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FORECAST FOR ANOTHER CENTURY OF WEATHER PROGRESS

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ABSTRACT

The process of forecasting scientific advances in meteorology during the coming century entails many of the same considerations which one encounters in forecasting the weather. Accomplishments during the early '70s should to a considerable extent be the logical outcomes of studies already in progress, and may be predicted by simple extrapolation. Advances during the '80s and later decades will result more and more from ideas which today have yet to be conceived. Any reasonable forecast of progress during the 21st century will have to anticipate such non-meteorological factors as world cooperation or conflict.

It is 100 years almost to the day since a resolution authorizing the creation of a National Weather Service was passed by the Congress of the United States and signed by the President. It is quite appropriate that we should be gathered here now to commemorate this occasion. Yet that event of a February day in 1870 would be receiving no notice in 1970 were it not for what has taken place in the intervening years, and, to some extent, what happened beforehand.

The resolution appears to have passed without difficulty, but this would hardly have been the case without the devoted efforts of such persons as Cleveland Abbe. Attempts during earlier years to induce Congress to enact similar legislation had failed. It was only after Abbe had actually established and operated a storm-warning system at the Cincinnati Observatory, and after he and other dedicated men had engaged in various activities best described as lobbying, that a National Weather Service finally became a reality (see Abbe, 1916).

From its beginning as a storm-warning service, what soon became known as the Weather Bureau underwent the many administrative reorganizations which seem to characterize a successful enterprise. Simultaneously the scope of its services and activities continued to expand, and, some years later, among the pages of the *Scientific American*, we can find a brief article (Anonymous, 1907) entitled "The World's Greatest Weather Bureau."

Of course, the history of meteorology in the United States is not synonymous with the history of the several national weather services. Half a century after the inauguration of the storm warnings, we encounter the establishment of the American Meteorological Society. It is fitting that we should commemorate this event also.

Again, our occasion for celebration is not simply the event of a December day in 1919. It is also the untiring organizational efforts of such persons as Charles F. Brooks, and the great services which this continually growing Society has subsequently rendered to meteorology in particular and to the world in general.

My talk today, however, is not concerned directly with the many accomplishments of the past century, nor with the events of earlier centuries, but rather with the advances to be expected in the coming one. I shall consider past events only in the manner in which a weather forecaster would consider past weather in predicting the weather to follow. In short, I shall be presenting a forecast, but, rather than a weather forecast in the usual sense, it will be a forecast of the state of the art of weather forecasting, and, more generally, of scientific advances in meteorology.

The '70s are but six weeks old, yet so many predictions of what they will bring to mankind have already appeared that by making another prediction, even though it is concerned with but one specialized aspect of human activity, I may appear to be jumping on the bandwagon. I therefore welcome the opportunity to devote some speculation to the less heavily trodden territory of the '80s and subsequent decades. This will inevitably entail some non-meteorological considerations. I am quite familiar with the shortcomings of extended-range forecasting; nevertheless, I find it quite appropriate that *some* meteorologist, and preferably one who has some familiarity with weather forecasting, should devote some effort to predicting something other than the weather. I feel that this is so because the weather forecaster, more than most persons, should be familiar with the great variety of factors to be considered in making a forecast, and the

dire consequences of failing to give some factor due recognition.

Consider first the process of forecasting the weather at short range, say a day or two in advance. Ideally we should begin with a precise determination of the present state of the atmosphere. In practice we must be content with recent past states, since weather observations are ordinarily a few hours old by the time they are ready to be used. Moreover, the observations frequently contain inaccuracies, and, more important, there are extensive areas of the globe where observations are virtually absent.

We must now extrapolate our best attainable estimate of the state of the atmosphere into the future. Modern practice stipulates that we should base our extrapolation upon the governing physical laws. To put these laws to best use we should express them as mathematical equations, to be solved with a digital computer. Yet we were making creditable forecasts long before the era of the computer, as we still do when no computer is handy. This we do by examining the weather over the past few days, and then extrapolating forward by rules based upon years of experience with the weather rather than physical principles. To a considerable extent this means taking the presently existing individual weather systems, such as cyclones and anticyclones, and displacing them in the manner in which they have recently been moving, or in which systems in similar locations most frequently move, while also allowing them to grow or decay when appropriate indications are present.

Whoever would forecast the future of meteorology at short range, say five years in advance, will find his knowledge of the present no better than the weather forecaster's knowledge of present weather. The data are seldom up to date; scientific papers do not ordinarily appear in print until several months or a year after their results have been obtained, and the grapevine is not infallible. Moreover, some published results or conclusions are simply not correct, and the forecaster may not have had the opportunity to examine the more recent papers with a critical eye. Finally, he may be unfamiliar with the newer work outside of his own specialty, and, unfortunately, even within his specialty when the work has appeared in a foreign tongue.

We certainly have not formulated the physical principles which govern the evolution of the state of meteorological knowledge, much less any mathematical equations representing these principles. Our forecast must therefore be a forward extrapolation from the state of meteorology during the past several years, the rules for extrapolation being based upon a knowledge of history in general and meteorological history in particular. To a considerable extent the accomplish-

ments of the next few years may be predicted to be the outcomes of studies already in progress.

In forecasting the weather at somewhat longer range, say three or four days, and to some extent even at short range, we must anticipate the appearance of weather systems which have not yet formed. Recent experience indicates that forecasts by computer can indeed capture the development of new systems (Smagorinsky, 1969). Likewise, if we base our forecast upon experience rather than dynamics we can often recognize situations where new systems are likely to develop. In neither case, however, can we be certain that the new systems will be predicted to occur in the right place at the right time. If these systems truly form as a result of the instability of a preexisting state, as theoretical investigations tend to imply, the location of a new system cannot be predicted, either dynamically or empirically, if the perturbation giving rise to it is below the threshold of detection.

Likewise, in predicting scientific developments more than a few years ahead we must anticipate not only the solution of problems already under study, but the appearance of new problems which today are not recognized, or have aroused little interest. It seems evident that there is no sure-fire method of predicting what these problems will be, nor just when a burst of activity will occur. Twenty-five years ago, for example, a meteorologist might have foreseen a growing interest in the microphysics of clouds, but who would have guessed that the meteorological journals would contain articles devoted to the physical properties of silver iodide, or who, if offered this information by a clairvoyant, would have guessed why?

In forecasting the weather still farther in advance it becomes increasingly necessary to look beyond the atmosphere. The sea-surface temperature is the external quantity most frequently cited as affecting the course of the weather, but such factors as snow cover over the continents and ice in the oceans exert some influence, while irregular variations in solar activity play a poorly understood but perhaps important role. These factors of course affect the forecast even at short range, but are especially significant in predicting a week or more ahead.

Likewise, in predicting what is to happen even a few years ahead, but especially as the range is extended into the 21st century, non-meteorological considerations become increasingly important. Whether the world is at peace or at war, whether the people are well fed or starving, and whether the environment is a garden or a junkyard will determine to a considerable measure the nature and extent of meteorological progress. It seems difficult to justify any claim that one can predict these matters, although there has been no shortage of attempts to do so.

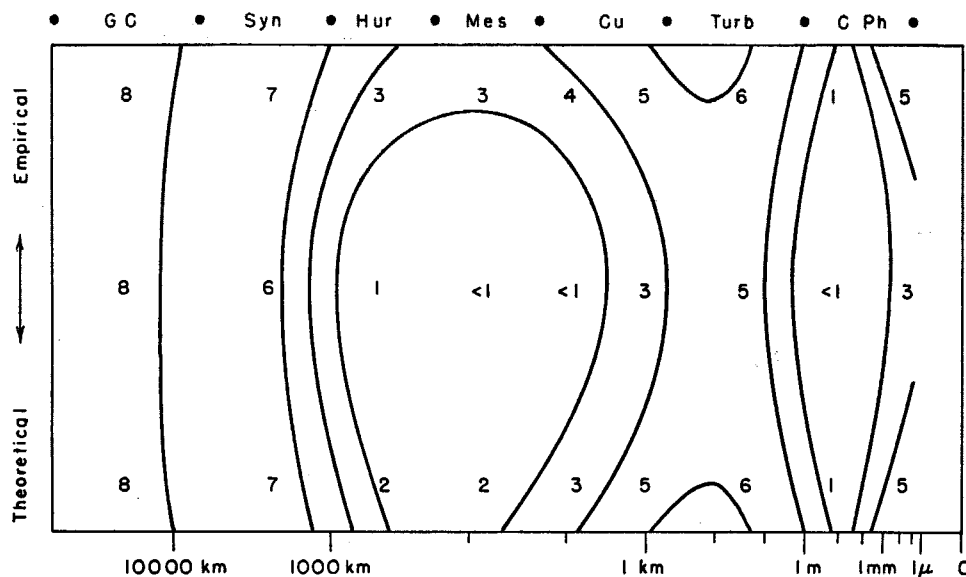


FIG. 1. Synoptic chart of the current state of meteorological knowledge. Horizontal coordinate indicates scale of phenomenon under investigation. Equal horizontal distances indicate equal increments of tenth-root of characteristic length. Intervals marked "GC," "Syn," etc., indicate approximate locations of general circulation, synoptic, hurricane, meso-, cumulus, turbulence, and cloud physics scales. Vertical coordinate indicates extent to which investigation is empirical or theoretical. Numbers are subjective estimates, in tenths, of ratio R of what we know to what we want to know. Curves are isopleths of R at intervals of 0.2.

At this point we should note a recent practice of the Weather Bureau, the issuing of probability forecasts. Since uniformly perfect prediction is unattainable, a probability forecast contains the maximum information which the forecaster can supply to the user. If the forecaster specifies a 70% probability of rain tomorrow, for example, he means, ideally, that among all weather situations which as nearly as he can determine are like the present one in each relevant feature, 70% will be followed on the next day by rain.

In this connection it should be added that the original storm warnings issued a hundred years ago under Abbe's guidance were officially called "probabilities." Percentages were not stated, but the uncertainty was implicitly recognized. A few years later the term "indications" was substituted, but not until 1889 did the term "forecasts" receive official sanction.

Unfortunately, a segment of the public tends to look upon probability forecasting as a means of escape for the forecaster. After all, if he has admitted some possibility of rain and of no rain, he is not unequivocally wrong in either event. What the critics of probability forecasting fail to recognize or else are reluctant to acknowledge is that a forecaster is paid not for exhibiting his skill but for providing information to the public, and that a probability forecast conveys more information, as opposed to guesswork, than a simple forecast of rain or no rain. Further misunderstanding is illustrated by an occurrence of the past summer, when a farmer found that he would soon need to protect a crop from dryness. When the

forecast specified an 80% probability of rain, he breathed easily and took no action. When the rain failed to develop and the crop was damaged, he indignantly phoned the Weather Bureau and informed them that they should know enough never to announce an 80% probability of rain unless it was sure to rain.

Similarly, in predicting the future of meteorology, particularly in the 21st century, a probability forecast would undoubtedly convey the most information. However, if I should choose this course, it would certainly be as a means of escape. It is hardly likely that anyone will use the information conveyed in this talk as a basis for future decisions.

I shall therefore present the more conventional type of forecast. In line with standard meteorological practice, I shall accompany the forecast with a "map discussion"—a description and evaluation of the present situation, together with the reasons for the expected developments. Since I anticipate many more advances than can readily be enumerated in this account, I shall concentrate upon my own particular interest, the dynamics of the lower atmosphere.

Again in line with standard procedure, my map discussion begins with the current synoptic chart (Fig. 1). In this chart, different locations represent different types of meteorological investigation. The horizontal coordinate indicates the scale of the phenomenon being investigated. At the extreme left is the general circulation, followed by phenomena on the scales of extratropical cyclones, tropical hurricanes, meso-systems, cumulus, turbulence, and finally, at the extreme

right, the microphysics of clouds. The vertical coordinate denotes the extent to which the investigation is empirical or theoretical. At the top are pure data collections and studies consisting mainly of data processing. At the bottom are studies based upon pure physical reasoning or manipulation of mathematical equations. In between come models, with laboratory models displaced in the empirical direction, and numerical models displaced in the theoretical direction.

The quantity R whose isopleths appear on the chart may be described as the ratio of what we know to what we want to know. Highly subjective estimates of R have been made for each type of investigation. These estimates are plotted on the chart, in tenths, and isopleths are constructed at intervals of 0.2.

At the extreme left we observe a region of rather high values, reflecting our reasonably good understanding of the systems of largest scale. This region is bounded on the right by a narrow zone of steep gradient—in effect, a quasi-stationary front, which hopefully will soon advance. By and large this zone marks a transition between systems whose behavior conforms fairly well to the dynamics of dry air, and systems where moisture plays an essential role. Still farther to the right we encounter somewhat higher values of R as we reach the scale of the simpler convective systems and ordinary turbulence. The very low values assigned to the large cloud physics scales represent our meager knowledge of the interaction between cloud physical processes and the turbulent motion within clouds (Mason, 1969), while the microphysical processes by themselves are somewhat better understood.

In general, our observational knowledge of a given scale is somewhat ahead of pure theory. Except for the largest scales, where numerical simulation and laboratory models have reached an advanced state, both observation and theory hold a lead over modeling.

Turning now to the details, we note that the qualitative theory of the general circulation is in fairly good order, at least for an ideal dry atmosphere. We can account for the conversion of the internal energy supplied by external heating into the kinetic energy of large-scale motions. What we have not satisfactorily identified is the reason why troughs and ridges tend to tilt toward the east with increasing latitude, thereby transferring angular momentum poleward and maintaining strong trade winds and prevailing westerlies. The problem is receiving considerable attention, and I anticipate that it will be solved by the middle '70s. Furthermore, I expect the answer to be relatively simple.

The quantitative theory will be aided by new types of observation. One of the most spectacular achievements of the past year is the measurement of tempera-

tures by infrared sensing from satellites. Although the present system is called experimental, it has already yielded upper-level temperature charts which, for the globe as a whole, are better than any obtained from conventional measurements. An operational version with higher spatial resolution may be anticipated for the early '70s. The satellite will also measure sea-surface temperatures wherever the sky is reasonably clear. Sea temperature supposedly varies rather slowly, and where the sky is cloudy the observation on the most recent clear day should serve fairly well, but I anticipate that we shall also discover the existence of shorter-period fluctuations of sea temperature of an intensity not previously suspected.

A comparable achievement is the higher-resolution photography of clouds from satellites. This will continue with increased coverage, and will be especially valuable in conjunction with the temperature measurements. Polar-orbiting satellites will monitor continental snow cover and oceanic ice. From the new data we shall obtain more reliable estimates of the global balance of heat and water. We shall begin to study the balance of liquid water, a feature which has yet to receive much attention. Through these studies we shall by the late '70s achieve a much clearer picture of the part played by water in the general circulation, and we shall better appreciate the role of the tropics, where the influence of water is greatest.

The theory of the fluctuations of the general circulation, as opposed to the average general circulation, is still in its infancy. We do not even know whether the year-to-year variations are mainly systematic or mainly random. Progress will be assured by continuing advances in the speed and capacity of computers, as typified by the anticipated "Illiac IV," scheduled for operation during the current year. Accompanying refinements in numerical simulation of the general circulation will include greater horizontal resolution. We shall, furthermore, allow the simulated atmosphere to produce its own clouds, which in turn will alter the incoming and outgoing radiation. Sea-surface temperature will enter as a dependent variable. However, some of our numerical experiments will return to coarser resolution, and use the time thus gained to extend the solutions over many years. From these experiments, and from the sea-surface temperature fields obtained from satellites, we shall by the late '70s acquire a reasonable understanding of the connection between sea-temperature and atmospheric-motion patterns, and by the early '80s the year-to-year fluctuations of the general circulation will be moderately well understood. By the middle '80s, with ever more powerful computers, we shall numerically produce an ice age.

A step down the scale, extratropical cyclones and anticyclones still present a problem as to their origin.

The immediate energy source seems to be the general circulation rather than external heating, and baroclinic instability provides a mechanism for producing cyclones from an essentially zonal flow. But new cyclones do not wait for the flow to become zonal before developing. Does baroclinic instability of an irregular flow provide the mechanism?

The '60s saw many excellent studies of baroclinic instability, but the interconnections between these studies were not always apparent. I expect during the '70s a more unified theory of baroclinic and other types of stability of uniform flows, and important results concerning the instability of flows which are neither parallel nor steady-state. The cause of extra-tropical-cyclone formation will then become firmly established.

For studying the subsequent behavior of representative cyclones, temperature measurements from satellites will play only a minor role, since we can pick our cyclones in regions where conventional observations are plentiful. Cloud photographs, however, have already revealed associated cloud structures which formerly had not generally been recognized. With the aid of tomorrow's computers we shall be able to simulate the coarser features of these cloud structures, and assess their significance for cyclones as a whole, but only after we have included the effect of the clouds upon radiation.

At a somewhat smaller scale, tropical cyclones still present some mysteries. We do not understand their formation or maintenance, and we shall not until we acquire a better understanding of the dynamics and energetics of moist air in general. I anticipate that this basic knowledge will be forthcoming by the middle '70s.

Sequences of satellite cloud photographs will aid in establishing typical histories of hurricanes prior to maturity. Continuing aircraft and radar observations will yield improved pictures of detailed hurricane structures. Deeper understanding will come only after further numerical simulation, with high horizontal resolution and a realistic treatment of water substance. By the later '70s simulations of the large-scale tropical circulation will reproduce the development and motion of systems which are unmistakably hurricanes. By the end of the '70s hurricanes will be forming regularly in general-circulation experiments, and during the '80s we shall learn what factors cause one year to produce many hurricanes while another produces relatively few.

The mesoscale systems of chief interest are decidedly moist. Are they simply aggregates of smaller systems, or do the separate portions interact with one another? Do fronts form long lines merely because two large air masses cannot very well meet one another

in anything but a long line, or does the activity at one part of a front help to reinforce some other part?

It is not clear that observations alone can answer these questions. Realistic numerical models can supply the answers, and these may be anticipated during the early '80s.

As we reach the cumulus scale the status of current theory begins to improve. It is mainly the details that are less well understood. A cumulus cloud is more readily observed than a hurricane with some of our newer instruments; there are so many cumulus clouds that we can wait for one to come, instead of transporting the instruments to the clouds. Detailed line-of-sight motions within cumulus clouds have been successfully observed by Doppler radar; a system of three Doppler radars (see Lhermitte, 1968) can yield complete wind fields. I anticipate further developments along these lines during the early '70s, resulting in recorded histories of fields of motion within each of a sizable collection of cumulus clouds. These observations will tell us whether we have been missing any significant aspect of cumulus behavior. Computers available in the later '70s will allow for simulation of cumulus motion with moderate resolution, and the role played by such processes as entrainment and radiation can be more readily evaluated. A cumulonimbus is vastly more complicated than a cumulus, and successful numerical simulation is unlikely before the middle '80s.

Boundary layer turbulence and certainly clear air turbulence are essentially dry phenomena. Because of their three-dimensional nature, an enormous amount of computation is required to simulate them numerically, but, with the advent of larger computers, moderately realistic simulations over limited volumes of the atmosphere will become feasible by the middle '70s. This will lead by the late '70s to the establishment of more realistic methods for parameterizing turbulent effects in the simulation of larger-scale motions. By the late '70s fairly realistic three-dimensional simulations of moist turbulence will become feasible, and new results concerning the interconnections between cloud-physical processes and turbulent motions within clouds will be forthcoming.

The phenomena which I have mentioned cover but a fraction of meteorology. I have, for example, omitted all of the high atmosphere of the earth, let alone the atmospheres of other planets, where theory and observation are rapidly developing and progress seems inevitable. In fact, my topics are all closely related to the problem of weather forecasting.

To some meteorologists forecasting is not a part of the science at all; it is simply an application. Let me therefore turn to the problem of predictability, the question of the degree to which the present and

past states of the atmosphere and its surroundings actually determine the future. The theory is moderately well developed (Lorenz, 1969).

First of all, the basic limiting factor is the rate at which two separate hypothetical states of the atmosphere, each evolving according to the same physical laws, will diverge from one another. It is now reasonably well established that either immediately, or within a day or so, the difference between two states will proceed to double in magnitude about once every three days, until it becomes rather large. If the two states are taken to be the true and the predicted states, the growth and eventual domination of the error in prediction becomes apparent.

What is not obvious is any absolute minimum size for the error at the beginning. It now appears that inevitable errors in observing the minute scales of motions will rapidly induce errors in the cumulus scale and thence the mesoscale, until after a day or two the error in the cyclone scale, although not large, will attain an order of one degree in the temperature field. An absolute range of predictability is thereby established.

What remains to be done is to verify the latter hypothesis, using as realistic a numerical formulation as possible. This should be accomplished in the middle '70s. I furthermore forecast that the maximum range at which the location of a migratory storm is predictable will be determined to be considerably less than a month. Stated otherwise, if a probability forecast of the longitude of a storm a month ahead is issued, all longitudes will be about equally probable.

Returning to weather forecasting, I predict that by the early '80s the problem of forecasting one or two days ahead will be solved. By this I do not mean that the forecasts will be nearly perfect; they will simply be as good as they can be, in view of the limitations which will have been established.

The problem of forecasting at a range of a few hours will require a few more years to solve, not because the forecaster is less aware of what will happen at very short range, but because more will be and should be expected of him. Probability forecasts at ranges of two weeks or more, obtained by making several different computer forecasts from slightly differing initial states, will become feasible in the early '80s, but these will prove only slightly superior to forecasts which can be made today by simple statistical procedures.

The '60s were the decade when thoughts of weather modification, other than simple cloud seeding, passed from the bizarre to the respectable. Weather modification, like forecasting, may be only an application of science, but I anticipate by the middle '70s a develop-

ing interest in weather modifiability, the study of the extent to which weather may be modified. A companion subject will be weather controllability, the study of the extent to which weather may be modified in a pre-chosen fashion.

It is fairly well established that individual cumulus clouds are modifiable. I expect that by the late '70s we shall show that they are moderately controllable through judicious distribution of a seeding agent, although the engineering problem of distributing the agent will require some time for solution. By the late '80s we shall demonstrate that tornadoes may be rendered less violent. Although the recent attempt to modify Hurricane Debbie, while encouraging, is far from conclusive, I anticipate that by the end of the '70s we shall demonstrate by realistic numerical simulation that slight decreases in the intensities of hurricanes may be achieved. Extratropical cyclones and anticyclones will prove to be modifiable but not appreciably controllable, while the mean state of the general circulation will prove to be partially controllable if massive tampering with the environment is admitted.

No carefully prepared forecast of meteorological progress can afford to ignore certain non-meteorological factors. I do not maintain that these factors are predictable, but, if they are not, this does not lessen their importance; it simply lessens the predictability of meteorological progress.

Prominent among these considerations is the extent to which we receive financial support from our government. This is especially significant for the short-range forecast. There are numerous indications that the support for science as a whole will be low during the next few years, although meteorology in particular will likely fare considerably better. Inexpensive and expensive projects seem to suffer together from budgetary cuts, and the result will be a general retardation of scientific progress.

For a longer range forecast this factor seems less significant. The present reduction in scientific support does not mean that support will remain low for a generation, any more than the increased support a decade or so ago proved that it would remain high for a generation. The degree of support may be expected to undergo continual oscillations; the timing of these oscillations does not appear to be predictable.

In this connection it should be added that while our country should continue to be a leader in meteorology during the '70s, it would be rather egotistical to assume that this will always be so. For the long-range forecast, support by all governments, and also by non-governmental organizations in many nations, may be as important a consideration as support by our government alone.

A factor influencing and influenced by governmental support, but by no means completely controlling it nor controlled by it, is the general public attitude toward science. The immediate tendency seems to be away from science in general, although again meteorology in particular may fare somewhat better. A capable scientist will not abandon his field simply because it is losing prestige, but the production of new scientists will suffer. In an age when the wrongs of the world are becoming more widely acknowledged, it is natural for young students to choose fields which appear to be more closely associated with the problems of society; this is all to the good. It is discouraging, however, that many of these students cannot see the sciences among these fields. For the '80s I anticipate a moderate drop in the number of scientists at the peak of their creative careers. The trend will be partly reversed as young people come to recognize that the solution to many of the problems which concern them may ultimately be found through careful scientific research.

One of these problems is the manner in which our environment is presently being treated by those who do not know, or, when they have been informed, do not care. Everybody talks about pollution today, but meteorologists have a special contribution to make. By the middle '80s the same techniques which will have produced an ice age on a computer should, with a few modifications, reveal the long-term climatic effects of loading the atmosphere with carbon dioxide, dirt, and such ostensibly harmless substances as water. Minor modifications of potentially dangerous operations may be shown capable of rendering them relatively harmless.

An even bigger problem is the equally talked-about population problem. One cannot, incidentally, anticipate the course of the pollution problem independently of the population problem, for with the type of living which many of today's citizens have come to expect, and tomorrow's will not willingly forego, more people will inevitably mean more of the activities which, as presently practiced, will poison and uglify the environment, whether they be conducted by individuals, industries or bureaucracies. I have nothing to contribute to the solution of the population problem, and will simply note that any forecast which misjudges the size or age distribution of future populations will inevitably misjudge the extent and direction of future scientific progress.

For the 21st century, and perhaps for the close of the 20th, the giant question may be not whether there will be too many people but whether there will be any at all. This is by no means a crank question. There have been many serious published discussions, and

I shall simply take note of a recent article in *Science* (Platt, 1969), estimating the half-life of the human race at 20 years or less.

Nuclear and biological war are the most frequently mentioned villains. I do not feel that it has been very well demonstrated that these would wipe out the last member of the human race. The state of science would be completely altered, but this would cease to be a very important consideration.

Personally I do not look upon such disasters as inevitable, or even nearly so. They are simply possibilities which cannot be ignored in any serious extrapolation into the future. Perhaps, then, it is permissible for me to close this talk on a happier note, since, after all, we are supposed to be celebrating a happy occasion. To the best of my knowledge every forecast of the state of meteorology today, made prior to World War II, has been more or less a failure, and the one dominating reason for this failure is failure to forecast the invention and development of the computer. It is doubtful that any other innovation during the past century has had a similar impact upon our field, although the radio is a close competitor, and the airplane deserves consideration. The satellite may be discounted, since satellite operations as we know them would be impossible without computers. The automobile has had a far greater effect upon man, at least in our country, but not upon meteorology.

I forecast that there will be at least one new invention during the coming century whose impact upon meteorology will be comparable to that of the computer. What this development will be I do not know; if I did, I should make every effort to become the inventor, or, lacking that ability, to become a stockholder. Beyond the day of this invention I can no longer predict where meteorology will go, except to say that progress in some direction will be abundant.

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