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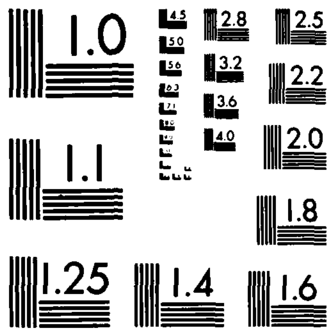
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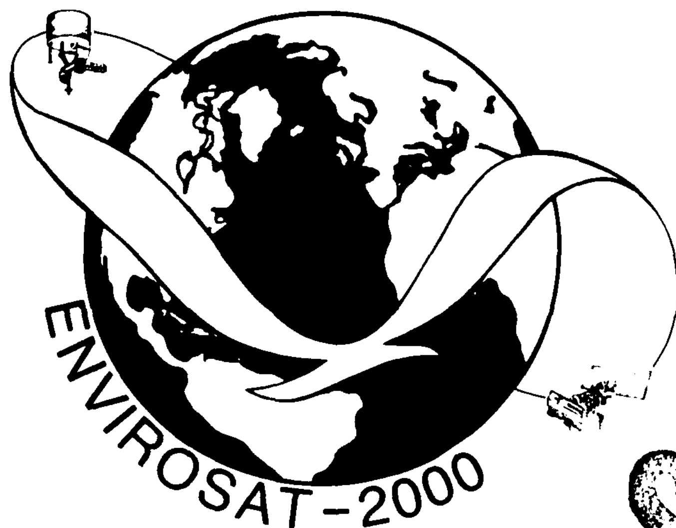
ENVIROSAT—2000 Report

Numerical Weather Prediction and Satellite Observations

August 1985



U.S. DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
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1) Sufficient observations of the atmosphere

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2) Sufficient knowledge of atmospheric mechanisms

3) Sufficiently powerful means of computation

Solutions to these problems were adequately advanced by midcentury to allow the use of the scientific approach, but future advances must continue to be made to improve weather forecasting. Since 1960, observational weather satellites have played a large role in improving our ability to determine the initial state of the atmosphere, and they promise to play an ever larger role in the future.

ENVIROSAT—2000 Report

Numerical Weather Prediction and Satellite Observations

Frederick G. Shuman, NWS

Washington, D.C.
August 1985

U.S. DEPARTMENT OF COMMERCE
Malcolm Baldrige, Secretary

National Oceanic and Atmospheric Administration
Anthony J. Calio, Deputy Administrator

National Environmental Satellite, Data, and Information Service
William P. Bishop, Acting Assistant Administrator

NUMERICAL WEATHER PREDICTION AND SATELLITE OBSERVATIONS

ABSTRACT

The history of the scientific approach to weather forecasting is traced through the 20th century, including a projection to the year 2000. It is felt that such a review may foster a better understanding of the problems we face and will face in the future. During the first half of the century, little could be done, even on an experimental basis, because of the overwhelming need for tools that did not appear until midcentury. It is remarkable, however, that there were scientists who thought about weather forecasting in optimistic terms. There was a consistency throughout this preliminary period in determining exactly what was required for a successful beginning. It could not have been otherwise, because the natural laws dictate rather clearly these three requirements:

1) Sufficient observations of the atmosphere ;

2) Sufficient knowledge of atmospheric mechanisms ;

3) Sufficiently powerful means of computation .

Solutions to these problems were adequately advanced by midcentury to allow the use of the scientific approach, but future advances must continue to be made to improve weather forecasting. Since 1960, observational weather satellites have played a large role in improving our ability to determine the initial state of the atmosphere, and they promise to play an ever larger role in the future.

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I. 1900 TO 1955: CONDITIONS NEEDED FOR RATIONAL FORECASTING

At the turn of the 20th century, weather forecasting as a national service was 30 years old. It was based on simultaneous observations, collected by telegraph in Washington, D.C., from stations at ground level over the continent. Its methodology consisted of mapping wind, temperature, humidity, cloud, and rainfall systems on sequential charts, noting their movements, accelerations, and developments, and predicting, principally through persistence and trends. Added to these primary tools were such physical relationships as could sketchily be drawn from the natural laws and a wealth of experience and art accumulated by individual forecasters.

In 1904, Vilhelm Bjerknes, a Norwegian physicist, published a paper entitled "Weather Forecasting as a Problem in Mechanics and Physics,"[1] which was a first in two respects. It was a clear recorded statement of the possibility of making what he called **rational forecasts** and what today are called **numerical weather predictions**, and it clearly and inextricably linked the observational problem with numerical weather predictions. Quoted below is a translation of the first part of Bjerknes' now famous paper.

> If it is true, as every scientist believes, that subsequent atmospheric states develop from the preceding ones according to physical law, then it is apparent that the necessary and sufficient conditions for the rational solution of forecasting problems are the following:
>
> 1) **A sufficiently accurate knowledge of the state of the atmosphere at the initial time.**
>
> 2) **A sufficiently accurate knowledge of the laws according to which one state of the atmosphere develops from another.**
>
> The determination of the state of the atmopshere at the initial time is the task of observational meteorology. This problem has not yet been solved to the extent that is necessary for rational forecasting. There are two major gaps in the observations. The first one is that only land stations participate in the daily programs of the weather services. Over the seas, which cover four-fifths of the Earth's surface and must therefore exert an overwhelming influence, no observations are made for the purposes of current weather analysis. Furthermore, the observations which are used in current analysis are only made at the surface of the Earth, and all data pertaining to the state of the higher layers of the atmosphere are missing.
>
> But we already have the technical means which will enable us to fill these two gaps. With the help of wireless telegraphy, we will be able to include among the reporting stations the ships moving in fixed routes. And to judge by the great forward steps which have been made in recent years in the techniques of upper-air soundings, it will be possible to obtain daily observations of the higher atmospheric layers not only from fixed land positions but also from traveling stations on the sea.

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[1] V. Bjerknes. "Das Problem der Wettervorhersage, betrachtet vom Standpunkte der Mechanik und der Physik." Meteorologische Zeitschrift, January 1904, pp. 1–7. (Translated by Yale Mintz, University of California at Los Angeles.)

> We can hope, therefore, that the time will soon come when either as a daily routine, or for certain designated days, a complete diagnosis of the state of the atmosphere will be available. The first condition for putting forecasting on a rational basis will then be satisfied.

Bjerknes went on to discuss his second condition, and concluded, "...as we now see the problem, ...we do have sufficient knowledge of the laws of atmospheric processes upon which a rational weather forecasting system can be based." He added the caveat, "But it must be admitted that we could have overlooked important factors on account of the incompleteness of our knowledge."

This was the situation viewed from the turn of the century; the application of science awaited the development of observational and related technology. As it turned out, Bjerknes' conclusion was largely correct. There was some important new knowledge yet to be developed, but the major, most basic physical laws were already known. Still, in spite of Bjerknes' remarkable foresight, his vision was limited in several respects; what he foresaw was based on technology that was then current or well along in its development.

The major thing that Bjerknes did not clearly foresee was the enormity of the computations required. With the meager computational tools then available, he thought that the only feasible methods could be manual graphical methods, which were later found to be woefully inadequate. Modern electronic computers are a third necessary, though unforeseen, condition for the practice of numerical weather prediction.

During World War I, Lewis Fry Richardson[2], a British physicist and mathematician with a lifelong active interest in meteorology, actually carried out an experimental 6-hour numerical weather prediction. For initial time, he chose 7 a.m. G.m.t., May 20, 1910, because the data collection for that time was, he said, "...one of the most complete sets of observations on record." In particular, there was available a set of upper-air observations over Western Europe of pressure, temperature, and humidity taken by instrumented balloons, as well as the more conventional surface observations and upper-air observations of wind direction and speed taken by uninstrumented balloons and theodolites. The instrumented balloon observations were experimental, intended for meteorological research, and not collected on an operational schedule.

Richardson deduced his initial data from analyzed maps published by Bjerknes, whose works exercised considerable influence throughout Richardson's study. Richardson tabulated the initial data at five levels in the vertical; in the horizontal, he tabulated data at an array of points spaced about 200 km (125 miles) apart. Each point represented data averaged over an approximately square area about 200 km on a side. The array covered an approximately square area about 1,000 km (620 miles) on a side. The five levels were at the ground and at 2.0, 4.2, 7.2, and 11.8 km above mean sea level (about 6,600, 14,000, 24,000, and 39,000 feet). There were 12 upper-air stations within the overall square, and 7 nearby, which had been used in the analyses. It is interesting to note that the average spacing between the 12 stations (i.e., if they had covered the same area but had been separated by equal distances) was about 290 km (180 miles), compared with about 335 km (210 miles) for the present upper-air network over the contiguous United States. Richardson's prediction consisted of the 6-hourly change at only two points, centered at the initial time (i.e., from 4 to 10 a.m. G.m.t.).

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2 L. F. Richardson. Weather Prediction by Numerical Process. (London: Cambridge University Press, 1922.) Republication by Dover Publications, Inc., New York, 1965, 236 pp.

As a prediction, Richardson's results were a failure, and he blamed the observations, saying, "It is claimed that the (results) form a fairly correct deduction from a somewhat unnatural initial distribution." The major error was a predicted pressure change at ground level that exceeded, by far, any observed change (145 mbar compared with less than 1). It is undoubtedly true, as he said, that the enormous predicted change was due to errors in the wind observations, but if he could have carried his prediction forward, say for 24 hours, the initial large change would not necessarily have destroyed the usefulness of the prediction. The error was presumably the manifestation of a spurious external gravity wave, which would have traveled rapidly about his region of computation but might have been removed at the end. For such an extension of his prediction, however, he not only would have had to use a much larger area suitably covered with upper-air observations, as he well knew, but he also would have had to reduce his time step from 6 hours to about 20 minutes, which would have lengthened the calculations by a factor of 18. The latter requirement was not discovered until 1928. It is purely mathematical, arising from the necessity of numerically approximating the true equations.

A 10-inch slide rule and a table of five-place logarithms were the only computing tools Richardson used to carry out the routine of numerical weather prediction, little else being available in those days. In opening the last chapter of his book he said, "The two great outstanding difficulties are those connected with the completeness necessary in the initial observations and with the elaborateness of the subsequent process of computing." He was already involved in a process of so many calculations that "to trace the weather for the whole globe" would require 64,000 computers (human) by his estimate. It is doubtful that so many people could be successfully organized to perform such intricate functions, let alone the 1,152,000 people that would be required if the correction factor of 18 were applied to his estimate. In the preface he said, "Perhaps some day in the dim future it will be possible to advance the computations faster than the weather advances and at a cost less than the saving to mankind due to the information gained. But that is a dream." Undaunted, however, Richardson put forth with verve the following in the last chapter:

> After so much hard reasoning, may one play with a fantasy? Imagine a large hall like a theatre, except that the circles and galleries go right round through the space usually occupied by the stage. The walls of this chamber are painted to form a map of the globe. The ceiling represents the north polar regions; England is in the gallery, the tropics in the upper circle, Australia on the dress circle and the antarctic in the pit. A myriad computers are at work upon the weather of the part of the map where each sits, but each computer attends only to one equation or part of an equation. The work of each region is coordinated by an official of higher rank. Numerous little "night signs" display the instantaneous values so that neighbouring computers can read them. Each number is thus displayed in three adjacent zones so as to maintain communication to the North and South on the map. From the floor of the pit a tall pillar rises to half the height of the hall. It carries a large pulpit on its top. In this sits the man in charge of the whole theatre; he is surrounded by several assistants and messengers. One of his duties is to maintain a uniform speed of progress in all parts of the globe. In this respect he is like the conductor of an orchestra in which the instruments are slide rules and calculating machines. But instead of waving a baton, he turns a beam of rosy light upon any region that is running ahead of the rest, and a beam of blue light upon those who are behindhand.
>
> Four senior clerks in the central pulpit are collecting the future weather as fast as it is being computed, and despatching it by pneumatic carrier to a quiet room. There it will be coded and telephoned to the radio transmitting station.

Messengers carry piles of used computing forms down to a storehouse in the cellar.

In a neighbouring building there is a research department, where they invent improvements. But there is much experimenting on a small scale before any change is made in the complex routine of the computing theatre. In a basement an enthusiast is observing eddies in the liquid lining of a huge spinning bowl, but so far the arithmetic proves the better way. In another building are all the usual financial, correspondence and administrative offices. Outside are playing fields, houses, mountains and lakes, for it was thought that those who compute the weather should breathe of it freely.

Richardson was a brilliant scientist, among the ablest of his time. The book cited here amounts to a textbook in numerical weather prediction, and is of more than historical interest even today. Had he had equipment to handle the hydrodynamical problems he was working on, he might well have solved many of the problems that were encountered and solved later by many. Optimism is a tool of the researchers' trade; without it, they would worry too much and never get anything done. In any event, in spite of his overoptimism about what might be done with the technology he knew of, Richardson must be credited with adding to Bjerknes' necessary and sufficient conditions the third one:

3) **A sufficiently powerful means of computation.**

This condition made the purely dynamical approach appear hopeless. Nevertheless, the observational situation continued to improve. Weather forecasting by any method is an initial-value problem, and forecasts will generally improve with better observations and better understanding of the atmosphere. Observations thus contribute both directly and indirectly to forecast accuracy, which provides the incentives to improve the observational network. The growth of civil and military aviation, in particular, imposed heavy requirements for improved forecasts.

By 1937, airplanes equipped to sound the upper air were flying daily from about 30 airports in the United States. In addition, a network of stations observed winds in the upper air by releasing uninstrumented balloons and visually tracking them with theodolites. This was a vast improvement, but at the same time both sets of upper-air observations were severely limited. Airplanes were limited to heights of about 4 km (13,000 feet) and balloons to about 6 km (20,000 feet), and neither method was all-weather. Clouds interfered with the visual tracking of balloons, and stormy conditions with airplanes. So the best that could be done was to sound about half of the atmosphere in the vertical. This might have been sufficient for numerical weather prediction had the third condition been fulfilled.

Since the early 1900's, pressure, temperature, and humidity had been experimentally observed in the upper atmosphere by means of sensors and recorders tied to ascending balloons. The accuracy and vertical extent of these observations were sufficient; the main problem was timely recovery of the recorder. This was really a problem in telecommunications, a condition that was implicit in both Bjerknes' and Richardson's discussions. By 1940 the problem had been solved by replacing the recorder with a lightweight radio transmitter, moving the recorder to the ground, and linking it with a radio receiver. The result was the **radiosonde**. Soon radio direction finders were added to the system, which resulted in all-weather observations of wind speed and direction. The **rawinsonde** regularly reaches altitudes of about 30 km (100,000 feet) and remains the standard with which new upper-air observational systems are compared. Bjerknes' first condition was thus fulfilled, but not the third one, which he did not foresee.

The third condition was fulfilled on June 10, 1952, when the Institute for Advanced Study in Princeton, New Jersey, announced the successful development of the first stored-program parallel electronic computer. The computer was developed by the Institute Electronic Computing Project, directed by the Hungarian-American mathematician and mathematical physicist John Louis von Neumann, who designed the logic of the system. The fundamentals of von Neumann's design are still to be found in today's computers, from hand-held programmables to supercomputers.

Von Neuman's interest in hydrodynamics had led him to work with the Moore School of Electrical Engineering at the University of Pennsylvania when the Electronic Numerical Integrator and Computer (ENIAC) was well along in its development. The ENIAC was a forerunner of stored program machinery. The physical laws governing the behavior of fluids are stated in the form of simultaneous nonlinear partial differential equations. Due primarily to the equations' nonlinearity, mathematics can barely deal with them. It was von Neumann's intention to take the brute force approach of numerical experiment, but for this far more powerful computational facilities were required than existed at that time. Nor was the ENIAC to be adequate, so he set out to build the new type of computer at the Institute. Since numerical weather prediction is a large and important scientific problem in hydrodynamics, it was appropriate that he chose it for intensive application of the first modern computer. Three problem areas were chosen altogether; the other two were engineering and numerical mathematics.

In 1948, two years after the Institute Electronic Computing Project was organized, the Meteorology Group was formed within the Project. The goal of the Group was to develop and demonstrate the feasibility of numerical weather prediction. Led by Jule G. Charney, the Group first succeeded in integrating the physical equations, in a much simplified form, on the ENIAC. The integration took 24 hours for a 24-hour forecast. Operational feasibility was demonstrated when the Institute machine was available; the same equations were integrated in 5 minutes.

II. 1955 TO 1985: THE DEVELOPMENT OF OPERATIONAL NUMERICAL WEATHER PREDICTION

Within 3 years of the announcement by the Institute for Advanced Study, the relevant computer science and technology were transferred to commercial production, and the U.S. Government acquired one of the first modern commercial computers, an IBM 701, and dedicated it to numerical weather prediction. By the summer of 1955, numerical weather predictions were being produced on a twice-daily schedule.

Now, Bjerknes' two conditions, and the third one that came from Richardson's work, were in the nature of thresholds; they were sine qua nons, constituting minimal requirements for the beginning of numerical weather prediction as a practice or as a serious research tool. Once they had been fulfilled and the feasibility of numerical weather prediction had been demonstrated, these "conditions" underwent a radical metamorphosis into a set of open-ended problems that must be solved in order to extend, to improve, and to exploit to the utmost the new method of weather forecasting and research. With operational numerical weather predictions a reality, we now speak not of necessary and sufficient conditions, but of **broad areas of science and technology in which future advances are essential for improvements in numerical weather predictions.** The following is a list of such areas:

1) **Quality and density of observations in time and three-dimensional space**

2) **Knowledge of atmospheric dynamics and physics**

3) **Computer power**

4) **Telecommunications that ensure timeliness of data acquisition and product delivery**

5) **Mathematical knowledge and know-how in numerical methods**

6) **Statistical enhancements and interpretations of dynamical predictions**

7) **Understanding and experience of the forecaster to interpret guidance, and to effectively relay its benefits to the user**

It should not be surprising that the threshold conditions, appropriately transformed, appear in our list. As then, observational technology is inextricably linked with the practice of numerical weather prediction. The importance of dense and accurate observations is derived from the physical laws themselves. Numerical prediction of future states of the atmosphere is an initial-value problem, that is, the prediction must proceed from a known initial state. Inherently, the accuracy of the prediction will depend on how well the initial state is known, which involves both accuracy and density of observations.

There are many gaps remaining in our scientific knowledge and understanding, especially of the effects of small-scale events on the larger features being numerically predicted. These events occur on a scale so small that they are unobservable in sufficient detail, nor can they be described in detail with the network of points in space and time used for calculation. An example is thunderstorms, which are individually a few miles across. They contain strong vertical currents that throw momentum, heat, and moisture up and down through more than 80 percent of the atmosphere in the vertical. When they occur in large clusters, which is the usual case, they significantly affect larger scale systems. This situation is not as hopeless as it may at first seem. The occurrence of the large clusters is related to the distribution of temperature and moisture on observable scales, so the problem is one of relating the occurrence and effects of thunderstorms to large-scale features that can be observed and predicted in some detail. There are many such problems.

The power of computers, although now about 10,000 times greater than that of our first one in terms of both speed and storage capacity, remains a limitation. The atmosphere is a gas and may be considered continuous from the standpoint of numerical weather prediction. The basic natural laws reflect this; mathematically, they are expressed in the differential and integral forms of calculus. But our computing machinery is digital and can only perform the basic arithmetic functions (addition, subtraction, multiplication, and division). As a result, we cannot deal with the equations as they stand. We convert differentials into differences between adjacent points separated by finite intervals of space and time, and convert integrals into summations. The resulting equations are finite-difference equations, which are only approximations to the differential equations. The closer adjacent points are, the more nearly do the finite-difference equations approximate the differential equations. But more powerful computers are needed to increase the resolution in this way. For example, for a given forecast period over a given area, to halve the intervals between points in time and the three spatial dimensions would result in 16 times as many points and, therefore, 16 times as many calculations. Because of deadlines on issuance of forecasts, this would require the computer to be 16 times faster.

In 1955, the first products of numerical weather prediction could not compete successfully with those made by forecasters. It was soon found, however, that numerical weather predictions used as guidance by forecasters improved their products. By 1960, numerical weather prediction had advanced to the extent that some of its products not only surpassed in quality those made by forecasters, but also could not be successfully improved upon by them. The improvements at that time came principally from advances in areas 2, 3, and 5 in the previous list. Numerical weather predictions then began replacing products formerly made by forecasters. From about 1960 onward, replacement continued, and a rich new variety of products came into being; now about 95 percent of the output of the National Weather Service's National Meteorological Center (NMC) near Washington, D.C., is automatic--untouched by human hands.

In 1960, when the first operational weather satellites appeared, the main limitations on numerical weather prediction were the sparsity of observations over oceans, especially of the upper air, and the need for more computer power (numbers 1 and 3 in the list). The rapid advance of computer technology promised to deliver more powerful computers, but the limit had been reached, or nearly so, with conventional observational technology. There were about a dozen fixed ships taking radiosonde observations over the northern oceans, but fixed ships are very expensive platforms. Indeed, their number has decreased because of their cost.

From the beginning, as Bjerknes had noted, a major problem has been coverage, particularly over oceans but also in uninhabited continental regions such as Arctic Canada and Alaska. Seventy-one percent of the Earth's surface is covered by oceans and seas, and only 29 percent by land. Furthermore, there is a marked variation with latitude of the distribution of sea and land. Table 1 divides the Earth's surface into four equal zones separated by the three latitude circles: 30° N., the Equator, and 30° S. The numbers of radiosonde stations shown were taken from the list published in 1985 by the World Meteorological Organization, Geneva, Switzerland.

Table 1
Radiosonde Stations

Latitude Zone	Land	Water	Number of Radiosonde Stations	Land Area per Radiosonde Station (sq km)
90° N. - 30° N.	50%	50%	443	144,000
30° N. - 0° N.	29%	71%	208	175,000
0° S. - 30° S.	23%	77%	86	339,000
30° S. - 90° S.	15%	85%	50	390,000

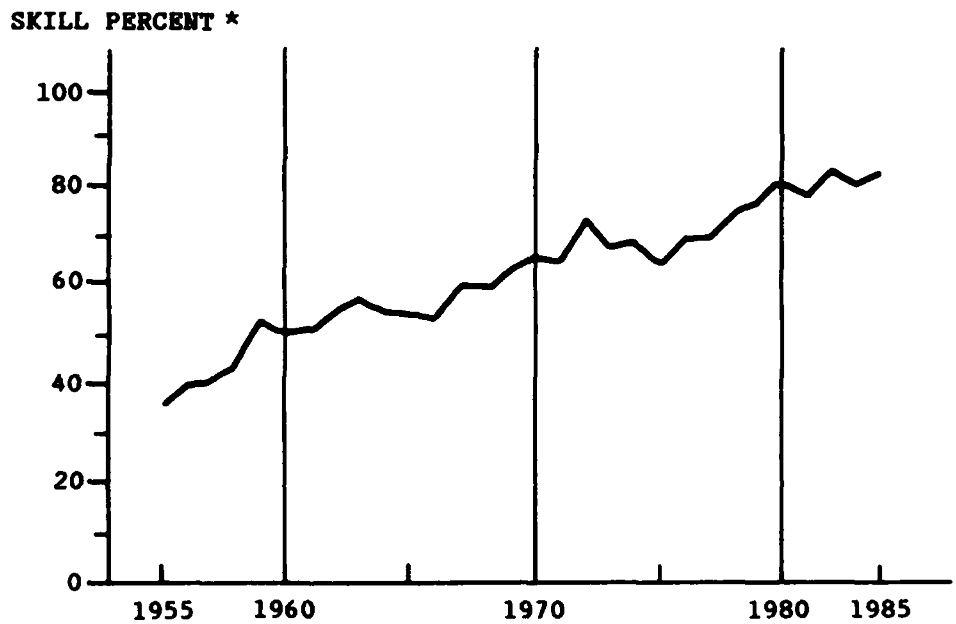
The table shows that the percentages of land may be roughly translated into how well each quarter of the Earth is covered with conventional observations, but only roughly. The last column shows that, besides the logistics of land versus water, there are socioeconomic and geopolitical factors that determine how well the atmosphere over various parts of the Earth is observed.

The satellite platform is free of the logistics which dictate that conventional observations must overwhelmingly be over land. The first weather satellites, which were polar orbiters, did indeed provide a uniformity of coverage over the globe that was unknown until then. At first they provided observations only of cloud cover, which have many important uses but do not directly provide the information that numerical weather prediction needs at initial time. However, analysts learned to retrieve locations of storm centers and wind maxima (jet streams) from them, as well as some information on the intensity of storms, all of which were and still are useful in determining the initial state over data-sparse areas.

What numerical weather prediction needs are simultaneous observations in three dimensions of temperature, pressure, humidity, and wind direction and speed over the globe. On the scale with which numerical weather prediction presently deals, to a very high degree of approximation, pressure at a given point is equal to the weight of all the air above it. What this means is that the height of the observation can be calculated from pressure, temperature, and to a lesser degree humidity, and need not be observed. More generally, of height, pressure, and temperature, only two need to be observed; the third can be calculated. An important exception to this is that there must be one place in the vertical where both pressure and height are known. This is generally at Earth's surface, but could be anywhere they are both observable.

In October 1972, through carefully selected radiometric multichannels, indirect vertical soundings of the atmospheric temperature were achieved on an operational basis. These have improved greatly, but not to the extent that they can replace balloon-borne instruments. However, over much of the Earth, up to 80 percent, indirect soundings from satellites are the only information about the upper air that is available. Indeed, the global coverage they provide has enabled extension of numerical weather prediction to the full globe and, thereby, has resulted in predictions for longer periods. Indirect sounding by radiometry is in its infancy. Further engineering development and scientific research are highly likely to continue to pay large dividends.

The 30-year era of operational numerical weather prediction saw advances in all seven of the broad areas of science and technology listed previously, and skill reacted accordingly. The problem of measuring the skill of weather forecasts is as complex as the problem of describing the state of the atmosphere, and there are not many long-term internally consistent records of skill. Figure 1, however, shows the record of a score that has been kept for 30 years. It shows a better than doubling of skill, from about 38 percent to about 81 percent. Specifically, it describes a 36-hour prediction of the pattern of pressure at about 18,000 feet over North America.



* The "skill percent" is derived from the so-called S_1 score.[3] On the presumption that a chart with an S_1 score of 20 is perfect for all practical purposes and one with 70 is worthless, "skill percent" = $2(70-S_1)$.

Figure 1.
Record of Skill for 36-Hour Predictions of Pressure Patterns at About 18,000 Feet Over North America

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[3] S. Teweles and H. Wobus. "Verification of Prognostic Charts." Bulletin of the American Meteorological Society, V. 35 (1954), pp. 455–463.

III. 1985: MODERN NUMERICAL WEATHER PREDICTION

Figure 2 is a schematic of the guidance and forecast process. The guidance products are prepared at the National Meteorological Center. The start of the process must await the acquisition of observations in sufficient numbers and with sufficient global three-dimensional coverage. The lapse between nominal time of observation and start of the guidance process is a matter of judgment on the balance between accuracy and timeliness of delivery of the products. The observations come from many sources:

- 2,500 daily soundings of pressure, temperature, wind, and humidity from rawinsondes
- 12,000 daily soundings of temperature and pressure from polar-orbiting satellites
- 2,500 daily observations of cloud-tracked winds from geostationary satellites
- 2,300 daily observations of winds and temperatures from commercial aircraft
- 50,000 daily surface observations from land stations
- 5,500 daily surface observations from ships and buoys, including sea surface temperature
- 60,000 daily observations of sea surface temperatures from satellites
- Visible and infrared imagery, including 20-minute time-lapse animation, from geostationary satellites covering about one-third of the globe
- Global visible and infrared imagery, with less detail, from polar-orbiting satellites

At the core of the guidance system are numerical weather analyses and predictions made on state-of-the-art computers. Statistical guidance products are prepared from the numerical weather predictions made with dynamical atmospheric models. These are for specific locations and are made from statistical relationships derived from a vast body of historical data. Examples of predicted variables are maximum and minimum temperatures at major cities, ceiling and visibility at large airports, and probability of rain and snow. Their accuracy is limited to a degree by their developmental data base, but mainly their accuracy reflects the accuracy of the numerical weather predictions from which they are produced.

Subjective guidance is also prepared from dynamical model output. It is in the form of messages and manually drawn charts, and constitutes interpretations and modifications of dynamical model output. From the standpoint of product count, subjective guidance represents only a minor part of the whole guidance package--about 5 percent of the total. It remains an essential part, however, especially in the realm of weather itself--heavy precipitation and the demarcation between rain and snow. This is precisely where dynamical models are weakest.

At the local forecaster's disposal are not only the three types of central guidance, but also many observations from the local area. The local observations supplement the central guidance with areal detail, and also are more timely, by several hours, than those incorporated by central guidance. They are most helpful in ranges less than 18 hours, but provide little, if any, useful information beyond 36 hours. For the very short ranges and

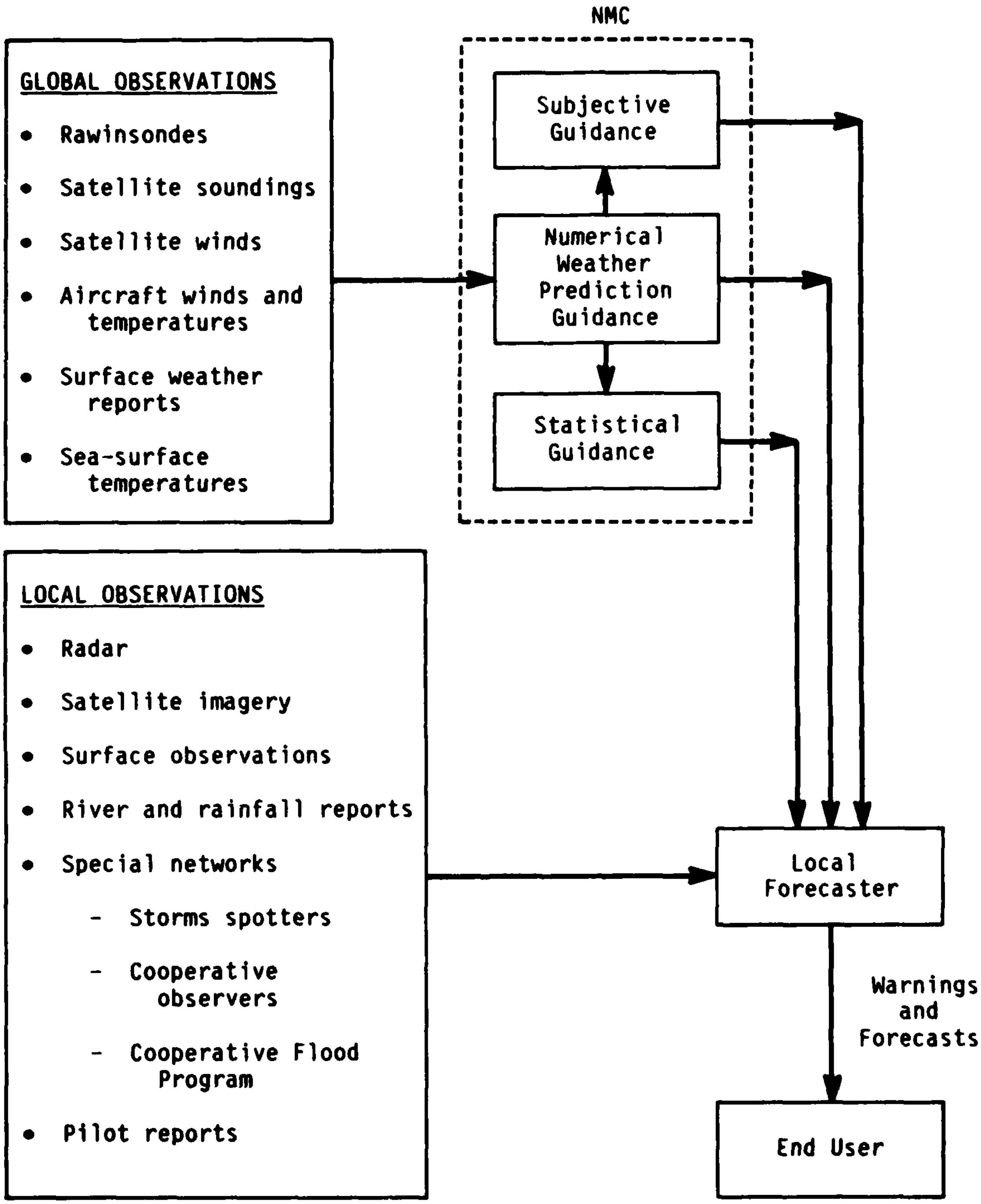

Figure 2
National Weather Service Guidance and Forecast Process

very small scales, local observations are crucial. A dramatic example is the report of an approaching tornado made by storm spotters stationed around a city or town. Approach of a flash flood on a stream or small river is another.

Several dynamical models are run at the National Meteorological Center, each with its own purpose. The principal observational cycle is twice daily, at noon and midnight G.m.t. (7 a.m. and 7 p.m. e.s.t.). The operation of the Center is geared to this cycle, the models running twice daily. The Limited-Area Fine-Mesh Model (LFM) is begun about 1 hour after data time. This model was designed some 20 years ago for computers 50 to 100 times slower than current ones and, therefore, runs very quickly. Its purpose is to provide field forecasters with a first, quick look at results from the current observational data set. It carries seven levels of information in the vertical, and the intervals between points in the horizontal is about 200 km. It covers North America and adjacent waters. Values on the lateral boundary are taken from a global numerical weather prediction made during the previous cycle.

The next model is run about 2 hours after data time and is also regional, but covers the Northern Hemisphere. It has three nested grids of points. The innermost grid, C, covers North America and adjacent waters, an area similar to the LFM, which is the area of primary interest. Grid C has 83 km intervals between points. Grid B has half the resolution, with intervals of 166 km, and covers a much larger area. Grid A has half again as much resolution, with intervals of 332 km, and covers the hemisphere. The purposes of nesting are to provide better predictions at the boundary of the innermost region and to alleviate numerical "shocks" at boundaries where grids change size. The model carries 16 levels of information in the vertical. The whole system of which the model is a part is called the Regional Analysis and Forecast System (RAFS). This is the "bread and butter" of the Center, fulfilling some 90 percent of the requirements laid on the Center. It provides the national guidance for all domestic forecasting, which is the most important function of the National Weather Service.

The global model is run last, about 3 hours after data time. Being global, it must wait for late data from remote areas. It carries 18 levels of information in the vertical. Its numerical system is different, using spherical harmonics, but is equivalent to a finite-difference system with intervals of about 140 km. It produces longer period forecasts, to 10 days, and provides wind and temperature forecasts for international aviation, and weather forecasts for shipping on the high seas.

The global model is run again just before the data from the next observational cycle begin to arrive. This is a "clean-up" run that takes in late data. In fact, it is run four times daily in this mode, because a significant number of conventional observations are taken at 6 a.m. and 6 p.m. G.m.t. (1 a.m. and 1 p.m. e.s.t.). Perhaps a more important function of this forecast and analysis cycle is to take in satellite data, which come in a virtually continuous stream. The 6-hourly cycle results in satellite data being no more than 3 hours off time. The forecast part of the cycle is only 6 hours, just long enough to provide a forecast at the same time as the next incoming conventional data set. The analysis of the new data then consists of correcting the difference between the 6-hour forecast and the observations. In this way, all data received at the Center are incorporated, although some satellite data and late conventional data get into the system through a 6-hour numerical prediction.

There is a fourth model, called the Movable Fine-Mesh Model (MFM), but it is not run regularly. It was originally developed to predict hurricane tracks. It does not have sufficient resolution to define the inner structure of hurricanes well, so cannot predict their development. It has 10 levels and intervals of 60 km. It covers an area only large enough to include a typical hurricane and its immediate environs. As the hurricane moves during the prediction, the model area is kept centered on the hurricane, whence the model's name. The model is held on call and run when a hurricane threatens North America.

The dynamical models are run on a CDC Cyber 205, one of the most powerful "supercomputers" on the market. The Cyber 205 is supported by two NAS 9050s and one NAS 9070. Three IBM 4341s are used for communications, to receive and relay data, and to transmit outgoing products. The speed of the Cyber 205 is highly dependent on the programs being run. For dynamical models, it is about 120 million results per second. The three NAS machines, taken all together, total about 35 million instructions per second (MIPS). The three IBM machines are much slower, totaling about 2.16 MIPS taken altogether.

The internal random access storage capacity of the Cyber 205 is 32 megabytes (about 2.5 million decimal digits can be stored in 1 megabtye of memory), and its peripheral storage capacity is 9,600 megabytes. Bulk data transmission to and from the supporting NAS machines is generally done through the peripheral memory. The two NAS 9050s each have 16 megabytes of random access memory; the NAS 9070 has 32 megabytes. The three NAS machines share 55,915 megabytes of peripheral storage on disks, and, in addition, they share 20 tape drives. There are about 20,000 tapes in NMC's library, each capable of storing more than 5 megabytes, but much less is usually stored on them. Each of the three IBM machines has an internal storage capacity of 4 megabytes, and they share peripheral disk memory of 8,200 megabtyes.

IV. 1985 TO 2000: THE FUTURE

The requirements for weather prediction using the laws of nature are so open-ended that we must first place a boundary around them before they can be discussed intelligently. For all practical purposes, the atmosphere may be treated as a continuous gas. The natural laws governing its behavior infer that in order to predict it perfectly, we must observe and know everything about it, everywhere, at some initial instant. We would also have to know and predict everything that is happening at its two boundaries, both upper and lower. At the bottom, there is evaporation not only from oceans and other bodies of water, but also from the soil, so that the state of the soil would not only have to be known at the initial instant, but would also have to be predicted. The state of the sea, including its temperature, would also have to be predicted.

At the top, not only the incoming invariant part of the solar radiation would have to be known, but also the variability of the sun's radiation and all other incoming radiation from whatever sources would have to be known and predicted. General purpose computers are digital; for perfection, they would have to be infinitely fast and have infinite storage capacity to hold the infinite amount of information. Perfect prediction may not be attainable even in principle. Just as modern physics tells us that there are fundamentally unpredictable events on the smallest scales, there is a body of developing theory that is pointing to the notion that there are fundamental limits on the predictability of the behavior of fluids.

Perfection, of course, is not to be realized, but its definition gives a sort of perspective on what to expect in the future. The game that must be played is to "match" the numerical weather prediction models with the characteristics of the data available, our knowledge and ability to deal with the natural laws, and the computational facilities available. A guiding principle is to include no effect that is weaker than the strongest effect that must be omitted. To understand the next 15 to 25 years, the state of technology relevant to numerical weather prediction must first be predicted. The following are in the nature of reasonable assumptions, and as others before us have done, we base them on technology extant or presently under development.

A. COMPUTERS

Computers will remain digital. From the first computer used for operational numerical weather prediction, an IBM 701, to our present supercomputer, a Cyber 205, the growth rate of power of our NMC computers has on the average been 38 percent compounded annually. Stated another way, computer power on the average has doubled every 26 months. Projecting this growth rate to the year 2000, we will have computers 120 times more powerful than the Cyber 205, and by the year 2015, 2,900 times more powerful. This projection is not unreasonable, in view of well-publicized efforts here and abroad to develop much more powerful computers. A 120-fold more powerful computer would allow a tripling of the resolution (the number of points in each dimension of space and time); a 2,900-fold increase would allow a sevenfold increase in resolution. Faster computers will also allow for generally more realistic physical effects, such as radiation.

B. OBSERVATIONS

Although observations may not set as fast a pace as computers, improvements will be substantial. Improvements will come mainly through indirect sounding techniques. Present infrared sensors on satellites give seven independent pieces of information in the vertical, spaced about 250 km apart in the horizontal. The major problem with infrared sounders is that they cannot penetrate clouds. The present polar-orbiting sounder system includes a microwave channel that peaks in the lower atmosphere and at least partially overcomes this problem. The planned Advanced Microwave Sounding Unit (AMSU) will provide nine independent pieces of information below 10 mbar, including three below 400 mbar, where most of the cloud cover occurs. This, combined with advanced infrared instrumentation and data reduction procedures, will yield more accurate and virtually all-weather indirect soundings of temperature from satellites. There is little indication, however, that indirect temperature soundings in the foreseeable future will attain sufficient accuracy and resolution to replace those from balloon-borne instruments, where obtainable.

Particularly promising is the UHF wind profiler under development at the Wave Propagation Laboratory of the National Oceanic and Atmospheric Administration (NOAA) Environmental Research Laboratories. The equipment, which is ground based, transmits radar pulses upward and receives echoes from small turbulent eddies. Experimental results indicate detail and accuracy superior to conventional wind soundings from rawinsondes.

The Wave Propagation Laboratory has also experimented with ground-based, upward-pointing infrared hardware to obtain temperature soundings, and has found that it performs best in the lower levels of the atmosphere, where satellite-based equipment is at its worst. A combination of the two sources of information is better than either by itself. The ground-based equipment cannot scan large areas of the Earth, as satellites do, but it can operate remotely and, if placed on buoys, could result in improved indirect soundings over oceans.

C. TELECOMMUNICATIONS

The Global Telecommunications System should undergo much improvement in the future, but it will keep its present pattern. The system is worldwide and serves all nations, having been set up by international agreement and participation. A principal feature is a trunk circuit girdling the globe, connecting Washington, Tokyo, Melbourne, New Delhi, Cairo, Moscow, Prague, Offenbach (near Frankfurt), Paris, and Bracknell (near London). From each of these cities there are many feeder lines. Conventional observations are collected centrally in each nation and exchanged on the Global Telecommunications System. The performance of the system is uneven because of the widely varying levels of technological development of the many participating countries. This situation is expected to improve gradually.

D. DYNAMICAL MODELS

Models will react to the advances in science and technology. Resolution will certainly be greater, to match more dense and more accurate observations, particularly from satellites, but also from ground-based instruments with the new technologies such as infrared, microwave, and lidar sounders. Concurrent advances in science will be required for the high-resolution models to yield improved predictions. Prediction accuracy and range will also depend more on how well the interchange of heat, momentum, and moisture at the upper and lower boundaries is handled. This, in turn, will require the improved observations of sea surface temperature that are projected.

The repertoire of models will be similar, but some of the increased speed of computers will be used to run them more frequently. There will be a very high resolution mesoscale model, with intervals of about 5 km. It will have as many levels as will contribute to performance, perhaps as many as 50. Its area will be larger than the MFM, perhaps as large as the United States. Rather than movable, the area is more likely to be relocatable, but fixed for the duration of a prediction. Rather than standing alone, it may be the innermost part of a nested model, combined with a regional model. Rather than being held on call, as with the MFM, it may be run on a regular and frequent basis, perhaps as often as eight times daily, with its area centered on the "problem of the day." Its uses will include the prediction of hurricanes, heavy precipitation, flash floods, squall lines, and clusters of thunderstorms. An interval of 5 km is sufficiently small to resolve the central pressure and the radius of maximum winds (typically 50 km) within a hurricane, which is necessary for the prediction of development. The model will be supported by surface observations, radiosondes, indirect temperature sounds from geostationary satellites and ground-based profilers, indirect wind soundings from UHF equipment, ground-based Doppler radar (NEXRAD), and possibly wind soundings made with lidar echoes from aerosols.

There will be a regional model run four times daily, with intervals of 20 to 30 km, and up to 50 levels. As with the present regional model, this grid will be the innermost of several covering the Northern Hemisphere. It will be run 30 to 60 minutes after nominal data time and delivered to the field more quickly, so that the 12-hour prediction will be meaningful guidance. It will be supported at 6 a.m. and 6 p.m. G.m.t. by satellite and ground-based indirect soundings combined, which will give temperature, wind, and humidity.

There will be a global model with intervals of 50 to 100 km and 25 to 50 levels. Its starting time will depend mainly on computer availability, and may be delayed by conflicts with the mesoscale and regional models. In other words, its starting time may be similar to that of the present global model. It will be run daily to 30 days. Products from the first 10 or so days will be used directly as guidance, but the later ones will be used to predict average conditions over periods of 5 or so days. Daily runs of the global model to 30 days will enable statistical treatment of ensembles of consecutive runs to produce probability statements about the longer ranges.

E. DATA VOLUME

As a rule of thumb, the density of observations should be roughly comparable to the density of points in the grid of the dynamical model that the observations support. However, observations need only be dense enough to describe adequately the weather systems being predicted, whereas the density of points in a model's grid must be additionally dense in order to approximate differentials with sufficient accuracy. A ratio of from 3:2 to 7:2 is reasonable for distance between points of observation compared with distance between grid points. For example, a regional model with 30 levels and intervals of 30 km should be supported by observations separated by 45 to 105 km at 9 to 20 levels. It is important to point out, in this connection, that observations at "points" must represent physically independent pieces of information. It is all right, even advantageous, for an observation at a "point" to represent average conditions near the nominal location of the observation, but increase of density by interpolation, while useful in a mechanistic sense, does not add to information content.

In the case of a mesoscale model with, say, 40 levels and intervals of 5 km, the supporting observations using these ratios would have to be taken at intervals of 7.5 to 17.5 meters at 11 to 27 levels. Although such high observational density is not projected for the year 2000, the model described above will still make sense. Much in the mesoscale is determined by larger atmospheric features interacting with known mesoscale geographic features such as mountains, lakes, and ocean shorelines.

F. BEYOND 2000

There is some research and experimental modeling going on with features that are considerably smaller than the grids of the models being projected. In particular, thunderstorm cells are less than 5 km across, and tornadoes are only 100 to 1,000 km across. In 15 years, this work will be regarded very seriously in terms of possible applications, and perhaps will be applied within 25 years. This work is in another realm of dynamics, and many assumptions that have been valid up to now do not hold. In particular, nonhydrostatic pressures and turbulent exchanges of heat, momentum, and moisture are primary in this realm. This, in turn, results in enormously greater computer requirements, as well as observational requirements.

It was impossible for Bjerknes or Richardson to imagine a "computing engine" that could add more than 100 million 15-digit numbers in 1 second, as present-day supercomputers can. Likewise, scientists of that day could hardly be expected to foresee the reality of artificial satellites. As late as 1948, at least one professor, in teaching a course in differential equations at a leading U.S. university, "proved" that a rocket could not escape Earth's gravitation field. His mathematics were impeccable, but he did not foresee the imminent development of fuels with a sufficient energy release per mass.

With history as a guide, we should expect the unexpected. Perhaps the year 2000 is too early to hope for dramatic breakthroughs, but they will surely come and upset any predictions of the future made theretofore.

APPENDIX A

GLOSSARY OF ACRONYMS

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AMSU – Advanced Microwave Sounding Unit

CDC – Control Data Corporation

ENIAC – Electronic Numerical Integrator and Computer. The first electronic computer, developed by the Moore School of Electrical Engineering, University of Pennsylvania, and installed at the U.S. Army's Ballistic Research Laboratory, Aberdeen Proving Ground, Maryland. ENIAC is now in the collection of the Smithsonian Institution, Washington, D.C.

G.m.t. – Greenwich Mean Time

IBM – International Business Machines

LFM – Limited-Area Fine-Mesh Model

MFM – Movable Fine-Mesh Model

MIPS – Million Instructions per Second

NAS – National Advanced Systems

NEXRAD – Next Generation Weather Radar

NMC – National Meteorological Center

RAFS – Regional Analysis and Forecast System

UHF – Ultrahigh Frequency

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