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Three Approaches to Atmospheric Predictability

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Abstract

One stated aim of the Global Atmospheric Research Program is the determination of the extent to which the atmosphere is predictable. Since errors in observation are inevitable, the accuracy of extrapolation into the future is limited by the rate at which separate solutions of the governing equations diverge from one another. Three basically different methods for investigating the growth rate of errors have been exploited.

The dynamical method compares numerical solutions of special systems of equations. Small errors appear to double in less than a week, the growth rate decreasing when the errors become large. The empirical method examines naturally occurring analogues. Moderately large errors amplify by nearly 10% in one day, but extrapolation of the results suggests that small errors would double in about three days. The dynamical-empirical method uses derived equations for the errors, with observed spectral properties of the atmosphere appearing as coefficients. Only the last method treats smaller-scale features explicitly. Small-scale errors appear to grow very rapidly, meanwhile inducing errors in the larger scales, which then double in two or three days. The dynamical method probably overestimates the doubling time because of special numerical approximations used to suppress computational instability.

An absolute maximum range of a few weeks for predicting a particular day's weather is indicated. A considerably denser observational network will be required before this ideal range can be approached in practice. The outlook for major improvements in short-range forecasting is favorable.

1. Introduction

One of the practical benefits which it is hoped will follow from the Global Atmospheric Research Program (GARP) is the development of a capability for producing greatly improved weather forecasts. Over the years there have been those who have envisioned a day when the weather might be predicted far in advance with virtually no error, perhaps with the accuracy with which solar eclipses are predicted now. Others have steadfastly maintained that there are certain limitations upon the possible accuracy of weather prediction, which no system of forecasting can ever hope to overcome. An important aim of GARP has therefore been the determination of the extent to which the weather is really predictable. Once we possess such knowledge we may at any future date ascertain how closely we have reached the ultimate goal of producing the best attainable short-range or long-range forecasts, and we shall be in a favorable position to decide whether the remaining possible improvements justify the further efforts needed to realize them.

The belief that man can make useful even if not perfect predictions of the weather must have first been inspired by the observation that there is some regularity in the sequence of weather events; for example, in some regions dark clouds often foreshadow a heavy shower. Today we are more inclined to base our belief in predictability upon the premise that the atmosphere is governed by a set of physical laws, which may be formulated in a manner expressing future states of the atmosphere and its environment in terms of the present.

If the laws can be so formulated, one may justifiably ask whether perfect prediction may some day be realized. Three basic reasons indicating that this is not the case may be cited. First, the system of governing laws is not strictly deterministic. Next, even if the laws were deterministic, perfect prediction would be impossible in practice because the laws are not perfectly known. Finally, even if the laws were perfectly known, perfect prediction would not be attainable because the current state of the atmosphere and its environment cannot be perfectly measured.

Although it would be an interesting task to determine what limitations are placed upon predictability by Heisenberg's Principle of Uncertainty, the problem is purely academic because of greater limitations due to other obvious uncertainties. Among these are the effects of biological activity, and, in particular, human activity, which for our purposes must be considered nondeterministic. Local cumulus convection, for example, may be affected by fires, while if one wishes to make exact predictions at very long range he must anticipate the creation of large lakes by the construction of dams.

For the present, however, these intrinsic uncertainties in the governing laws may be overlooked, because they are of minor importance compared to the uncertainties arising from our incomplete knowledge of the laws. We do not completely understand, for example, what determines when a cloud consisting entirely of minute water droplets will become converted into a cloud containing many larger drops, which will then fall out as rain. On a worldwide basis, such lack of knowledge places far greater limitations upon predictability than any uncertainty as to the locations of fires or lakes or other man-made features.

Perhaps one can visualize the day when all of the relevant physical principles will be perfectly known. It may then still not be possible to express these principles as mathematical equations which can be solved by digital computers. We may believe, for example, that the motion of the unsaturated portion of the atmosphere is governed by the Navier-Stokes equations, but to use these equations properly we should have to describe each individual turbulent eddy—a task far beyond the capacity of the largest computer. We must therefore express the pertinent statistical properties of turbulent eddies as functions of the larger-scale motions. We do not yet know how to do this, nor have we proven that the desired functions even exist.

Supposing, however, that we some day master the problem of formulating exact equations, we still cannot make perfect forecasts from imperfectly observed initial conditions. We cannot even make good forecasts at extended range, unless our equations possess the property that separate solutions, differing only slightly at some initial time, will continue to differ only slightly as time progresses. Empirical evidence indicates that this is not the case.

Most weather elements exhibit noticeable diurnal and annual variations. The fundamental diurnal and annual frequencies are accompanied by overtones, a familiar example being the semidiurnal atmospheric tide. There are also indications of certain other periodicities. When all known or suspected periodic variations are subtracted out, however, there still remain pronounced nonperiodic fluctuations.

Theoretical considerations indicate that if separate solutions of the governing equations, nearly identical at some initial time, remained nearly identical as time progressed, the atmosphere would proceed to vary periodically. The observed absence of complete periodicity therefore implies that separate solutions of the atmospheric equations diverge from one another, ultimately becoming as different as two solutions chosen at the same time of day and year but otherwise randomly. It follows that good predictions at sufficiently long range are unattainable, if the initial state is imperfectly known.

If we suppose instead that we can some day learn to observe the atmosphere without error, but if we acknowledge that our equations must forever contain some imperfections, we find that shortly after the initial moment the state of the atmosphere is imperfectly known, just as surely as the initial state is imperfectly known if our observation system is imperfect. Again, the divergence of separate solutions of the equations assures us that we cannot make good forecasts at sufficiently long range.

Knowing that we cannot predict into the indefinite future, we face the question, "How accurately can we some day predict the weather at any specified range?" The answer to this question depends upon *how rapidly* separate solutions of the atmospheric equations diverge from one another.

Let us refer to the difference between two states of the atmosphere, or between two solutions of the governing equations, as an *error*. The case of most obvious interest occurs when, at some initial time, one state is the true state of the atmosphere, and the other is the state of the atmosphere as it has been observed. There is no necessity, however, to restrict our attention to errors resembling those errors of observation which would be likely to be made in practice.

2. The dynamical approach

How, now, are we to determine the typical growth rate of small errors? The best known line of approach is a dynamical one, and it is based upon special systems of differential equations designed to resemble those which govern the atmosphere. In short, two or more solutions of the equations, originating from slightly different initial conditions, are obtained by numerical integration, whereupon the rate of amplification of the differences between the solutions is readily evaluated.

During the early stages of planning for GARP, it was recognized that the tendency for small errors to amplify might place a limit upon the range of practical predictability, and that too rapid a growth rate could conceivably render some of the objectives of GARP unattainable. It thus became essential to establish a reasonable estimate of the growth rate. At that time there were in existence three rather extensive working mathematical models of the general atmospheric circulation, namely, those developed by Smagorinsky (1963), Mintz (1964), and Leith (1965). Each model possessed its own distinctive features, but the models were alike in representing the state of the atmosphere by several thousand numbers.

Following a special conference, each of these investigators decided to use his model to study the growth rate of small errors. The results obtained from the separate models did not agree. Mintz found that after an initial period of adjustment, small errors tended to double, in the root-mean-square sense, in about five days. Smagorinsky deduced a considerably slower growth rate, while Leith obtained no systematic growth at all. It appeared, however, that Leith's atmosphere was varying nearly periodically, so that little growth was to be expected. In Smagorinsky's and Mintz's models, the growth rate subsided as the errors became larger.

In their report concerning the feasibility of a global observational system, Charney *et al.* (1966) conclude that a reasonable estimate of the doubling time for small errors is five days. If this conclusion is accepted, it is not unreasonable to entertain the possibility that good day-to-day forecasts up to two weeks in advance may eventually be produced. Such an achievement would of course demand a better observational system than the one currently existing.

Subsequent numerical experiments performed with more and more elaborate numerical models seem to confirm a doubling time of somewhat less than a week. However, even the most recent models share certain shortcomings with the earlier ones. Specifically, the equations of a model can never be the exact equations of the atmosphere. It thus becomes important to seek other means of estimating the growth rate.

3. The empirical approach

Such means are afforded by a second line of approach, which is empirical, and is based upon the natural occurrence of analogues, i.e., similar weather situations. We certainly cannot repeat the procedure of the numerical experiments, using the real atmosphere, for even though we might succeed in introducing a disturbance, and study the behavior of the disturbed state, we should then not know how the undisturbed state would have behaved. However, in principle, if we wait long enough, we may expect to encounter a state which rather closely resembles some state which has previously occurred. Either state is then equivalent to the other state, plus a small error, and the growth of the error may be studied by observing the behavior of the atmosphere subsequent to the two states.

In practice this procedure may be expected to fail, because of the high probability that no truly good analogues will be found within the recorded history of the atmosphere. Accordingly, we note that moderately large errors may in general be expected to amplify at a slower proportional rate than small errors (cf. Lorenz, 1968). By studying mediocre analogues, i.e., states bearing only a moderate resemblance to one another, we may hope at least to obtain a maximum estimate for the doubling time for small errors.

We are now completing a study of this sort. Our basic data have been the heights of the 200-, 500-, and 850-mb surfaces at a grid of 1000 points over the Northern Hemisphere, for the years 1963–1967. We have compared each state of the atmosphere with each other state occurring within one month of the same time of year, but in a different year, thereby comparing altogether about 400,000 pairs of states. As a measure of the difference between two states, or the error, we have taken the ratio of a weighted root-mean-square height difference to an estimate of the normal value of this weighted difference for the time of the year.

There are indeed no truly good analogues. In fact, the smallest error encountered is more than half as great as the average error. The smaller errors do indeed grow more rapidly, with larger-than-average errors tending to decrease rather than increase. The smallest errors amplify by nearly 10% in one day; thus it may be inferred that truly small errors would double in not more than eight days—a result which, incidentally, is in agreement with the numerical experiments.

Presumably, however, the doubling time of small errors is considerably less than that of the smallest encountered in the study. If we introduce the postulate that the principal nonlinear processes are represented by quadratic terms in the dynamic equations, we can extrapolate the results of the study to obtain a doubling time for truly small errors. This turns out to be slightly less than three days.

4. The dynamical-empirical approach

In both the dynamical and the empirical procedures the state of the atmosphere is represented or described by numerical values of the weather elements at points separated by several hundred kilometers. The errors which are indicated as doubling in several days are therefore errors in representing the larger-scale features of the atmosphere. It seems likely that errors in smaller-scale features will double much more quickly. An error in estimating the intensity of a thunderstorm, for example, should amplify at least as rapidly as the thunderstorm itself, doubling in perhaps 20 minutes. At the same time, this error may be instrumental in producing errors in the larger scales. A third line of approach explicitly takes this possibility into account.

The new approach is partly dynamical and partly empirical. A system of equations whose dependent variables describe the spectral distribution of the errors is first derived from the original atmospheric equations. Numerical values of the coefficients appearing in the new equations are based upon the observed spectral distribution of atmospheric energy.

In the only study of this sort so far completed (Lorenz, 1969), we have used as dependent variables the contributions of 20 different scales of motion to the mean-square error. Each scale covers an octave of the spectrum, so that wavelengths from 40,000 km down to 40 m are included. In place of the actual atmospheric equations, we have used the equations for two-dimensional incompressible flow. The coefficients are based upon an estimated spectrum of atmospheric kinetic energy.

When the initial error is confined to the smallest scale of motion, it is found to grow very rapidly, at the same time inducing errors in slightly larger scales. These in turn grow slightly less rapidly, and induce errors in still larger scales. In the course of half an hour, errors in the cumulus-sized scales have become appreciable, while after two days the errors have invaded the synoptic scales. Large errors in all scales are present after two weeks.

If small-amplitude initial errors are instead contained in the medium or larger scales, they quickly induce errors in the smallest scales, which then proceed to behave as if they had been present from the beginning. Thus, regardless of the initial spectral distribution of the errors, the errors in the most rapidly amplifying scales, i.e., the smallest, will soon dominate the field, and only somewhat later will they succeed in inducing further errors in the larger scales. It follows that if the initial-error amplitude is small enough, a further reduction in the amplitude by a factor of two will increase the range of predictability of all scales, and hence of the atmosphere as a whole, only by the doubling time for the smallest scale present, perhaps a minute or two.

Indeed, we may extrapolate our results to the case where still smaller scales are admitted. We then conclude that the atmosphere possesses an *intrinsic* range of predictability, of perhaps three weeks. Presently we are far short of our goal of making the best possible forecasts, and our observation system requires major improvements. However, if the hoped-for improvements are some day realized, no further improvements will ever appreciably increase the range of predictability.

We must be quick to note that our conclusion is based upon a number of assumptions which cannot be rigorously defended. We are a long way from incorporating the true atmospheric equations into our procedure. Nevertheless, we believe that the evidence favoring our conclusion is substantial.

We must also observe that our conclusion applies only to prediction of the conditions on a specific date. Nothing is stated, for example, about the possibility of saying whether next summer will be a warm one or a cool one. We maintain that it is not possible to say which days during the coming summer will be the warmer ones or the cooler ones.

5. Further considerations and conclusions

One result of our computations to be noted is that once the errors in the synoptic scales have become noticeable but not large, further doubling, in the root-mean-square sense, requires somewhat more than two days. This doubling rate is consistent with the one deduced by the empirical procedure, but it is appreciably more rapid than that indicated by the dynamical studies. We must therefore note a particular shortcoming of the dynamical approach.

In the earlier days of numerical simulation of the atmosphere, it was found that the numerical solutions, after behaving in a reasonable fashion for perhaps several weeks, would suddenly go into wild oscillations. This phenomenon was eventually recognized as a type of nonlinear computational instability by Phillips (1959), who also accounted satisfactorily for its presence. Various computational schemes, which by no means duplicated the manner in which the real atmosphere is prevented from blowing up, were eventually devised to overcome the instability.

It seems likely that these schemes, which prevent certain computational errors from becoming unduly large, may also have a damping effect upon real errors, and thereby raise the doubling time above its proper value. We have tested one scheme for this effect. The scheme was devised by Arakawa (1966), and was used by Mintz in his study of error growth.

In short, we have repeated the dynamical-empirical procedure, using new values of the coefficients in the equations, which are the values which the coefficients would assume if the Arakawa computation scheme were a part of the equations governing the real atmosphere. We have assumed in addition that scales of motion too small to be resolved by the computational grid used in the numerical experiments are completely absent.

Using the coefficients compatible with the Arakawa computation scheme, we find that small-amplitude errors should double in five days. This is almost exactly the doubling time actually obtained by Mintz. With the more appropriate coefficients, small-amplitude errors are indicated as doubling in about 2.5 days.

The effect of the Arakawa computation scheme is to deemphasize the smallest scales actually retained, while treating the larger scales in an essentially correct manner. We venture the guess, then, that if Mintz's computations were to be repeated with a considerably closer grid-point spacing, so that the smaller synoptic scales would no longer be the smallest scales retained, a doubling time of three days or less would be found. Of course, substantially decreasing the grid-point spacing would enormously increase the required amount of computation.

It thus appears that all three approaches lead to nearly the same result, namely, that small errors in scales large enough to be resolved by conventional grids should double in slightly less than three days, in the root-mean-square sense. Once the errors have attained a moderate size, they will grow less rapidly. In the scales too small to appear in conventional analyses, the errors may grow very rapidly indeed.

Are these results encouraging or discouraging? Certainly they must be discouraging to those who may have hoped that two-week forecasts, sometimes mentioned in connection with GARP, could actually be pushed closer to a month. They do not even offer encouraging prospects for predicting the positions of migratory cyclones and anticyclones two weeks ahead. In another respect, they are rather promising.

In the numerical solutions obtained in the dynamical-empirical procedure, we have found that the spectra of the errors at intermediate stages of the computation tend to resemble the initial spectra of errors which would be present if the observational data were confined to a regular network of points. The larger scales are almost free of error and the smaller scales are completely dominated by errors, while there is rather narrow band of intermediate scales where the errors are medium sized. We are thus led to postulate a sort of additive law for predictability.

Specifically, if the largest scale of motion not resolved by the observational network has an intrinsic range of predictability of, say, three days, introducing a fine enough network to resolve all scales of motion (an impossible task, of course), would increase the realizable range of predictability of all the larger scales by just three days. Likewise, improving the network so that the largest remaining unresolved scale has an intrinsic range of predictability of one day, instead of three days, would increase the realizable range of predictability of the larger scales by two days. Systems unresolved by the present network are probably intrinsically predictable at least three days ahead; reducing this figure to one day by improving our network does not seem to be beyond our capabilities.

To be able to forecast 16 days in advance as well as we now forecast 14 days in advance would not be a particularly spectacular achievement. To be able to predict three days ahead as well as we now predict one day ahead would be a major accomplishment. Indeed, it is altogether possible that one of the practical outcomes of our efforts to improve our observational network will be a new level of excellence in short-range forecasting.

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COSPAR WG VI Report: "Systems Possibilities for an Early GARP Experiment"

COSPAR Working Group VI (Application of Space Experiments to Meteorology, Morris Tepper, Chairman) completed a special report on "Systems Possibilities for an Early GARP Experiment." The report was requested by the ICSU-WMO Joint Organizing Committee for GARP (JOC) and presented to the committee at their recent meeting in Princeton.

Twenty-four technical experts from seven countries (France, U.S.A., U.S.S.R., Federal Republic of Germany, German Democratic Republic, Japan, United Kingdom), WMO and JOC met in London in October 1968 to review the development status and applicability to GARP of various observing techniques and to decide what techniques could be combined in the mid-1970s to provide observational capability for a large-scale but not necessarily complete GARP experiment.

According to the recommendations of Working Group VI, the following components will be contained in the suggested early GARP Experiment. Constant-level balloons tracked by satellites will be used for wind tracers at low levels (below freezing level) in the tropics and at high levels (200–150 mb) in the tropics and mid-latitudes; all balloons would carry temperature sensors (and possibly humidity) and the high-level balloons would also carry a radio altimeter to determine the height of the isopycnic surface. Four geostationary satellites will provide nearly complete coverage of the Earth up to about 30° and useful coverage up to 50–55° latitude. High-resolution, sequential cloud photographs will allow determination of wind fields wherever and whenever the cloud elements are suitable wind tracers; infrared observations will allow cloud heights to be deduced. Low-orbiting, near-polar satellites will carry narrow-field infrared and probably microwave spectroradiometers, the observations from which will permit the derivation by inversion techniques of temperature and water-vapor vertical profiles. The satellite system will also carry equipment for radio relay of observations from ground based (ship, remote stations, etc.) stations.

In combination with rapidly expanding conventional observing networks and data that can be derived empirically from cloud cover or radiation observations provided by U. S. and U.S.S.R. operational meteorological satellite programs, the space-based system described in the report will provide a substantial augmentation of the kind of global observations of atmospheric state variables required for realistic numerical models of the general circulation. While the data set that could thus be obtained will not be ideal—from the viewpoint of the modelers—it will be a significant step forward towards the goal of a "complete" data set (parameter, vertical and horizontal domain, time) to study the large-scale features of the atmospheric general circulation.

The report is in press and will be available from the JOC (headquarters at WMO, Geneva). Copies are also available from WG VI, until the limited supply now on hand is exhausted; please address requests to Mr. Stanle Ruttenberg, Secretary, COSPAR Working Group VI, NCAR, Boulder, Colorado 80302.

National and International GARP Committees Meet at Princeton

The U. S. Committee for the Global Atmospheric Research Program (GARP) held its second meeting on January 27–28, 1969, at the newly dedicated Geophysical Fluid Dynamics Laboratory of ESSA on the Forrestal Campus of Princeton University, Princeton, N. J. The Committee, which functions under the sponsorship of the National Academy of Sciences, is charged with the responsibility of defining and developing the U. S. role in the program. The deliberations at Princeton were concerned mainly with matters pertaining to the contents and preparation of the preliminary plan for U. S. participation.

The Joint (GARP) Organizing Committee of the International Council of Scientific Unions (ICSU) and the World Meteorological Organization (WMO), which is responsible for formulating and coordinating international activities of the Global Atmospheric Research Program, also held its second meeting at Princeton during the week of January 27th. Prof. Bert R. Bolin, University of Stockholm, is chairman of the JOC. U. S. representatives on the international group are Dr. Joseph Smagorinsky, Princeton University, and Prof. Verner E. Suomi, University of Wisconsin. Other members are: V. A. Bugaev, U.S.S.R.; F. Moller, Germany; A. S. Monin, U.S.S.R.; P. Morel, France; Y. Ogura, Japan; P. R. Pisharoty, India; C. H. B. Priestley, Australia; J. S. Sawyer, United Kingdom; R. W. Stewart, Canada.

The U. S. Committee is chaired by Prof. Jule G. Charney, Massachusetts Institute of Technology, with Dr. Smagorinsky and Professor Suomi serving as Vice Chairmen. Other members of the U. S. Committee are: Alfred K. Blackadar, Pennsylvania State University; John W. Firor, National Center for Atmospheric Research; Robert G. Fleagle, University of Washington; Richard M. Goody, Harvard University; Douglas K. Lilly, National Center for Atmospheric Research; Gordon J. F. MacDonald, University of California-Santa Barbara; Thomas F. Malone, Travelers Insurance Company; Walter H. Munk, University of California-San Diego; Owen M. Phillips, Johns Hopkins University; Herbert Riehl, Colorado State University; Henry M. Stommel, Massachusetts Institute of Technology; and James A. Van Allen, University of Iowa.

Atlantic Expedition 1969

The *Atlantic Expedition 1969* is the first of several GARP oriented field programs to get under way this year. Under principal sponsorship by the German Research Society, and directed by Karl Brocks of the University of Hamburg, the expedition will re-visit the trade wind and equatorial zones of the central and eastern Atlantic Ocean, where the German scientists started their oceanic and marine meteorology research observation program with the cruise of the first *Meteor* in the 1920's. Subsequent to this remarkable and fundamental exploration German researchers always retained strong interest in the tropical Atlantic Ocean. In 1965 the second *Meteor* went on an extensive cruise, also directed by Brocks; the 1969 undertaking is a greatly enhanced and broadened continuation of the 1965 venture.

The time of the cruise is 15 January–15 May for the two German research vessels *Meteor* and *Planet* on a route generally from the North Sea to the northeastern tip of Brazil and then back on a slightly different course. For part of the experiment the U. S. research vessel *Discoverer* and the British vessel *Hydra* will join the project. At long last a little fleet will be available to attack the problems of air-sea interaction, of the upward transfer of energy from the boundary layer and of some aspects of the larger scale dynamics and energetics of the trades. For this purpose the ships will form an equilateral triangle with side of 750 km; this will permit computations of vorticity, divergence, mean vertical motion, slope of the trade inversion and the upward turbulent transfer of heat, moisture and momentum against the (presumably) mean sinking motion in an air current moving toward substantially lower absolute vorticity. The *Meteor* will be allowed to drift with the ocean current. Two buoys are attached: one for profile measurements from one to eight meters height in the atmosphere and for measurements of water temperature to seven meters depth. The second buoy is gyro-stabilized; flux measurements will be made by the correlation method and at the same time the oceanic wave spectrum will be measured. Finally, very detailed observations within some millimeters of the ocean surface will be made partly in order to determine how far interface processes are controlled by the molecular properties of the two media.

In addition to this principal experiment a large number of additional measurements are being made, ranging from ionospheric physics to geology, oceanography and upper atmosphere. Not all these projects can be described in the above detail here. They are the responsibility of a large group of participating German universities. Excellent summaries of the research objectives and plans for measurements are contained in a booklet issued by the German Research Society.[1]

After studying this booklet and hearing more detail about some of the plans one cannot but acknowledge the very competent and ingenious design of the whole undertaking, from research objectives to measurements to evaluation, with evidently rather modest means relative to the scope of problems attacked. Great advances in geophysical knowledge should result from the program which will be about finished by the time this summary reaches BULLETIN readers. Belatedly, we wish the very best of luck to our German Colleagues and their international collaborators for their major effort.

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[1] Atlantic Expedition 1969 (GARP), printed by the German Research Society in July 1968, in German and English. Obtainable through the Meteorological Institute, Hamburg, Von-Melle-Park 6, 2 Hamburg 13, Germany.