Bjerknes Memorial Lecture

Richard J. Reed[1]

The Development and Status of Modern Weather Prediction[2]

Abstract

The progress made in weather prediction since national weather services began issuing forecasts is traced and assessed. Specific contributions of J. Bjerknes to this program are pointed out. Lessons learned from the historical record concerning factors and conditions responsible for the important advances are considered, and a limited evaluation is then made of the increase in forecast skill that resulted from these advances. Finally, some comments are offered on the future prospects of weather prediction.

1. Introduction

We gather tonight to celebrate the memory of Jacob Bjerknes, one of the towering figures in the history of meteorology. In a long and distinguished career that spanned a period of more than 50 years, Bjerknes made monumental contributions to our knowledge and understanding of the atmosphere and left a lasting mark on meteorological practice. He was a keen observer of atmospheric phenomena who possessed an extraordinary ability to find order in the complexities of nature and to explain his findings in simple physical terms. He was both practitioner and scientist, some of his greatest scientific achievements coming early in his career when he served as Chief of the Bergen Weather Service.

Because so much of Bjerknes's work has had a bearing on the theory and practice of weather forecasting as it exists today, I have chosen as the subject of this memorial lecture the development and status of modern weather prediction. My primary aim will be to trace and assess the progress made in weather prediction since national weather services first began issuing forecasts shortly after the middle of the last century. Once the historical record is laid out, I will pause to consider what can be learned from this record concerning the factors and conditions that have been responsible for the important advances that have taken place. Next I will attempt a limited evaluation of the increase in forecast skill that has resulted from these advances, and finally I will offer some comments on the future prospects of weather prediction.

Where appropriate, I will point out specific contributions of Jack Bjerknes (as he preferred to be called) to the progress that has been made in weather forecasting, but I will not attempt an overall assessment of his remarkable career. Hopefully others more qualified than I will undertake this important task in future lectures or writings. Despite his many accomplishments and honors, Bjerknes was a modest man. I trust that he would approve of our decision to focus attention in this lecture on the subject to which he devoted much of his life's work rather than on his personal achievements alone.

During the period under consideration, weather forecasting was transformed from a practical art to a partly quantitative science. Thus it will be convenient in the discussion that follows to divide the period into three eras: a first extending from 1860 to 1920 in which forecast practice was based almost entirely on human experience and skill, a second extending from 1920 to 1950 in which physical concepts received increasing emphasis, and finally the modern era in which physical-numerical methods have been introduced and become firmly established. I will refer to these as the empirical, transitional, and scientific eras, respectively.

2. The empirical era: 1860–1920

The first regular issue of storm warnings by a national weather service was begun in the Netherlands in June 1860. Public forecasts in England commenced in 1861 and in France, in 1863. In the United States the establishment of a national weather service was delayed by the Civil War until 1870, when the predecessor of the present organization was formed within the Army Signal Service. The first forecasts were issued by the Signal Service shortly thereafter.

The basic tool used in early forecast practice, and indeed an important tool to the present day, was the synoptic weather map. The first rudimentary weather maps were constructed as early as 1820 by H. W. Brandes, a German astronomer, mathematician, and engineer. The maps were prepared for the whole of the year 1783 and were based on data collected by the Mannheim Meteorological Society from a network of European stations. These maps, and others prepared elsewhere during the first half of the last century, indicated the potentialities of synoptic mapping for weather study and prediction, but they were hardly suitable for making forecasts, since they were of necessity prepared long after the event. It was not until the invention of the telegraph about the year 1845 that a means existed for the rapid communication of weather information and hence for the preparation of weather maps on a current basis. As early as 1851, James Glaisher constructed a series of maps from telegraphic reports for display at the World's Fair held that year in London. Nearly a decade elapsed, however, before routine prepa-

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ration of current maps was begun in France, England, and the Netherlands. The maps were soon used for issuing storm warnings and other forecasts.

During the next 50 to 60 years, experience gained in the use of weather maps constituted almost the sole basis of prediction. Forecasting was essentially an exercise in isobaric geometry, seven fundamental configurations being recognized in accordance with a classification scheme proposed by Abercromby. Past movements of the pressure systems, statistics on storm tracks, and a host of empirical rules were employed to project low-pressure centers and other features forward in time. The attendant weather conditions were estimated from the observed relationship of clouds and precipitation to the pressure pattern, from models of such relationships, as for example given also by Abercromby (Fig. 1), and from a knowledge of local effects.

The status of weather prediction at the end of this era is well documented in a book published by the U.S. Weather Bureau in 1916 entitled *Weather Forecasting in the United States.* Although forecast practice differed somewhat from one country to another, this book gives no doubt a faithful account of the state of the art at that time. In a preliminary statement on the forecast problem, Prof. A. J. Henry, one of the contributors to the book, noted that "After an experience of many years, the forecasters of the Weather Bureau continue to make forecasts of every character as to future weather conditions solely on the basis of synoptic weather maps. . . . By the continuous use and study of daily synoptic weather maps meteorologists generally recognize . . . the two fundamentals of modern weather forecasting. These are (1) weather travels; (2) the character of the weather is in general largely determined by the atmospheric pressure distribution." He then described the charts employed at that time—the isobaric chart (which also contained isotherms) and auxiliary pressure change, temperature change, and cloud charts. Most of the remainder of the book was devoted to a detailed description of the application of these charts to the forecasting of cold waves, frosts, high winds, fog, snow, sleet, thunderstorms, and the like, with copious use of examples and frequent reference to a bewildering variety of empirical rules.

From the foregoing account it would appear that physical principles and theoretical concepts played little, if any, role in practical weather prediction up to the time of the First World War. Certainly the basis for a more scientific approach to forecasting existed. The fundamental laws of mechanics and thermodynamics had long been known, and application of these laws to the atmosphere had been and was being made. Ferrel's work on the winds and general circulation, done in the 1850s, can be said to mark the beginning of theoretical or dynamical meteorology. Papers on atmospheric thermodynamics appeared in the 1860s that treated such topics as dry and moist adiabatic processes, and in 1889 Von Bezold published a voluminous work entitled *On the Thermodynamics of the Atmosphere.* So a theoretical foundation of sorts existed during the era in question, but its impact on forecast practice was obviously slight. It must not be supposed, however, that efforts to inject scientific ideas into forecast practice were totally lacking. Indeed, at one time a small group, known as the "Study Room," was formed within the Signal Service, with Cleveland Abbe as its leader and Ferrel as one of its members, for the purpose of upgrading the scientific capability of the Service. But this effort was temporary and seemed to have little lasting influence.

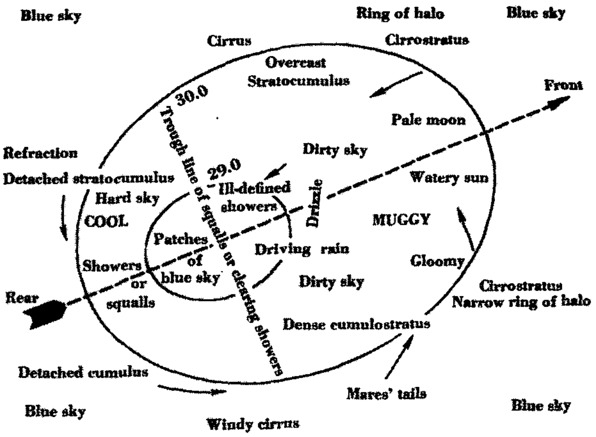

FIG. 1. Abercromby's model of weather distribution in a cyclone (1883). (Taken from Petterssen, 1969, p. 13; reproduced by permission of McGraw-Hill and F. H. Ludlam.)

Weather forecasting during this era also suffered from a lack of regular upper air measurements. Sporadic soundings were taken by manned balloons and later by unmanned balloons and kites. But adequate, three-dimensional mapping of the atmosphere on an operational basis had to await the introduction of the radiosonde in the 1930s.

Despite these shortcomings and limitations there can be little doubt that forecasting had become a useful art during its early years. This is attested to by the steady increase in the level of public support that it enjoyed and by the wide range of special weather services that were continuously added. By 1920 these included, in the United States, marine, river and flood, agriculture, fruit frost, hurricane, forestry and fire weather, and finally, at the very end, general aviation services. It must not be forgotten, too, that a substantial improvement in observational practices and networks was achieved during this era. Contributing to this improvement was a strengthening of the international cooperation that has characterized meteorology from its inception.

Clearly, by the close of the era, progress had been made on many fronts, but in the most important area of all, forecast methodology, stagnation had set in. The inherent limitations of the empirical method ruled out the hope of significant further improvement in forecast skill. Forecasting had reached a dead end. New directions were needed before further progress was possible.

3. The transitional era: 1920–1950

In 1918, events transpired in a seemingly unlikely place, the small town of Bergen on the west coast of Norway, that were to revolutionize meteorology and weather prediction. A year earlier, in 1917, Vilhelm Bjerknes had returned to his native Norway from Leipzig, Germany, to found the Geophysical Institute in Bergen. He brought with him his two young pupils, Halvor Solberg and his son, Jacob Bjerknes, both about 20 years of age. While still in Leipzig, the young Bjerknes had utilized direct analysis of the surface wind field to study the motion of convergence lines, which he found to be a characteristic feature of weather maps. The results of his work appeared in his first scientific paper published in the *Meteorologische Zeitschrift* in 1917.

V. Bjerknes, of course, was at this time already a famous theoretical hydrodynamicist, but he set as an early goal of his Institute the improvement of forecast services in Norway as an aid to agriculture and fishing. Because of World War I, which was then still in progress, Norway was largely cut off from the outside world. To compensate for the resulting deficiency of weather data and to aid the studies begun in Leipzig on convergence lines, the Bjerkneses conceived the idea of establishing a dense network of stations within Norway itself. At V. Bjerknes's instigation, and with supervision from his young helpers, the number of stations was soon increased by tenfold (from 9 to 90). Moreover, at the same time, the elder Bjerknes managed to bring about a reorganization of the Norwegian Weather Service in which a new forecasting division was established at Bergen with his son, Jack, in charge. It was in this setting—a newly formed weather service, drawing its lifeblood of data from a unique network of observations and headed by a young man who, in his method of analysis, was breaking with traditional methods—that the discoveries that were to reshape meteorology took place.

These discoveries were not long in coming. By November 1918, Jack Bjerknes had completed his famous paper, "On the Structure of Moving Cyclones," and the following year it was published in *Geofysiske Publikasjoner.* In this paper he identified for the first time the warm front and cold front (though he did not yet call them by these names), he described the three-dimensional motions and the related cloud and precipitation distributions in the vicinity of the fronts, and he inferred the source of the kinetic energy of the cyclone, namely, the release of the potential energy stored in the warm and cold air masses. It does no discredit to Bjerknes to note that his findings were foreshadowed in the works of many earlier investigators. Dove, Loomis, Fitzroy, Jinman, Blasius, Hildebrandsson, Eckholm, Bigelow, and others had espoused the notion that cyclones are composed of opposing currents of warm and cold air. Though expressed in a crude schematic form, and without explicit depiction of fronts, Shaw's cyclone model of 1911 was strikingly similar to the later Bjerknes model. Likewise, Bjerknes's ideas on the energetics of the cyclone were preceded by Margules's classic paper on the subject. Thus various elements of Bjerknes's model existed at an earlier time (Fig. 2). However, the great merit of Bjerknes's work was that it arranged the ob-

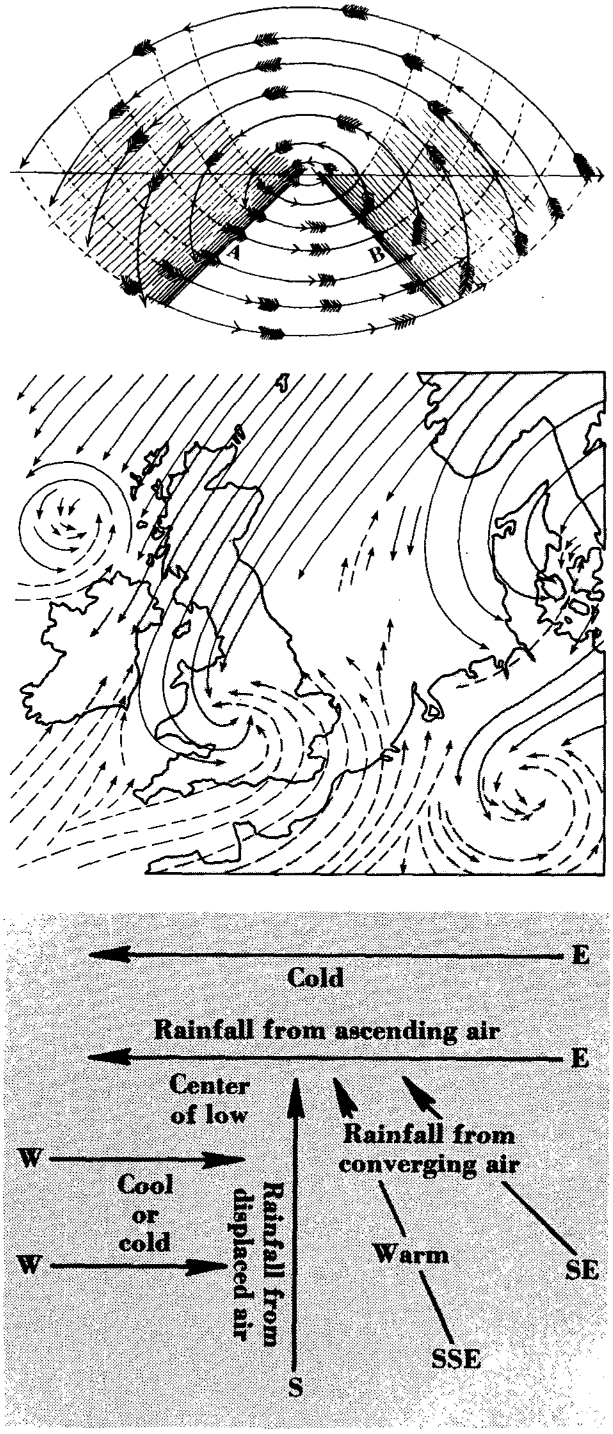

FIG. 2. Early cyclone models. (Top) Model of Master Mariner Jimman (1861) showing opposing currents and wind shift lines (fronts). (Middle) Fitzroy's model (1863) showing cyclonic whirls between tropical and polar air currents. (Bottom) Shaw's model (1911). (Taken from Petterssen, 1969, p. 11, p. 12, and p. 14, respectively; reproduced by permission of McGraw-Hill, and also by permission of F. H. Ludlam for top figure.)

servations in a coherent three-dimensional picture and gave them physical substance.

Four years after the appearance of his first epic paper, Bjerknes, in collaboration with Solberg, produced a second, equally earthshaking work entitled "Life Cycle of Cyclones and the Polar Front Theory of Atmospheric Circulation." In this work, Bjerknes and Solberg introduced the idea that cyclones form as wave disturbances on the boundary surface separating tropical and polar air masses and that, once formed, they undergo a characteristic life cycle. During the course of this cycle the cyclone passes through successive stages—from open wave, to occluded cyclone, to dying vortex completely embedded within the cold air. The discovery of the occlusion process, in which the tongue of warm air narrows and is forced aloft by the spreading of the cold air at the surface, is generally credited to Tor Bergeron, who, with Rossby, joined the Bergen School in 1919.

The impact of this paper on meteorology was enormous. Theoretical work on cyclone formation was stimulated, a new conception of storm structure and evolution was implanted, old conflicts regarding the thermal structure of cyclones were resolved, and the practice of weather forecasting was forever altered. A new method of analysis was introduced that not only gave a more precise and logical description of the current state of the weather but also provided a basis for anticipating the future sequence of events.

Like many new ideas, those of Bjerknes were resisted at first, in this case by entrenched interests within the national weather services. In fact it was 1938 before his methods were finally adopted by the U.S. Weather Bureau. But the power of great ideas cannot be denied, and eventually frontal analysis became standard practice throughout the world. Of the part that the elder Bjerknes played in the momentous discoveries of the young men of the Bergen School, we have his own words: "During 50 years meteorologists all over the world looked at weather maps without discovering their most important features. I only gave the right kind of maps to the right young men, and they soon discovered the wrinkles in the face of the Weather."[3]

The era from 1920 to 1950 was marked by other important advances in the field of weather prediction. Foremost among these was the development of networks of stations providing regular upper air observations, a development made possible by the invention of the radio meteorgraph or radiosonde. With this development, regular mapping of data at upper levels began, and knowledge of upper level flow patterns was extended well beyond that gained earlier from special studies employing swarm or serial ascents. On the basis of the newly acquired knowledge, Rossby and his colleagues at Chicago introduced the concept of jet streams and in addition documented the existence of both long and short waves in the upper westerlies. The existence of a system of large circumpolar waves had earlier been inferred by Bjerknes in his famous paper with Solberg. This inference was based on their finding that surface cyclones tend to occur in families. In later papers, Bjerknes viewed the short waves as the upper extensions of the individual members of the cyclone family.

Another noteworthy development of this era, which was of symbolic importance if not of enduring practical value, was the application of the principle of conservation of absolute vorticity, either through the Rossby wave formula or through trajectory methods, to upper level prognosis. This constituted the first quantitative use of a dynamical principle in the forecasting of large-scale flow patterns and as such was a direct forerunner of numerical weather prediction.

The introduction of weather radar into meteorological practice in the late 1940s was another major event of the era under consideration. The radar provided the forecaster with a valuable new tool for locating and tracking severe weather phenomena, such as thunderstorms, squall lines, and hurricanes, and for observing fine-scale features of the precipitation patterns in large storms.

Finally, it is worth remarking that the practice of forecasting was facilitated during the 1920–50 period by advances in communications, notably by the introduction of the teletypewriter and facsimile and by the use of radio in transmitting data from ships at sea.

In summary, then, the era from 1920 to 1950 saw dramatic breaks with the past. Surface analysis was revolutionized by the introduction of frontal concepts. Upper air soundings added a new dimension to the atmosphere. Dynamic principles were applied quantitatively for the first time in the prognosis of motion systems.

4. The scientific era: 1950 to present

The attainment of successful weather prediction or prognosis by physical-numerical methods in the early 1950s and the introduction of these methods into routine operational use shortly thereafter heralded the dawn of a new era in the history of weather forecasting. Despite the many advances enumerated above, weather forecasting remained essentially an art until the middle of this century. With the advent of numerical prediction it has become increasingly an exact science.

The first concerted effort to apply the principles of physics to weather prediction was begun by V. Bjerknes shortly after the turn of the century. In a paper that appeared in 1904 entitled "The Problem of Weather Prediction Considered from the Point of View of Mathematics and Mechanics," Bjerknes asserted that "dynamic meteorology poses only one problem whose solution really justifies the work, a problem, which, by the way, encompasses all the others: the forecasting of the future states of the atmosphere." He then proceeded to formulate the problem in modern terms, noting the need first to diagnose the current state of the atmosphere, that is, to establish initial conditions, and then to arrive at the future state by time integration of the hydrodynamical equations. V. Bjerknes set as his lifelong goal the achievement of a solution to this problem. Though he did not realize his ambition, his guiding spirit can be

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[3] *Geofysiske Publikasjoner,* 1952, p. 18.

seen in many of the developments that finally brought numerical prediction to fruition.

In 1922, Lewis F. Richardson, the eccentric English genius, made a pioneering attempt, described in his book *Weather Prediction by Numerical Process,* to apply the hydrodynamical method to an actual weather situation. Although his effort was sound in principle, the experiment ended in failure because of data deficiencies and computational difficulties that were later traced to the numerical differencing scheme. Richardson's failure discouraged further efforts at numerical prediction until the late 1940s when a group at the Institute for Advanced Study in Princeton, under the leadership of Charney and von Neumann, again took up the challenge and within the span of a few years succeeded in making the first useful predictions by numerical means. The groundwork for this sudden advance was laid by Rossby and by Charney and Eady in their theoretical studies of barotropic and baroclinic waves. These studies, in turn, were preceded by aerological investigations by Bjerknes and others that provided the necessary observational background. Charney, in fact, credits Bjerknes's work of 1937 on the upper wave and its role in cyclogenesis with having led directly to his own work on baroclinic instability.[4]

A crucial factor in the development of numerical prediction, which has not been mentioned as yet, was, of course, the advent of the high-speed electronic computer. We have only to read Richardson's imaginative and amusing account of the operation of a numerical prediction factory, employing great numbers of workers pounding away at old-fashioned desk computers, to appreciate the futility of attempting numerical prediction without such an instrument. Indeed it was the advent of the computer that provided the group at the Institute for Advanced Study with the impetus for renewing the attack on the prediction problem in 1946.

In the 20 years since its operational use, numerical prediction has grown rapidly in sophistication. Simple one-level barotropic models have been superseded by multilevel baroclinic models. The forecast domain has been expanded from regional to hemispheric and recently to global dimensions. The useful range of prediction has been extended from 1–2 days to 3–5 days. During the last few years, models employing nested, fine-mesh grids have been used to increase the accuracy and usefulness of shorter-range predictions for limited areas.

Needless to say the practice of weather forecasting has been profoundly altered by the developments that have taken place in numerical weather prediction. Prognostication of the pressure pattern has been taken over almost entirely by the computer, though surface prognosis has through the years been somewhat improved by human intervention. Forecasts of specific weather elements, such as temperature or wind, are sometimes made directly by the computer and sometimes by the forecaster with the aid of the guidance material generated by the computer. The usefulness of dynamical prediction has been considerably enhanced in recent years by the application of regression analysis to computer products. In this method, known as Model Output Statistics (MOS), large samples of past data are used to derive statistical relationships between variables contained in the computer output and weather elements that cannot be directly or adequately predicted by the dynamical method.

From the foregoing it may seem that the role of the forecaster has been greatly diminished by the development of numerical prediction and that it is only a matter of time before he suffers the fate of the dinosaur. But this would be an unwarranted conclusion. Countless situations exist in which human judgment is required in weather prediction, be it in forecasting local weather events, severe convective storms, or hurricanes. Numerical prediction is just one weapon in the forecaster's arsenal, albeit the most powerful one. Statistical methods, extrapolation techniques, and empirical rules still have their place in weather forecasting and will continue to have a place for the foreseeable future.

The final major event that must be mentioned in this thumbnail sketch of the development of modern weather prediction is the introduction of the meteorological satellite in 1960. With the arrival of this tool on the scene the capability for complete global weather observation was realized at last. Visible and infrared images from polar-orbiting satellites now provide day and night surveillance of weather systems over the entire earth. Under the watchful eye of the satellite, no longer is it possible for hurricanes or ocean storms to pass undetected through regions of sparse data, as happened formerly. Forecasting for oceanic and coastal areas has improved accordingly. Geostationary satellites, hovering over the equator, now send data back to earth every half hour for a substantial portion of the western hemisphere. These data allow small-scale, short-lived features to be identified and tracked and are helpful, too, in following the evolution of large-scale weather systems. Moreover, the geostationary satellite has proved exceedingly valuable as a means of obtaining winds in remote ocean areas through its ability to track cloud motions.

Radiometric methods have been developed for sounding the atmosphere from satellites. The soundings are already of use in prediction for the Southern Hemisphere and will no doubt have wider applicability as the sounding methods are further perfected, instrumentation is improved, and better methods are devised for assimilating the satellite data into numerical prediction models. In addition to the infrared sounders, which measure temperature and moisture profiles, experimental microwave sounders have been flown that are able to detect precipitation areas within large cloud masses.

Despite these and other advances, satellite meteorology is still in an early stage of development. Its contributions to weather prediction are already substantial. Its future impact is likely to exceed our powers of imagination.

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[4] Wurtele, 1975, p. 11.

5. The elements of progress

When viewed in quick historical perspective, the changes that have taken place in forecast practice during the past century are truly breathtaking. Before examining how these changes have affected skill in weather prediction, it will be instructive to pause briefly and review the elements that have contributed to progress.

A first element is technological innovation. This has provided the instruments and measuring systems or platforms that have blazed new paths—the airplane, radiosonde, radar, and satellite. It has provided, too, the communication facilities without which forecasting could not have achieved its present state—the telegraph, radio, teletypewriter, and facsimile. And finally it has provided the high-speed computer that allowed V. Bjerknes's impossible dream of prediction by physical-mathematical method to become a reality. It is hard to overstate the importance of new technology. But it is discomforting to think that it is an element of progress over which the meteorologist has little control. All of the major technological advances noted above have depended upon discoveries or developments in other fields of endeavor. And, in this modern age of advanced technology, it seems almost certain that the meteorologist will have to continue to look elsewhere for new technological opportunities. At best he can be alert to these opportunities and quick to adapt them to his own use.

A second element of progress is observational knowledge. This can take the shape of pure empiricism, such as underlay much of the early practice of weather forecasting, or it can take a higher form, as exemplified by the work of Jack Bjerknes, in which physical processes play an essential role in the description of atmospheric phenomena.

A third and final element is theoretical understanding. Without the theoretical contributions of the V. Bjerkneses, the Rossbys, the Charneys our ability to forecast the weather would be little advanced beyond that of 50–100 years ago. New ideas and the expression of these ideas in mathematical form have been prerequisites for true advancement in the past and will surely remain so in the future.

As has often been remarked, progress is best assured when the last two elements go hand in hand. Empiricism by itself is not sufficient. Theory divorced from reality is equally impotent. Both the theoretician and the empiricist are essential to progress, as the accomplishments of the Bjerkneses, father and son, so amply demonstrate.

6. Forecast improvement

It is of interest to ask what improvements in weather forecasting have been achieved as a result of the advances described above. Forecast improvement, in the broadest sense of the term, can come about because of an increase in forecast accuracy, by the provision of new types of forecast services, and by the better dissemination of weather forecasts and warnings to the public. Clearly it is not possible in a single lecture to treat a subject of such diversity in any depth. In the remarks that follow the principal emphasis will be on the first topic, the improvement in forecast accuracy or skill, but even so the treatment will be fragmentary. My object, quite frankly, will be to highlight some of the readily available and convincing pieces of evidence of increased predictive ability rather than to give a balanced treatment of the subject.

My remarks, too, will focus on the recent era, beginning about 1950, for which meaningful sets of homogeneous verification records exist. For the United States, at least, few records extend back further in time that are suitable for comparison with those that are presently kept. Verification statistics of one type or another, however, have been maintained from the earliest days of the Weather Service.

From such records as do exist it appears that only a slight increase in forecast accuracy was achieved during the 1860–1920 era. Certainly during the early part of the period, some increase was inevitable because of the expansion of the observational network and the accumulation of new empirical knowledge. But toward the end, the potential of the methods then in use had been pretty well exhausted, causing Milham, the author of a well-known textbook, to state in 1918 that, "The increase in accuracy during the past fifteen years has been small, and this would seem to indicate that present methods can yield no greater accuracy." [5]

In principle the introduction of frontal analysis and later of upper air analysis during the 1920–50 era should have resulted in some increase in predictive ability, and likely it did. However, the increase must have been small, since it is hard to find factual support for this belief, and there are even those who question whether any improvement took place at all. (see Willett).[6]

A much brighter picture emerges, however, when we examine the era from about 1950 to the present. Here substantial improvements have been made that can be well documented. There is even evidence of a public recognition that forecasting has changed for the better. For example, the following statement appeared in an article on climatic change in a recent issue of *Time* magazine.[7] "Everybody talks about the weather, but nobody can do much about it even today. Short-range forecasting has improved enormously in recent years, even though squalls occur on days when the weatherman insists the precipitation probability is near zero." Who can conceive of a similar compliment, as tainted as it may be, having been paid to the forecasting profession 20 or 30 years ago? The improved state of affairs in forecasting can be attributed mainly to the advent of physical-numerical methods, but observational advances and the development of useful statistical techniques must also be given credit. Let us now look at some of the highlights of progress, considering in turn three categories of forecasts: general, hurricane, and severe storm.

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[5] Milham, 1918, p. 407.

[6] Malone, 1951, p. 731.

[7] p. 49, 9 August 1976.

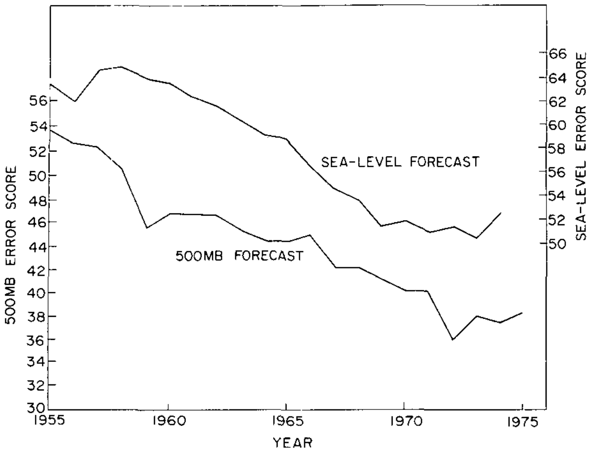

FIG. 3. Error scores for 30 h surface prognosis and 36 h 500 mb prognosis. (From Cressman, 1976).

General forecasts. Under this heading we will include both the public forecasts issued by local forecast offices and supporting forecast material provided by the National Meteorological Center (NMC) to the local offices. With this definition there can be no doubt that the most impressive advance in forecast skill has been in the area of pressure prognosis, that is, in the prediction of future pressure (or geopotential height) patterns and the associated wind fields. There also can be no doubt that this advance stems from the introduction of numerical methods. The S1 score used by NMC as a measure of the error in pressure prognosis shows a steady decline for 30 h surface prognoses during the decade from 1958 to 1968 (Fig. 3). In the 10 preceding years, when numerical guidance was lacking, the score fluctuated around the 1958 level. A corresponding decline in forecast error occurred during the same period for 36 h 500 mb prognoses. Particularly impressive has been the increase in prognostic skill at longer ranges. Larger-scale features of the upper level flow pattern are now well predicted 3 days in advance, and some skill in prediction of both pressure and temperature exists out to about 5 days. In earlier times, 48 h was the limit for which forecasts were attempted, and the skill at that range was slight. The formation and breakdown of large blocking patterns and the development of cutoff lows, events that were impossible or nearly impossible to predict in earlier eras, are now well handled on many occasions (Fig. 4). Also impressive is the markedly better prediction of exceptional cases, such as the mighty storms that develop rapidly in winter along the Altantic seaboard. The improved capability for forecasting these events has resulted largely from the introduction of limited-area fine-mesh (LFM) models.

Improvement in public forecasts of temperature and precipitation has not been commensurate with the improvement in pressure prognosis. However, examples of at least some improvement in capability can be cited. For instance, during the past five years, large errors in temperature prediction (defined as ≥10°F) have been

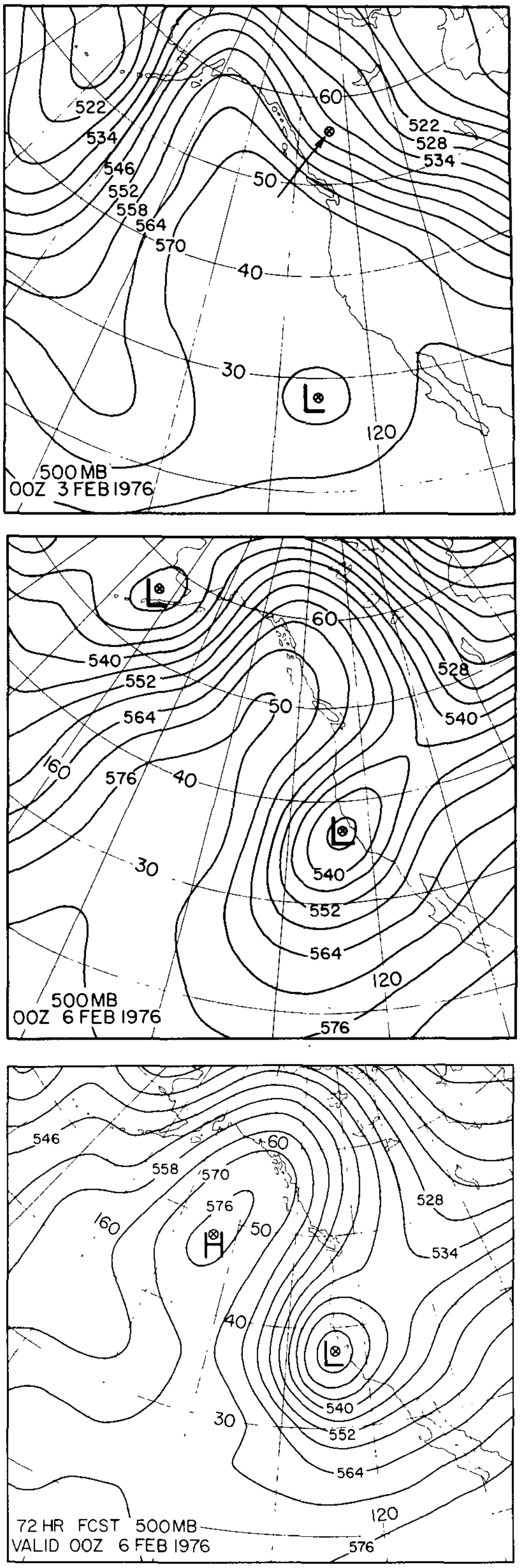

FIG. 4. Example of a highly successful 72 h prognosis of the development of a cutoff low aloft. (Top) 500 mb analysis for 0000 GMT, 3 February 1976. Arrow points to position of the vorticity center, which later developed into the closed low. (Middle) 500 mb analysis for 0000 GMT, 6 February 1976. (Bottom) 72 h 500 mb prognosis verifying at 0000 GMT, 6 February 1976.

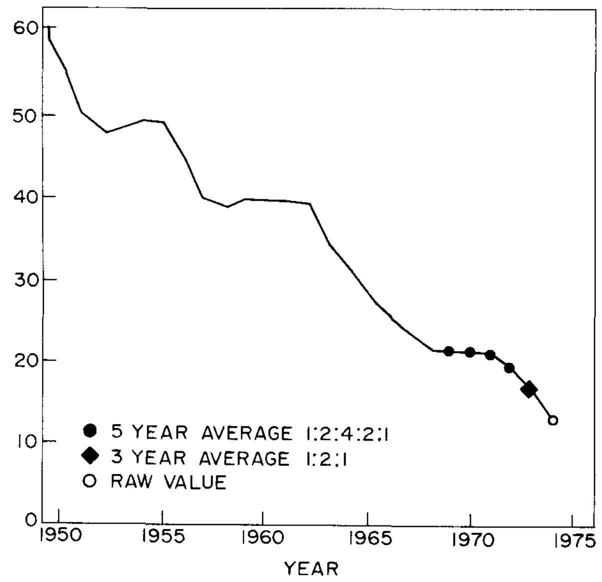

FIG. 5. Annual number of maximum temperature forecast errors ≥10°F at Salt Lake City. (From Cressman, 1976).

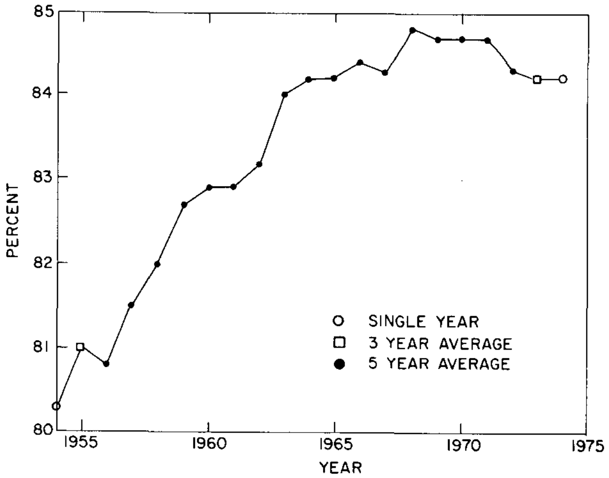

FIG. 6. Three station verification average for Boston, Chicago, and Washington giving percent of correct precipitation forecasts on a yes-no basis. (From Cressman, 1976).

reduced over the United States by one-third. The record at Salt Lake City is especially impressive. During the period since 1950, nearly a fourfold decrease in the number of large temperature errors has been achieved at that location (Fig. 5).

Examples can be found, too, of improvements in the prediction of precipitation occurrence. Since 1956 the percent of correct precipitation forecasts, on a yes-no basis, averaged for three major cities—Boston, Chicago, and Washington—has increased from about 80% to 84% (Fig. 6). Quantitative forecasting of precipitation has been more resistant to improvement. However, forecasts in the 24–36 h range, based on human modification of LFM prognoses, were the best on record in 1975, and recent tests conducted at NMC with *very* fine mesh grid models (VFM) indicate that a breakthrough may be in the offing.

Hurricane prediction. Records compiled by the National Hurricane Center (NHC) show that a substantial improvement in the prediction of hurricane movement occurred during the 1960s. For instance, between about 1958 and 1970 the mean error in forecasting the 24 h displacement of hurricanes was reduced by ~15%, or by 25 n mi. The improvement can be attributed in large part to the development and utilization of a variety of statistical regression methods. The data base in most regions is not yet suitable for attempting numerical prediction of hurricanes on fine-mesh grids, but some dynamical methods are in use that perform nearly at the level of the statistical methods.

In the case of a phenomenon as deadly as a hurricane a better measure of forecast success than the size of the position error is the effectiveness of the prediction or warning on public action. In terms of this measure, highly gratifying results have been achieved, the number of deaths having decreased in recent decades despite the increased coastal population. However, the heavy utilization of the coastal area has created the potential for future disasters of unprecedented magnitude. For this reason the NHC is devoting an increasing amount of its effort to educational and preparedness programs.

Severe storm prediction. It was not until the year 1952 that a separate center was formed within the Weather Service charged with the responsibility of forecasting tornadoes and other types of severe local storms. Prior to the establishment of the National Severe Storms Forecast Center (NSSFC), as it is now called, individual forecast offices issued severe storm warnings but only under highly restrictive regulations. District forecasters were permitted the use of the terms "severe thunderstorms" and "severe local storms." Only the Chief of the Bureau could use the phrase "conditions are favorable for *destructive* local storms." The use of the word "tornado" was forbidden to all. The reason for this prohibition, as given by Milham, was that "since a tornado usually covers an area only a few hundred feet wide and a few miles long, it is decidedly undesirable to alarm a whole state or several states with the forecast that a tornado could occur."[8]

The record tornado outbreak of 3–4 April 1974, in which 148 tornadoes occurred, many of the first magnitude, with a loss of only 307 lives, provides a dramatic example of the reduction of deaths that has resulted from the operation of the NSSFC. There is, of course, no sure way of estimating how many lives have been saved as a result of tornado warnings, but if allowance is made for the population increase and for fluctuations in the number and severity of tornadoes, there can be little question that a significant reduction in the death toll has been achieved in recent decades. According to Allen Pearson, the Director of NSSFC, the reduction "is primarily due to better communications, better warnings

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[8] Milham, 1918, p. 403.

due to radar-weather radio, increased participation by Civil Defense, and better forecasts."[9]

The skill in tornado prediction is not high, but it is well documented. For example, verification records reveal that about two-thirds of tornado deaths occur within watch areas that were designated 2–3 h in advance. In the case of family outbreaks, 77% of deaths were found to occur in designated watch areas. Also there is some evidence that forecast skill has increased since the NSSFC has been in operation. Between the first and second decades of the 1952–72 period, the number of forecast tornadoes that produced fatalities increased from about 40% to 60%. Thus the false alarm rate has diminished noticeably.

In summary of these remarks on forecast improvement, it can be said that skill in weather prediction has improved substantially since about 1950. The improvement can be attributed largely, but not solely, to the advent of numerical prediction. Prior to 1950, only slight gains in forecast skill were made. However, with the expansion of facilities and services through the years, the value and usefulness of weather forecasts have risen even when the increase in skill has been small.

7. Future prospects

It was not my original intention to remark on the future prospects of weather prediction. However, in the course of preparing this lecture I was reminded that Bjerknes late in his career—at a time when most men of his accomplishment would have been content to rest on their laurels or to return to scenes of past triumphs—struck out in a bold new direction that could have an important impact on the future development of weather prediction. It thus seems only fitting that mention should be made of some of the main directions in which weather forecasting now appears to be headed and of the particular direction taken by Bjerknes in the concluding phase of his career.

In my view we have every reason to be optimistic that weather forecasting will continue to advance. To begin with, the full potentialities of numerical weather prediction are far from being realized. It is known from predictability studies, such as those conducted by Lorenz, that the limit of deterministic prediction of individual synoptic scale weather systems is on the order of about 2 weeks. The present predictive capability of about 5 days for current operational models thus falls well short of the theoretical limit. Well thought out programs exist for closing the "predictability gap." Foremost among these is the combined World Weather Watch (WWW) and Global Atmospheric Research Program (GARP) effort, which, under the auspices of the World Meteorological Organization (WMO) and the International Council of Scientific Unions (ICSU), unites the nations of the world in a common effort to improve the accuracy and range of weather forecasts. The program consists of two basic components, one devoted to the acquisition of a truly global observing capability, with heavy reliance on satellite technology, and a second to the development of an enhanced modeling capability through better treatment of physical processes and through improved numerical techniques and methods of data assimilation. Because of the difficulty and complexity of the forecast problem, it would be unwise to expect an immediate, sharp increase in predictive ability to result from this program. However, we can feel confident that it represents a sound strategy for achieving steady progress in weather prediction.

Notable advances have already been made on some aspects of the modeling problem. Among these are the promising results achieved from the use of fine-mesh models. At this stage the improvements are entirely computational since model physics and data density are not changed, only the size of the computational grid. In the future when methods can be found for measuring the pertinent atmospheric variables on a much finer scale, it will be possible, for instance, to apply fine-mesh models to the prediction of hurricanes and severe storms. How this development will come about is not obvious at this time. An as yet undreamed of technology may well be needed. But the history of the past hundred years teaches us that seemingly fanciful hopes are sometimes fulfilled.

Also as regards the severe storm problem, we should note that dual-Doppler radars are already opening up new possibilities for the very short range prediction of tornadoes. Recent research studies reveal that many tornadic events are connected with the existence of a mesoscale, parent vortex aloft that makes a characteristic radar signature well in advance of the appearance of the tornado itself, the latter also having a distinctive signature. Surely ways will be found to capitalize on this discovery.

Another area in which we can see grounds for new hope is in long-range prediction, on the time scale of months to seasons. This is an area in which progress has been painfully slow, though not entirely lacking. The hope for accelerated progress springs in large part from the work done by Jack Bjerknes in his later years on the subject of air-sea interaction and from similar work done concurrently by Jerome Namias. Bjerknes's interest in this subject was spurred by a visit of Rossby to UCLA in 1957 in which the latter sought Bjerknes's support in establishing a joint oceanographic-meteorological project at the Geophysical Institute in Bergen for studying the physical basis of climatic change. Because of Rossby's untimely death, the project failed to materialize, but fortunately Bjerknes's interest, once stimulated, never waned, and he proceeded to devote the remainder of his life to the description and understanding of large-scale air-sea interactions and their related atmospheric teleconnections.

Bjerknes's most important work on the subject related to the response of the Hadley circulation to equatorial anomalies of ocean temperature. In brief, he found that in certain years the weakening or temporary elimination

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[9] Personal communication.

of the equatorial easterlies in the eastern and central Pacific during the Southern Hemisphere summer caused a cessation of the normal equatorial upwelling and the creation of above normal sea surface temperatures. The extra heat thus provided to the atmosphere intensified the Hadley circulation, especially in the winter (or Northern) Hemisphere, leading to an enhanced poleward transport of westerly momentum at high levels and a corresponding strengthening of the surface westerlies in the central and eastern North Pacific. Downwind effects on the large-scale circulation were observed in the region of the Icelandic low and over Western Europe.

These findings have obvious implications for long-range predictions, as Bjerknes himself well recognized. Indeed his first paper on the subject of the response of the Hadley circulation to anomalous ocean temperatures concluded with the statement that "a close watch of the temperature anomalies arising over the eastern tropical Pacific is likely to play an important part in future seasonal forecasting of climatic anomalies, over North America and even over Europe."[10] As his studies progressed, he grew in the conviction that his findings were of importance to long-range prediction. One of his last papers ended on this prophetic note: "In a still farther future we can visualize the creation of a worldwide service of synoptic oceanography having as one of its most important duties to maintain monitoring buoys reporting by way of communication satellites such data which enter into the construction of transequatorial profiles at several selected geographical longitudes. That would usher in the era when attempts can be made to give electronic computers the right input for global dynamic long-range predictions of the fluctuations of the coupled circulations of atmosphere and oceans."[11]

I can think of no better way to conclude these thoughts on the future prospects of weather prediction than by sharing with you this vision of Bjerknes.

8. Conclusions

This lecture has been long and multifaceted, as perhaps befits a subject as rich and varied as weather forecasting. Indeed it has been possible to do little more than scratch the surface of the subject. Along the way I have tried to develop a few major themes that, in conclusion, I will recapitulate.

1) Viewed over the span of a hundred years or more, the advances in weather prediction have been truly awe inspiring. We have good reason to honor men, such as Jack Bjerknes, whose achievements have made these advances possible, and, as members of the meteorological profession, we can all take pride in their accomplishments.
2) The elements of progress have been threefold: technological innovation, observational knowledge, and theoretical understanding. All three of these elements must be cultivated if weather forecasting is to maintain its proud record of accomplishment.
3) Forecast skill has increased through the years, slowly during the early years when empirical methods were dominant and then more rapidly following the introduction of numerical weather prediction in the 1950s. Despite the ascendancy of the physical-numerical method, a variety of talents, methods, and approaches contribute to the most effective practice of weather prediction. Dynamical and statistical methods can be joined to produce a better product than either alone. Human judgment still must be exercised at many points in the forecast process. At the local level, the role of the forecaster remains supreme and is unlikely to diminish in the foreseeable future.
4) Finally, the future is bright for weather prediction. Numerical modeling is still in a healthy state of development. Large observational programs have provided and will provide unique data sets for perfecting and testing more advanced models. Coupled ocean-atmosphere models may open the door to more successful long-range or climatic prediction. The enormous potentialities of the meteorological satellite have only begun to be exploited. Doppler radar and other new tools such as acoustic sounders offer exciting prospects for an improved capability in the prediction of severe storms.

In 1918 the time was ripe for a young man of imagination to strike out in new directions and thereby revolutionize the theory and practice of meteorology. The opportunities are no less today. May the spirit of Jacob Bjerknes live on in the never ending quest for greater knowledge of the atmosphere and in the use of that knowledge for the betterment of the human condition.

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[10] Wurtele, 1975, p. 524.

[11] Wurtele, 1975, p. 549.

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