ADVANCES IN NUMERICAL WEATHER PREDICTION

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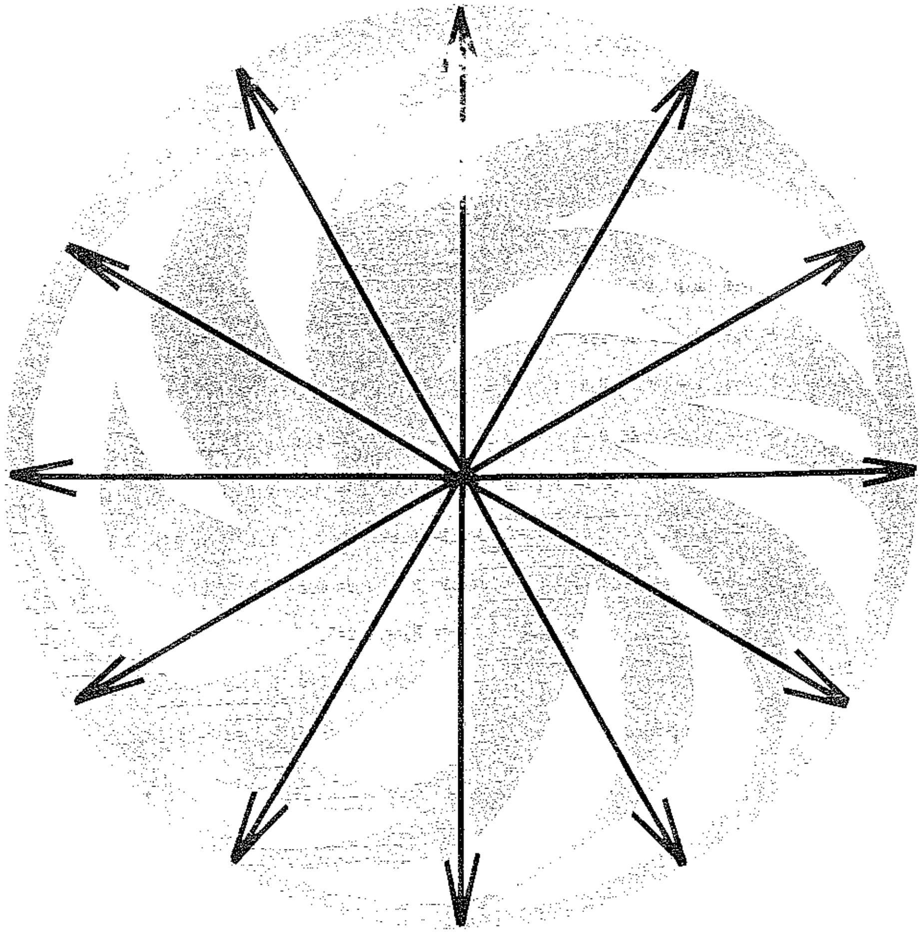

Atmospheric predictability

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It is indeed a pleasure to return to the Travelers Research Center, and to take part in this series of seminars on Advances in Numerical Weather Prediction. Although we may hold differing opinions as to the quality of weather prediction as it is currently practiced, the existence of the daily weather forecast is something which all of us take for granted. The situation has not always been thus.

About a hundred years ago, Admiral FitzRoy began to publish his weather forecasts in the daily newspapers in London. For this he was severely criticized by some of his colleagues in the Royal Society. Apparently they looked upon his forecasts as new scientific results, and felt that no scientist should announce his results to the public until he had taken all possible pains to verify them. FitzRoy could evidently have done so simply by waiting for the predicted weather to occur. In any event, following FitzRoy's death a few years later, the daily publication of the forecasts was discontinued (cf. Shaw, 1926).

Attitudes change, however, and today, in informal conversations, we often hear the weatherman being derided for too frequent use of such terms as "possibly" or "probably". It would appear that the sin of claiming that one can see the future has been replaced by the sin of admitting that one cannot see it too clearly.

Before I decided to become a meteorologist, I had always assumed that the weather was for the most part predictable, and that incorrect forecasts, of which the public seemed to be acutely aware, occurred simply because the technique of prediction had not yet been mastered. During my years as a student in meteorology nothing occurred to change this attitude. I believe that this opinion is also prevalent among the general public today.

One who has not devoted considerable time to the study of meteorology cannot be criticized for holding such an opinion. After all, such other natural phenomena as eclipses of the sun are predicted years or even centuries in advance, and, as the day of a predicted eclipse arrives, people who have traveled from far-away points will gather on open hillsides to watch the shadow of the moon speed by, knowing that they will not be disappointed, except, perhaps, by a bad weather forecast. It is not immediately obvious why the spectacular eclipse should be more readily predictable than the equally spectacular tornado. Perhaps we can imagine a future world where the time and path of a tornado will be predicted many days ahead with high accuracy, and where, as the day of the tornado arrives, adventurous souls from miles around will gather on nearby hillsides to watch the funnel roar by, feeling reasonably confident that they will not have to flee when it departs from its predicted course.

Let us consider for a while the methods of weather forecasting which are currently in use, with an eye to deciding whether the technique of forecasting has been mastered, or whether there is room for improvement. By and large, the procedures used today fall into three categories. First and most familiar is *synoptic* forecasting. This is the subjective method, and the only one which was in general use at the outset of World War II. Here the forecaster assembles all the information which he can digest concerning the present and recent past state of the atmosphere. He then analyzes the data to obtain a picture of the weather situation in terms of systems, such as areas of high and low pressure, air masses and fronts, and cloud systems, and, on a more local scale, thunderstorms and even individual clouds. On the basis of the way these systems are behaving, he extrapolates their positions and configurations into the future, being careful to add any new systems whose genesis he feels is indicated. He then translates his prognosticated weather pattern into forecasts of the weather at locations of interest.

His estimate of how a system will behave is based upon his knowledge or opinion of how similar systems have behaved in the past. His mind will be loaded with situations which are somewhat like the present, but he can never discover a past situation which is identical with the present one, and his success in forecasting will depend to a large extent upon his ability to recognize which features of the current situation are really relevant. The requisites for a good forecaster are therefore a keen analytical mind and a vast amount of experience with the weather.

Yet even the best forecaster cannot assimilate all the available information concerning the current weather picture, and his experience cannot cover all the possible quirks of the atmosphere. Occasional incorrect forecasts are therefore inevitable; nearly all of us remember the heavy snowstorms which have not been predicted even six hours in advance, and the predicted heavy storms which have nevertheless failed to arrive.

Post-mortem discussions are routine practice among many forecasters, and sometimes, when a forecast has failed, it is possible to identify one feature which, had it been given proper attention, would have led to a correct forecast. On other occasions the forecasters may be unable to discover any clear indication that what actually did happen was about to happen. The disillusionment with synoptic methods of forecasting which has arisen from possibilities of this sort has led many meteorologists to seek methods which, once developed, will not rely upon human judgment and alertness.

One procedure which fulfills this requirement is *statistical* forecasting. Here the relevant features of the atmosphere are expressed as numbers, which are substituted into mathematical formulas. The output of these formulas is more numbers, which express the predicted weather features. The formulas are statistical in that they are based wholly upon the statistics of past weather behavior. These statistics are really nothing more or less than experience, expressed in the form of numbers.

Statistical formulas have been with us for a long time, but it is mainly since World War II, with the development of electronic digital computers, that they have shown promise of competing with the synoptic forecaster in routine practice. In principle, the computer can assimilate far more information concerning the current weather situation than the human forecaster, but at present it is considerably less versatile than the human brain in its ability to put this information to use. For this we should not blame the computer; if it cannot accomplish a certain mental task, it is because we have not yet learned how to teach it to accomplish the task. Today we are teaching computers certain skills which a few years ago might have seemed beyond their grasp; among these is the translation of English into Russian, a task which is seemingly far removed from the simple arithmetic for which the computers were originally designed. Yet some skills are more subtle than others; a computer with a complete dictionary knowledge of the English language might still find it difficult to understand the writings of a poet. Some day the weather forecaster may learn how to instruct the computer to do everything which he himself does in extrapolating the weather pattern. In the meantime, statistical forecasting has not overcome the shortcomings of synoptic forecasting in day-to-day practice.

The third method is *dynamical* forecasting, otherwise known as *numerical weather prediction.* This method was envisioned many years ago, and was set forth in great detail in the remarkable book by Richardson (1922), but in practice it is almost wholly dependent upon computing machines, so that it did not really come into being until after World War II. Here the computer is instructed to determine particular solutions of the mathematical equations which represent the physical laws governing the atmosphere and its environment. In principle, by following the dynamical laws the computer should put the available information to use in the best possible way; there is no need to rely upon past experience with the weather. In actuality, however, a complete solution of the equations would overburden any existing computer, so that current dynamical forecasts have been based upon approximations which in some respects are rather crude, and which have often been selected on the basis of human experience. Thus dynamical forecasting, although competing with the other methods, has yet to establish its supremacy.

In short, we find that all the common methods of forecasting allow considerable room for improvement, and there is much justification for the claim that the technique of weather forecasting has not yet been perfected. It does not follow, however, that essentially perfect forecasts will be possible when the technique has been mastered.

It is in considering the dynamical laws governing the atmosphere, and also those governing eclipses, that we encounter very good reasons for believing that eclipses may forever remain more predictable than tornadoes. At first sight this may not seem to be the case. The laws say that the future positions and velocities of the sun, earth, and moon are determined by the exact present positions and velocities, along with any external influences such as perturbations by other planets; likewise, the future state of the atmosphere is determined by the exact present state, along with the intervening influences of the atmosphere's terrestrial and extraterrestrial environment. To this extent, the forecasting problems are similar.

However, only three numbers are needed to specify the location of the center of gravity of the earth with respect to some reference point, and three more numbers will specify the velocity. The same is true of the sun and the moon. Thus a total of only eighteen numbers describes the present sun-earth-moon configuration, from which the future configurations may be predicted. If the procedure is to be refined by including perturbations by Venus, Mars, or Jupiter, only six additional numbers per planet are needed. Such internal details as giant spots on the sun and tropical hurricanes on the earth are virtually irrelevant.

It would be hopeless to try to describe the current weather pattern with any precision by a collection of eighteen numbers. For one thing, the atmosphere has no simple set of moving points which could serve as analogues of the centers of gravity of the heavenly bodies. Even a knowledge of the position and velocity of the center of every storm currently in existence would not reveal the individual shapes and strengths of the storms, and, in any event, storms do not always maintain their identity from day to day. It has therefore proven more feasible to choose standard locations rather than standard weather features, and to use numbers to represent the values of the familiar weather elements—pressure, temperature, humidity, wind velocity, etc.—at the standard locations, which may be the locations of the regularly observing weather stations. One hundred numbers may still be too few to describe the relevant features of a single storm, and many thousand will be needed for a reasonably adequate picture of the whole atmosphere.

Thus it is that a description of a state of the atmosphere is far more involved than a description of the sun-earth-moon configuration. This fact by itself does not mean that weather is any less predictable than eclipses; it merely shows that much more labor is required to predict the weather. However, the physical laws have told us only that perfect predictions are possible with a perfect knowledge of current conditions. The myriad numbers used to describe a state of the atmosphere still do not describe it perfectly, for there is always some uncertainty concerning the interpolations across the regions between observing stations; unsuspected thunderstorms may even be lurking there. Let us note, then, that in the strictest sense the astronomical measurements used in eclipse prediction are also not perfect. The really pertinent question then becomes the following: is it possible to make *almost* perfect forecasts of the future if the present is *almost* perfectly known, either in the case of eclipses or the weather? To be able to answer this question, we must be cognizant of the phenomenon of instability.

A physical system is said to be *stable* if, should it be slightly disturbed, it will thereafter behave only slightly differently from the way in which it would have behaved if it had not been disturbed. It is called *unstable* if, upon being disturbed, no matter how slightly, it will ultimately behave in a considerably different way. We generally regard the act of disturbing a system as introducing a small perturbation, and look upon an unstable system as one where small perturbations will proceed to grow, and a stable system as one where they will fail to grow.

Sometimes we regard a stable system as one where small perturbations will proceed to die out altogether, and call the system *neutral* if they fail to grow but also fail to die out. Among unstable systems, we may distinguish between slightly unstable systems, where the growth of small perturbation is slow, and highly unstable systems, where the growth is very rapid.

Perhaps the most familiar example of a system which may be either stable or unstable under suitable conditions is the spinning top. If it is spinning rapidly, it will continue to stand upon its point, and a slight disturbance will cause it to wobble but not to topple. If on the other hand it is spinning too slowly, it will immediately fall over, despite the fact that a slowly spinning or even a stationary top standing vertically upon its point constitutes a perfectly valid solution of the mathematical equations governing the motion of a top.

The rapidly spinning top is evidently stable, or possibly neutral. The slowly spinning top standing vertically is in a state of unstable equilibrium, and in general the slowly spinning top is unstable.

Another example of unstable behavior is afforded by the familiar pin-ball machine—preferably an old-fashioned one without lights and flippers. The first ball may strike several pins during its journey, traveling a few inches after striking one pin before striking the next. If the second ball could begin with exactly the same direction and speed, it might be expected to follow the same path. If, however, its direction differs from that of the first ball by only a tenth of a degree, it will be about a hundredth of an inch off course when it strikes the first pin, and, after it rebounds, its direction will differ by a whole degree from that of the first ball. It will then arrive at the second pin about a tenth of an inch off course, and, after rebounding, will make about a ten-degree angle with the direction which the first ball followed. This will probably be sufficient to make it miss the third pin altogether, or strike a pin which the first ball missed, after which its course will bear no further resemblance to that of its forerunner. The journey of the pin-ball is indeed unstable.

It is quite evident from this description that the journey of the ball, and indeed the detailed behavior of any unstable physical system, cannot be predicted very far in advance. Even if it were possible to measure the direction of the ball to within a thousandth of a degree, its path could be predicted only four pins ahead. And if somehow the direction could be measured exactly, some external disturbance—perhaps the vibrations from a nearby juke box—would soon introduce the inevitable perturbation.

We may therefore answer our question as follows: it is possible to make almost perfect forecasts of the future of a system if the present is almost perfectly known, provided that the system is stable, but not if the system is unstable.

Unlike the spinning top and the pin-ball machine, the atmosphere has the property that its motion will continue virtually forever. This occurs because the atmosphere is being continually driven by energy received from the sun. In principle the spinning top could be converted into a system of this sort by attaching to it a small motor, which would supply just enough energy to offset the amount dissipated by friction. For such systems there is a direct relation between stability and periodicity (cf. Lorenz, 1963).

If a real system is allowed to oscillate for a long enough time, it must eventually assume a configuration which resembles an earlier configuration, simply because the number of possible configurations, each bearing no resemblance to any of the others, is limited. The longer the system oscillates, the closer the resemblance between some pair of configurations must become. Ultimately the system will assume a state which is equivalent to a previous state plus a small perturbation. If the system is stable, it will thereafter continue to behave in an only slightly different manner from the manner in which it behaved following the occurrence of the previous state, until, after a similar lapse of time, it will again assume a state closely resembling the earlier states, whereupon it will repeat its previous behavior again. Thus its behavior will be *periodic*, repeating itself at regular intervals.

Conversely, if we can determine that a system is oscillating non-periodically, we can conclude that it is unstable. The instability is in this case the cause of the nonperiodicity, rather than vice versa, but the nonperiodicity may serve as an indicator of the instability.

We now come to the basic reason why astronomers have enjoyed more success in predicting eclipses than meteorologists in predicting the weather. The sun-earth-moon configuration is stable, or at most very slightly unstable, as evidenced by its great predictability. The atmosphere, on the other hand, is unstable.

Our evidence for the latter conclusion is necessarily indirect. We cannot test the atmosphere by creating a small disturbance and observing the consequences, because we could not then determine with sufficient accuracy what would have happened if we had not created the disturbance. We do observe, however, that the atmosphere is not periodic. To be sure, the atmosphere has predictable periodic components, particularly the pronounced variations with the time of day and the time of year. Superposed upon these, however, there are marked fluctuations which show no evidence of repeating themselves at regular intervals, and which therefore presumably cannot be predicted very far in advance.

Further indication of the instability of the atmosphere is afforded by a recent development in meteorology known as *numerical simulation*. The procedure for numerical simulation is in most respects identical with that for numerical weather prediction, but the initial conditions need not represent the present or any other actually observed weather situation, and the numerical solutions are extended over simulated periods of months or even years. These solutions are then treated as data, from which various climatological statistics may be evaluated. The purpose of numerical simulation is not to produce good weather forecasts, but rather to produce a realistic over-all behavior of the simulated atmosphere, which would be indicated by reasonable numerical values of the simulated climatological statistics.

One of the features of the over-all behavior of the atmosphere is its degree of instability, as measured by the rate at which typical small perturbations will grow. It is a simple matter to determine this rate for a simulated atmosphere—one simply performs the same numerical experiment twice, with slightly differing initial conditions, and observes how rapidly the two solutions diverge from one another, if they diverge at all.

Yet many problems remain. We have seen that the equations governing the atmosphere must be drastically simplified before they can be handled by even the largest existing electronic computer. The simplifications preferred by one investigator have generally differed considerably from those preferred by another, and, as a consequence, the results of different numerical simulations are somewhat contradictory.

The most sophisticated simulations are those of C. E. Leith, Y. Mintz, and J. Smagorinsky. Each of these has been used to estimate the growth rate of small perturbations. The results have been described and compared by Charney *et al.* (1966), who thereby concludes that a five-day doubling time for the amplitude of small perturbations is a reasonable estimate.

If the five-day doubling time is correct, there would seem to be no reason why we should not be able to make good forecasts more than a week in advance, once we have mastered the technique. Forecast errors three or four times as large as the present errors in estimating the initial weather ought to be tolerable. Forecasting a month or more in advance is another matter. It is hard to imagine that the errors in estimating the current state of the atmosphere will ever become so small that forecasting errors sixty-four times as large can be tolerated. Still it must be emphasized that the conclusion that small perturbations double in five days, rather than in some other time interval, is highly tentative; the true situation may be much better, or much worse.

We must also note carefully just what the existence of instability specifically implies; it says that the configuration of the atmosphere at a specific time in the future will differ considerably from the predicted configuration at that same time. Nothing is said as to how the general behavior over an extended period will compare with the predicted general behavior over that period. The apparent tendency of certain weather anomalies to persist over lengthy periods—for example, the frequent occurrence of prolonged droughts—suggests that such anomalies may be partially predictable. It is noteworthy that the thirty-day weather outlooks, which the United States Weather Bureau has been issuing for a number of years on a routine basis, specify only whether the month as a whole will be warm or cold, wet or dry. No attempt is made to say which days of the month will be the warm ones or the cold ones, the wet ones or the dry ones; any such attempt would appear highly unlikely to succeed.

Accepting the claim that the range at which good weather forecasts can be made is limited, what can we do to reduce the gap between the range at which good forecasts are possible, and the range at which they are now made? It is easy to suggest that we should perfect the technique of forecasting, and improve our observing system, but how is this to be accomplished?

Concerning the technique, the best prospects for immediate improvement seem to lie in the field of dynamical forecasting. No doubt improvements in synoptic and statistical forecasting are also feasible, but in the case of dynamical forecasting we already know some of the steps to be taken. For one thing, we can profit from a higher spatial resolution of the weather pattern, and we can incorporate such a resolution every time bigger and better computers become available. In addition, there are many physical features of the atmosphere which have yet to be included in the approximate form of the equations used in operational forecasting. For example, we know that numerical forecasts ought to be improved by including the presence of clouds.

Unfortunately a detailed description of the field of clouds, including the height of the base and top of each layer, and the total liquid water content, not to mention the drop-size distribution, would seriously overburden any existing computer. We must therefore be content with an approximate representation of the field of clouds. Among the possible approximations, we do not know which is best, and we shall have to rely upon extensive numerical experimentation with several different approximations before we have a suitable answer.

Similar problems arise when we try to include other physical factors. As a result, there is frequently a lag of a few years between the decision to include some feature and the actual incorporation of this feature into routine dynamical forecasting. Such a lag may seem unnecessarily long, and it is my opinion that it could be considerably reduced if the meteorologists charged with the improvements had unlimited access at all times to the fastest available computers.

As for the observing system, we suffer at present from a scarcity of observations, rather than from inaccuracies in our observing instruments. Areas of the oceans large enough to contain fully developed tropical hurricanes are on some days devoid of weather reports. Proposals for ameliorating this situation include an internationally administered global observation system, which, among other things, would include a collection of several thousand instrumented ballons drifting with the stratospheric winds, and instrumented buoys floating in the ocean, supplemented by radiometric measurements from satellites (see Charney *et al.*, 1966). Such a system would represent a major advance in global weather coverage.

It is my own opinion, however, that the ultimate in weather prediction will not be attained until some system has been developed for directly measuring the various weather elements at a distance, so that we may obtain a virtually continuous distribution of the conditions throughout the atmosphere. What this system will consist of I cannot say. Radiometric measurements from satellites already offer promise of continuous temperature records, but only above the clouds. Perhaps the system will involve further satellite measurements. Perhaps it will involve ground-based radars or lasers. Perhaps it will involve some invention as undreamed of today as the laser was a decade ago. But as long as we must place instruments in every portion of the atmosphere to observe every portion of the atmosphere, we shall be seriously restricted.

In closing let me say a word about the possibility of weather control, which has received considerable publicity in recent months. I refer not to limited control on a local scale, such as might be accomplished by cloud seeding, but to the more ambitious task of altering the day-to-day course of the global weather pattern. Certainly we can introduce disturbances which qualify as small perturbations. If we admit the instability of the atmosphere, we must accept the possibility that a small perturbation can ultimately alter the course of the weather.

But weather modification is not weather control unless we can modify the weather in a predetermined manner. Unless we can somehow introduce a disturbance whose amplitude is larger than that of the uncertainty in estimating the current configuration of the atmosphere, the effect of the disturbance will not grow to noticeable size until after the effect of the uncertainty has grown to appreciable size, i.e., until a time for which good forecasts are unobtainable, with or without the disturbance. Moreover, we have seen that present-day uncertainties may include the omission of an entire hurricane, which contains far more energy than a hydrogen bomb. With the anticipated improvements in global weather observations, there may yet come a day when the uncertainty in knowing the state of the atmosphere will be smaller than the disturbances which can be feasibly introduced. Until then, the effect of our attempted control will remain no more predictable than the effect of giving an additional shuffle to an already well-shuffled deck of cards.

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