the Northern Hemisphere. Africa and the desert areas bordering the Arabian Sea also pose a difficulty. It goes almost without saying that the vast empty areas of the Southern Hemisphere will be much more difficult to populate with observations. The World Meteorological Organization is now intensifying its activities through coordinated international action in planning and in arranging for extension of observing technology in an effort to alleviate these difficulties.

Summary

The last 10 years have seen a revolutionary change in the way weather forecasts are made. The basis for today's forecasts is a numerical calculation of the evolution of the energy distribution and motions in a physical model of the atmosphere. The benefits of this change have affected all types of weather forecasting. The substantial benefits to aviation are well established. The benefits to forecasts for the general public can't be conclusively documented but are strongly suggested. Our present limitations are mainly due to insufficient completeness of our atmospheric models. The removal of some of these deficiencies appears to be a relatively straightforward task. Other problems, particularly those of phase change of water, are more difficult. The eventual limitation to the prediction of atmospheric motions appears to be the supply of data describing the initial conditions, but I can safely say that solution of the other problems will require more than just a few years.

References and Notes

1. J. G. Charney and N. A. Phillips, *J. Meteorol.* **10**, 71 (1953).
2. P. D. Thompson, "Notes on the theory of large-scale disturbances in atmospheric flow with applications to numerical weather prediction," *U.S. Air Force Cambridge Res. Center, Geophys. Res. Paper 16* (1952).
3. B. Bolin, *Tellus* **5**, 207 (1953).
4. V. Bjerknes, "Meteorologische Zeitschrift," *Dynamic Meteorology and Hydrography* (Carnegie Inst. of Washington, Washington, D.C., 1911), pp. 99–130.
5. L. F. Richardson, *Weather Prediction by Numerical Process* (Cambridge Univ. Press, London, 1922).
6. J. G. Charney, *Geofysica Publ. 17* (1948).
7. ———, R. Fjörtoft, J. von Neumann, *Tellus* **2**, 237 (1950).
8. G. Árnason and L. P. Carstensen, *Monthly Weather Rev.* **87**, 119 (1959).
9. G. P. Cressman, in *The Atmosphere and the Sea in Motion* (Rockefeller Inst. Press, New York, 1959), pp. 475–485.
10. J. G. Charney, *Tellus* **7**, 22 (1955).
11. A. Eliassen, "A procedure for numerical integration of the primitive equations of the two parameter model of the atmosphere," UCLA, Dept. Meteorol. contr. AF 19(604)-1286, Sci. Rept. No. 4 (March 1956).
12. J. Smagorinsky, *Monthly Weather Rev.* **86**, 457 (1958).
13. K. Hinkelmann, in *The Atmosphere and the Sea in Motion* (Rockefeller Inst. Press, New York, 1959), pp. 486–500.
14. F. G. Shuman, *Proc. Intern. Symp. Numerical Weather Prediction, Tokyo, 1960* (Meteorol. Soc. Japan, Tokyo, 1962), pp. 85–107.

R. Courant, K. Friedrichs, H. Lewy, *Math. Ann.* **100**, 32 (1928).

16. G. P. Cressman, "A three-level model suitable for daily numerical forecasting," *U.S. Weather Bur. Nat. Meteorol. Center Tech. Mem. 22* (1963).
17. E. L. Fisher, "The study of low level wind field," New York Univ. Coll. Eng., Res. Div. contr. DA-36-039-sc-78091, phase 2 (The sea breeze project) (April 1958); Final Rept. (June 1958–Sept. 1959).
18. M. A. Estoque, *Quart. J. Roy. Meteorol. Soc.* **87**, 136 (1961).
19. H. A. Bedient and G. P. Cressman, *Monthly Weather Rev.* **85**, 333 (1957).
20. G. P. Cressman, *ibid.* **87**, 367 (1959).
21. Note, Communications of the ACM **4**, 164 (1961).