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THE FEASIBILITY
OF A
GLOBAL OBSERVATION
AND ANALYSIS
EXPERIMENT

THE FEASIBILITY OF A GLOBAL OBSERVATION AND ANALYSIS EXPERIMENT

A Report of the

PANEL ON INTERNATIONAL METEOROLOGICAL COOPERATION

to the

COMMITTEE ON ATMOSPHERIC SCIENCES

NATIONAL ACADEMY OF SCIENCES

NATIONAL RESEARCH COUNCIL

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March 31, 1966

Dear Dr. Seitz:

It is my pleasure to transmit to you the report of the Panel on International Meteorological Cooperation. The report has been reviewed and approved unanimously by the parent Committee on Atmospheric Sciences.

The Panel was established by the Committee two years ago to prepare a specific response from the United States scientific community to Resolution 1802 of the United Nations, which invited the International Council of Scientific Unions through its constituent unions and member academies "to develop an extended programme of atmospheric science research which will complement the programmes fostered by the World Meteorological Organization."

Particular attention is focused in this report on the scientific and technological components of an international cooperative effort to obtain a physical definition of the large-scale motions of the entire lower atmosphere. The implications of this effort with respect to improved weather forecasts and the exploration of climatic change are of great interest to many sections of the scientific community.

The preparation of the present report has benefited materially from extensive discussions with our colleagues in other countries, and from a detailed review of many of its ideas in connection with the White House Conference on International Cooperation held in late November 1965. I am particularly pleased to report the deep interest in this program by scientists in other parts of the world and the warm endorsement given by the participants in the White House conference.

We urge that this report be transmitted to the unions and adhering bodies of the International Council of Scientific Unions as our contribution to the development of an important and exciting international program.

Sincerely yours,

Thomas F. Malone

Thomas F. Malone, Chairman
Committee on Atmospheric Sciences

Dr. Frederick Seitz
National Academy of Sciences
Washington, D. C.

Committee on Atmospheric Sciences

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*Deceased December 2, 1965

FOREWORD

The development of new data-processing and space technologies has created unprecedented opportunities for advances in meteorological theory and practice. These developments have been noted at the highest levels of government and have led to recommendations for international cooperation in atmospheric research and weather forecasting. A fundamental requirement for both endeavors is a considerable expansion in data coverage. In November 1963, the Committee on Atmospheric Sciences of the National Academy of Sciences appointed the Panel on International Meteorological Cooperation to study the desirability and feasibility of conducting a global observational experiment to measure the state and motion of the entire lower atmosphere for a limited period of time.

The study logically fell into two parts: first, the evaluation of the scientific needs for observations on a global scale, and second, the determination of the technical feasibility of possible observational systems. In addition, since global observations of large-scale motions define the physical system only when the small-scale turbulent eddy transports of heat, momentum, and moisture are related to the properties of the large-scale flow, a series of regional observational experiments was studied as a source of data from which the necessary relationships could be inferred.

Many of the questions involved had already been discussed in various governmental reports, in reports of the World Meteorological Organization, and in a report issued by the *ad hoc* Committee on International Programs in Atmospheric Sciences and Hydrology, of the Academy's Geophysics Research Board, and under the chairmanship of S. Petterssen. In the preparation of the latter report, the subpanel on Atmospheric Transfer Processes, Structures, Circulations, Weather Prediction and Modification, under the chairmanship of R. M. White, had explored some of the scientific questions in considerable detail. The present report relies heavily on its conclusions. It has also made use of a position paper prepared by J. G. Charney for the Committee on Atmospheric Sciences. This paper was discussed by a group of scientists at a meeting at the National Academy of Sciences on April 29, 1962.

The first part of this study was conducted through informal discussion between the chairman of the panel and a group of consultants, and was supplemented by a series of computations bearing on the problems of predictability and data requirements. These were carried out at the following institutions: the Livermore Laboratories of the University of California, the University of California at Los Angeles, the Geophysical Fluid Dynamics Laboratory of the U.S. Weather Bureau in Washington, D.C., the National Center for Atmospheric Research in Boulder, Colorado, and the Goddard Institute for Space Studies of the National Aeronautics and Space Administration (NASA) in New York City. A study of turbulent-flux research was conducted by a working group under the chairmanship of R. G. Fleagle of the University of Washington, and a special study of the scientific requirements for observations in the tropics was made by H. Riehl of Colorado State University in collaboration with N. E. LaSeur of Florida State University.

It was obvious from the beginning that a global extension of the existing observational network by conventional means was not feasible. Although attractive possibilities exist for an extension of the network to presently unobserved oceanic regions by aerological soundings taken from commercial ships and from additional island stations, a full global coverage by this means did not appear economically feasible. It was likewise apparent that while remote radiometric measurements taken from a satellite could yield valuable information on the thermal structure of the atmosphere above cloud tops, and possibly also within clouds, they could not yield all the relevant dynamic parameters. The system that seemed to offer the greatest promise was one consisting of satellites collecting and transmitting data gathered by constant-volume balloons and fixed or floating buoys, as well as making radiometric measurements in the infrared, and possibly also the microwave regions of the electromagnetic spectrum. It was accordingly decided to confine the technical feasibility study to the investigation of this system. Establishment of the feasibility of a single system provides a concrete standard against which to compare others. In doing so we do not imply that this is the only possible system, or that some combination of several systems may not ultimately prove to be optimal.

The study of the feasibility of a satellite–balloon–buoy–radiometric system was undertaken by a number of working groups. A fully integrated balloon–satellite system was investigated by a group under the chairmanship of V. E. Lally of the National Center for Atmospheric Research. A satellite system for the location and interrogation of fixed and moving stations has been designed by the Goddard Space Flight Center of the National Aeronautics and Space Administration. Another such system, which was planned specifically for use with balloons, has been designed by the French National Center of Space Studies. While the latter two system designs are not integral parts of the present study, they do demonstrate the feasibility of the satellite as a data-collection and location instrument. Discussions were held with M. Tepper and L. Fong of NASA headquarters, J. W. Townsend, E. A. Neil, and G. D. Hogan of the Goddard Space Flight Center, and V. E. Suomi of the U.S. Weather Bureau to compare design concepts and to reconcile divergences in points of view. Similar discussions were held with J. E. Blamont and P. Morel of the French Center of Space Studies.

The study of ocean-surface observations was conducted by the aforementioned working group of R. G. Fleagle, and the study of satellite radiometry was conducted by D. Q. Wark of the U.S. Weather Bureau in consultation with a number of advisers in the fields of infrared and microwave spectroscopy. In addition, special studies of the problem of balloon dispersal were carried out by J. K. Angell of the U.S. Weather Bureau, F. Mesinger of the National Center for Atmospheric Research, and Y. Mintz of the University of California at Los Angeles. A list of all the contributors to the present study is given at the end of this report.

The report does not aim at completeness. Many important problems are not considered. For example, we do not consider the optimal number of polar-orbiting satellites, or what combination of polar-orbiting, equatorial, and possibly synchronous, satellites to use; nor do we go into the question of the starting time or duration of the global observation experiment, or the possibility of its location, as a first step, in tropical regions or primarily in a single hemisphere. Some of these latter questions involve political and economic as well as technological and scientific considerations and were deemed to be beyond the immediate scope of the Panel. It is hoped merely that the report will be accepted as a beginning in a series of evaluations that will lead eventually to an international cooperative effort to obtain a physical definition of the large-scale motions of the entire lower atmosphere. We invite comments and criticisms from interested scientists and technologists in all countries.

We gratefully acknowledge the support of this study by the Atmospheric Sciences Section, National Science Foundation, and the U.S. Weather Bureau, under the Task Order No. 9 of NSF-C310. Our special thanks are given to J. E. Blamont, Centre National d'Etudes Spatiales de France, for permitting the use of his description of the French EOLE experiment, and we are much indebted to the National Center for Atmospheric Research, the U.S. Weather Bureau, the National Aeronautics and Space Administration, and the University of California for providing computer time and programming assistance in performing the series of predictability calculations.

JULE G. CHARNEY
Chairman
PANEL ON INTERNATIONAL METEOROLOGICAL COOPERATION

October 1965

CONTENTS

I. SCIENTIFIC CONSIDERATIONS

1. Global Observations

II. TECHNICAL CONSIDERATIONS

3. Introductory Remarks

4. The Global Horizontal-Sounding Technique

APPENDIXES

PRINCIPAL CONCLUSIONS AND RECOMMENDATIONS

The principal conclusions and recommendations that have emerged from our study may be summarized as follows:

1. A major international research and development program directed toward an experiment to measure the large-scale motions of the entire lower atmosphere for a limited period of time is fully justified by scientific potential and technological capabilities.

2. A preliminary design study indicates that a system utilizing satellite tracking and interrogation of large numbers of constant-volume instrumented balloons and buoys is feasible for this purpose. It is strongly recommended that such a system be developed, and that efforts be made to reduce balloon weight and cost as far as possible. Efforts should also be made to ensure that the balloons will constitute no hazard to aircraft. This system should be supplemented by the use of satellite radiometric observations and conventional radiosonde observations in order to ensure satisfactory data coverage throughout the atmosphere.

3. The principal objective to be achieved by the global observation experiment is the definition of the entire atmosphere as a single physical entity. The integrity of this concept should not be lost through

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Scientific Considerations

CHAPTER ONE

GLOBAL OBSERVATIONS

The Problem: Large-Scale Atmospheric Motions

IMBALANCE BETWEEN THEORY AND OBSERVATION

The second World War marked a turning point in the science of meteorology. Throughout most of the preceding century meteorological observations had been gathered primarily to serve the needs of the weather forecaster rather than the scientist. It was only with the aid of indirect inferences from surface observations, and a very few upper-air observations, that a few gifted individuals had succeeded in identifying the principal features of the atmosphere and in establishing a rudimentary theory of its three-dimensional motion. However, this theory was too idealized to have any predictive power and therefore could not serve as a guide to the selection of observations. Beginning with the war, the extension of the upper-air network and the development of the high-speed electronic computer brought about a qualitative change in the relationship between theory and observation. Improved knowledge of the actual condition of the atmosphere led to the construction of more realistic physical models, and numerical integrations of the governing equations permitted direct comparisons with reality. As a result, the predictive functions of the weather services began increasingly to be taken over by the computer, and the physico-mathematical requirements for prediction began increasingly to influence the selection of observations. Meteorology had at last become a mature science, a science in which theory and observation exist on an equal footing.

We are now faced with an imbalance in the opposite direction. Advances in data-processing technology and physical understanding have so extended the scope and complexity of the numerical models that can be treated that it is becoming possible to deal with the circulation of the atmosphere as a whole and to attack directly the problem of long-range prediction. But such investigations are in danger of becoming mere academic exercises, due to the lack of observations to supply the initial conditions and to check the calculations.

NEED FOR GLOBAL OBSERVATIONS

The large-scale elements of the atmospheric circulation are so strongly coupled in space and time that they can be understood only in combination. Hence, if appreciable advances are to be made in our understanding of the general circulation and our ability to predict, the atmosphere must be measured on a global scale. If expense and manpower were no consideration, one would surely advocate the immediate extension of the present upper-air observing network to the entire globe. But to do so by conventional means would involve a prohibitive increase in costs, since the needed observations are mainly in oceanic regions that are accessible only to ships and aircraft, and these are very expensive observing platforms. Such costs are not likely to be borne by any country or combination of countries until it becomes evident that they would be offset by the economic benefits to be derived from an extension of forecast range and accuracy. One is thus involved in a dilemma: until global or hemispheric data for scientific studies and numerical prediction experimentation become available, no significant gains can be made in our understanding of the global circulation and in extended-range forecasting, and until such gains are made we are not likely to be supplied with the additional observations.

THE SATELLITE–BALLOON–BUOY–RADIOMETRIC SYSTEM

The saving factor is that a new dimension in observational capacity was added in 1957 by the advent of the earth-orbiting satellite, capable in principle of probing the entire atmosphere in a single half-rotation of the earth. One may hope that eventually remote measurements from satellites over the entire electromagnetic spectrum of radiation emited, scattered, or refracted by the atmosphere will permit the determination of the three-dimensional structure and motion of the atmosphere. For the present, however, it appears that the primary function of the meteorological satellite should be data collection. The satellite is ideally suited to track and receive information from immediate sensors located throughout the atmosphere. We have therefore studied a system consisting of satellites interrogating and transmitting information from sensors on balloons and oceanic buoys, as well as making remote radiometric measurements, and have come to the conclusion that such a system is scientifically and economically feasible. An experimental observational program carried out with this system for a limited period of time would supply the additional data needed for extending our knowledge of the circulation of the atmosphere and would lay the observational groundwork for extending the range and accuracy of weather prediction. The analysis of the data and their experimental use in mathematical forecasting models would then permit rational decisions concerning the rate of development of a fully operational system. Additionally, the data would lay the scientific basis for a rational approach to the problems of weather and climate modification on large scales.

DEFINITION OF THE ATMOSPHERE

HYPOTHESIS OF DETERMINACY

The atmosphere is a complex turbulent fluid containing eddies of many scales. The scientific problems which give rise to the need for a global observation system of the kind here contemplated are based on the hypothesis that the atmosphere is a determinate or near-determinate system on some macro-scale. Evidence for this hypothesis is given by observations in regions with dense observational networks and by serial observations at fixed stations. These show that the kinetic energy in the atmosphere is divided into two broad classes: one consisting of synoptic and planetary disturbances with characteristic spacial dimensions of the order of 1,000 km or more, and the other consisting of mechanically and convectively driven turbulence with characteristic dimensions in the range meters to kilometers. The corresponding characteristic times are, respectively, in the ranges days to months and seconds to minutes. With the exception of the thermal and gravitational tides, whose relative energies are small, there is a large gap in the spectra separating these two classes. Because of this separation in scale, it is plausible that the turbulent fluxes of momentum, heat, and water vapor are determined by the macro-scale flow and that the macro-observations will define the system as a whole.

Although this hypothesis underlies most of modern dynamic meteorology, no definitive observational studies have been carried out to determine its limits. The observed regularity of atmospheric motions is usually considered to be evidence enough that it has at least approximate validity. An essential part of a global observation program must be to design regional experiments over various types of terrain and sea conditions to determine the degree to which precise statistical relationships may be established between the turbulent fluxes and the relevant parameters of the large-scale flow.

Two qualifications must be made: the large-scale systems often contain narrow zones of strong wind and temperature gradient (fronts and jets) that may contain appreciable energy in intermediate space and time scales; an observational system designed for the large-scale motions will not define their structure explicitly. However, these zones may be thought of as internal boundary layers that form quickly and of necessity from the macro-motions, and are therefore determined implicitly by the macro-observations.

The atmosphere, and particularly the tropical atmosphere, also contains some meso-scale motions, most commonly associated with zones of cumulus convection. Because of a lack of observations the relationship between these motions and the macro-motions is not well understood. Since the release of latent heat energy in these meso-scale systems plays an important part in driving the circulation of the entire atmosphere, it is necessary that they be better understood. A regional observational program in the tropics to determine the interaction of the micro- and meso-scale systems with the large-scale motions is an essential part of a global observation program and should be given high priority.

CONCEPT OF THE ATMOSPHERE AS A SINGLE PHYSICAL SYSTEM

A second fundamental concept that underlies the need for a global observation system is that the macro-scale circulations of the atmosphere constitute a single, self-contained physical system with all its parts in mutual interaction.* In a period of a week or two a tropospheric influence can circumnavigate the globe. The evolution of the large-scale atmospheric motions for periods of this order or longer is therefore a global problem. It follows *a fortiori* that the problems of long-range weather prediction and the problems of climate and large-scale weather and climate modification are intrinsically global. Indeed, for periods of time that are longer than the periods of the large-scale forced oceanic circulations, the atmosphere and the oceans must be treated as a single dynamical system. Over shorter periods it is possible to regard the state of the oceans as known, except in their uppermost wind-stirred layers. A proper definition of the atmospheric system must therefore include at the very least: (a) a knowledge of the internal structure of the atmosphere from its lower boundary up to a level at which the mechanical, thermal, and material transports are small and above which there is small interference with solar radiation (10 mb is probably sufficiently high); (b) a knowledge of the mechanical and thermal boundary conditions at the air–ground or air–sea interface (including the state of the ground, the sea surface, and the wind-stirred layer in the sea); and (c) a knowledge of the radiative energy flux at or above the upper boundary.

It cannot be too strongly emphasized that a failure to preserve the concept that the atmosphere must be treated as a single system would greatly vitiate the benefits from substantial enlargement of the observational network. Anything short of complete coverage would leave the system physically undetermined and make long-range prediction impossible.

OBSERVATIONAL REQUIREMENTS

The optimal resolving power for the macro-scale observation system is not precisely known. Most estimates, based on synoptic evidence

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* Because of the strong nonlinear interaction between actual atmospheric systems, it is strictly not possible to isolate their separate effects; only their collective behavior can be observed. Although an isolation is often made for theoretical purposes by greatly idealizing the nature of the interactions—for example, by invoking periodicity and small amplitude approximations, by ignoring distant interactions, or by simplifying the geometry in physical or in Fourier space—the resultant analogues are not valid in describing the general circulation in all its spacial and temporal variability.

and numerical forecasting experience, place the optimal separation between observations at a few hundred kilometers in space and about 12 hr in time. Systems with much lower resolution will fail to define the macro-motions, while those with much greater resolution will be redundant because the turbulent micro-phenomena must in any case be treated parametrically. The observational system need not be homogeneous; it may be possible to trade time resolution for space resolution, or vice versa. For example, a system of continuously tracked constant-volume balloons at an average distance of 1,000 km might possibly give as good a resolution as a series of fixed stations at an average distance of 500 km observing every 12 hr. A final judgment cannot be made until the exact nature of the observational system is known.* The system that we envisage in the present study is, however, sufficiently flexible to give a wide range of resolution. Its properties will be described in later sections.

With regard to the types of measurement that should be made, the important quantities are the dynamical variables, pressure, temperature, wind, and moisture in all its phases. It would be desirable, but perhaps not essential, to measure ozone in the upper troposphere and lower stratosphere.

IMPORT OF GLOBAL OBSERVATIONS FOR SCIENCE

UNDERSTANDING CIRCULATION SYSTEMS

Truly global data gathered for even a limited period of time would constitute a treasure-house of scientific information that could be used over and over again for years of scientific study. Such data would not collect dust in the archives, which has all too often been the fate of the fragmentary observations taken in the International Years or in regional studies. The reason is that global measurements *define* the physical system, whereas the fragmentary or regional studies do not. Regional studies of phenomena on a synoptic scale generally fail to determine the vertical and horizontal boundary fluxes, and as a consequence all but the smallest scales of motion remain physically undefined. It is as if one were to try to account for the fluid motions

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* The accuracy of hypothetical observation systems can be tested by simulation experiments using numerical prediction models and objective interpolation schemes. Tests of this kind are now being made.

in a rotating heated tank by measuring the motions in only a small part and neglecting altogether to measure the heat flow through the boundaries. It is true that our present knowledge of atmospheric motions has been gained from just such fragmentary studies, but it is equally true that attempts to explain large-scale atmospheric variations for more than three or four days have met with signal failure.

The limited success that has attended short-term numerical predictions and general-circulation calculations suggests strongly that the availability of global data would open up an entirely new field of investigation—the study of phenomena on time scales from 4 to 5 days to infinity. One can imagine that the next generation of meteorologists will be dealing with life-cycles of cyclones, with fluctuations in amplitude of the quasi-stationary centers of action, and with variations in the mean strength and position of the westerlies with the same easy familiarity with which they now approach a 24-hr weather prediction. The evidence from rotating-tank experiments and from numerical-model calculations indicates that such phenomena are well within reach scientifically. The implications for long-range weather prediction, the understanding of climate, and a rational approach to climate modification are almost too obvious to bear comment. It is desirable, however, to list a number of specific scientific problems whose solutions would be made possible by the existence of a set of global observations.

1. *Large-scale circulation systems*

If the large-scale motions of the atmosphere are treated in linear approximation as dispersive wave-perturbations of a mean zonal flow, it is found that the maximum zonal and meridional group velocities are about 30 to 40 degrees of longitude per day and about 10 degrees of latitude per day, respectively. This means that even in the data-rich Northern Hemisphere spurious influences propagating from regions where observations are lacking or are inadequate (e.g., the Pacific Ocean and nearly everywhere south of 30°N) will contaminate any area within 4 or 5 days* and may encircle the globe in approximately 9 to 12 days. Now the life-cycle of a single cyclonic system,

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* In a numerical calculation with the global model of Y. Mintz and A. Arakawa, a localized perturbation of the flow initially introduced in the region 21–63°N, 153–207°W was observed to propagate across the pole and appear at 63°N and 40°E within 4 days. While this may have been due to the poor grid resolution near the poles, it does at least call attention to the little-considered possibility of meridional energy propagation.

involving the processes of birth, growth, and decay is the basic transient element of the general circulation, and its duration is usually in excess of 4 or 5 days. Hence one has no hope of understanding the processes involved in the general circulation without a considerable extension of the present network.

Moreover, the characteristic time scales of frictional decay of kinetic energy and of restoration of potential and internal energy by heating are of the order of a week or two, as are the characteristic time scales of exchange of energy and momentum between the large-scale eddies and the mean zonal flow. Thus, to verify the accuracy of a mathematical model of the atmosphere containing frictional dissipation and heat sources, observations on a global or at least hemispheric scale are needed.

2. *Southern Hemisphere circulations*

Notwithstanding the IGY, the Southern Hemisphere remains to a considerable extent a *terra incognita* for the meteorology of large-scale processes. Too little is known of its circulation patterns and their variations. The Southern Hemisphere differs from the Northern Hemisphere in the distribution of land and water and hence in the thermal and mechanical influences of the underlying surface. Although there is dynamical coupling between the two hemispheres, the time scale of the interaction is probably large, and there is undoubtedly a considerable degree of independence for smaller periods of time. The Southern Hemisphere and the Northern Hemisphere are thus, to a degree, independent natural laboratories in which we may conduct comparative studies of hemispheric circulations under varied boundary conditions. Here is a large-scale weather-modification experiment that nature places in our hands.

3. *Interactions between hemispheres*

Nevertheless, there is undoubted interaction between the two hemispheres, especially during the monsoon seasons. The nature of the interaction is poorly understood and would be revealed by the data.

4. *General circulation of the tropics*

The tropics and subtropics between, say, 30°N and 30°S are nearly as great a *terra incognita* as the Southern Hemisphere, and, like it, they cover half the earth's surface. They are the tropospheric source region of energy derived from the sun, but the manner in which this energy is used for driving the tropical circulations and the manner in which it is transferred in the form of sensible and latent heat to middle and upper latitudes is poorly understood. Many questions involving the exchange of heat, momentum, and kinetic energy could be answered by the data. For example, most of the tropics are covered by ocean; solar energy is converted to mechanical energy through evaporation of moisture and release of latent heat energy in small- and large-scale moist convective processes associated with disturbances in the equatorial convergence zone or the trades. How does this zone form? What are the roles of the disturbances? Are the most violent disturbances, the hurricanes and typhoons, important elements in maintaining the mean circulation? How are the tropical circulations coupled dynamically to the extratropical circulations? One cannot answer these questions without an order-of-magnitude increase of observations in the tropics.

5. *Equatorial currents*

The tropics are also the site of certain singular phenomena of great scientific interest—the so-called equatorial currents. It is known, for example, that there are equatorial currents at the base of the stratosphere similar to the equatorial undercurrents in the Pacific and Atlantic Oceans and the equatorial currents on Jupiter and the sun. Unlike the ocean currents, but like those of Jupiter and the sun, the atmospheric currents apparently extend uniformly around the earth. A much more extensive network is needed to investigate their nature and causes.

6. *Hurricanes and typhoons*

The tropical oceans are a breeding ground for hurricanes and typhoons. An understanding of the complete life cycle of these systems from birth to decay is not now possible, for one cannot observationally define the macro-environment in which they form nor how they interact with this environment. A major problem is to understand why a cold-core depression is converted into a warm-core depression; the existing networks do not contain the depression long enough to supply the answer. Much light would be shed on this problem by the global observations, especially if they included satellite cloud observations in the visible and infrared, and more especially if the satellite were of the synchronous type.

UNDERSTANDING AND MODIFYING CLIMATE

With respect to climate, if one seeks a statistical description of the atmosphere as a turbulent fluid, it helps little to borrow concepts from existing turbulence theory. These concepts have been developed for turbulence that is completely or partially homogeneous and isotropic. The macro-scale turbulence in the atmosphere is nonhomogeneous and nonisotropic everywhere and in every direction. One important lesson that has been learned from numerical studies of general circulation models is that there is unlikely to be any way to obtain the correct statistics of climate except as a property of a collection of individual instances of global circulation patterns, each of which must be describable with considerable accuracy. One is not spared the necessity of understanding the individual instances; the statistical behavior of the atmosphere, unfortunately, is not to be compared with that of a homogeneous perfect gas whose molecules might just as well be billiard balls.

With respect to climatic anomalies (long-period fluctuations in the general circulation), an important problem is to determine the extent to which these are random phenomena biased by small anomalies in land or sea surface conditions and the extent to which they are dependent on initial conditions. It is as if one were trying to predict the probable outcome of a game of roulette played with a slightly unbalanced wheel. One may solve this problem by Monte Carlo techniques, i.e., by playing the game repeatedly (performing simulation experiments with slightly varied initial conditions), but to do so with any hope of success, one must know the throw of the ball and the configuration of the wheel (the initial conditions and the dynamics of the system) with considerable accuracy.

The above remarks apply with even greater strength to the problem of weather or climate modification. If the man-made pertubations are small, it seems obvious that neither their individual nor their statistical consequences can be ascertained in a system which fails to accurately predict the individual motions.

POSSIBILITIES OF LONG-RANGE PREDICTION

1. *Present problems*

A truly global observation system would, in principle, supply the initial conditions for numerical prediction of the weather for arbitrarily long periods of time. However, the lack of observations is not the only limitation to forecast accuracy. At the present time numerical predictions are prepared on a routine basis, and with some degree of success, for periods of up to 3 or 4 days, for areas covering from one half to two thirds of the Northern Hemisphere. The omission of a number of important physical factors, including the release of heat of condensation and other forms of diabatic heating, automatically limits the forecast to these periods.

Another limitation is imposed by unresolved mathematical problems associated with the control of truncation error, especially in regions of strong gradients in the dynamic variables or in land elevation. These problems are now being investigated in experimental numerical calculations with fluid models, and there is reason to believe that they will eventually be solved.

Of a more fundamental nature are the problems of turbulent boundary-layer transport and cumulus interaction with meso- and macro-scale motions. These will require extensive and detailed investigation by observation, theory, and numerical experiment. At the present time only gross parametric estimates of the effects of these interactions are incorporated into our mathematical prediction models. When it becomes possible to compare the results of integration with observations over periods of time long enough for these effects to be clearly discernible, we may expect to learn a great deal more of the phenomenology of the turbulent interactions. This in itself may be enough for long-range prediction. In any event, such macro-scale investigations will usefully supplement the knowledge obtained from the detailed observational studies.

2. *Computer requirements*

Another problem must be considered: mathematical models of the global circulation incorporating all of the above-named effects as well as others, such as cumulus convection and radiative exchange, are exceedingly complex and require electronic computers of high speed and capacity. The requirements may be estimated from past experience. Experimental calculations have been carried out under the direction of J. Smagorinsky of the Geophysical Fluid Dynamics Laboratory of the U.S. Weather Bureau with a numerical model approaching in complexity that which is required for taking advantage of a global observation system. This model includes the boundary-layer fluxes, radiative exchange, and release of latent heat; it has nine levels in the vertical and a horizontal grid spacing of about 250 km. A 24-hr integration for a single hemisphere requires 18 hr of calculation on an IBM STRETCH computer. Moreover, Smagorinsky finds that the truncation errors are still unacceptably large in certain regions and that the horizontal grid spacing may have to be reduced by a factor of 2. This would increase the calculation time for a 24-hr prediction to nearly 1 week. The newest generation of computers, including those of IBM and CDC, which are at least five times faster than STRETCH, or some 10 to 15 times faster than the IBM 7094, barely bring global weather prediction within range.

However, designs exist and components have been built for parallel-processor computers, requiring no basic increase in add or storage time, with speeds some 100 times faster than the newest machines. It is clear that such speeds will ultimately be required for long-range prediction. Before adequate mathematical models can be developed, it will be necessary to perform a great number of experimental calculations with varied parameters and processes, and it must be possible to do these quickly if they are to lead inductively to greater understanding. Moreover, as has already been suggested, for very long-range prediction it will probably be possible only to predict averages or distributions, and these can be obtained only through manyfold repetitions of determinate predictions with varied initial conditions.

Computers of this scale and complexity may require a new mode of human organization for their effective use. Heretofore numerical weather prediction studies have been hindered both by the difficulty of programming changes in mathematical models and by the length of time required for the integrations. This has somewhat discouraged experimentation. The high-speed parallel-processor computers will presumably overcome the second obstacle, but without changes in organization and programming techniques, the first obstacle might become even more formidable. One may compare the computer to a large particle accelerator. The computer, like the accelerator, will be so expensive that few will be available, nationally or internationally. It must, figuratively speaking, contain a number of *ports* permitting a variety of experiments to proceed simultaneously. This is not simply a question of time-sharing or of remote control, but of program organization to permit easy changes in mathematical models. If such organization becomes possible, the computer will have many of the advantages of a laboratory experimental device without many of its disadvantages, namely those associated with the difficulties of modelling, of measuring, and of varying parameters and processes. One must, of course, presuppose stable mathematical integration schemes with controlled truncation error, but these, as has been mentioned, are now being developed.

3. *Theoretical limits of predictability*

A basic problem in long-range forecasting is concerned with the theoretical limits of predictability of the atmosphere as a determinate system. If one knew the laws of motion with perfect accuracy, had accurate initial grid data for all the atmosphere, and could reduce truncation error to negligible proportions, it would still be impossible to make determinate forecasts for arbitrarily long time intervals. This limitation is not a matter of quantum indeterminacy or of thermodynamic fluctuation; it derives fundamentally from the continuous character of the turbulence spectrum and the limitations of any observational net. As long as some turbulent energy remains at the mesh scale, then, no matter how much the observational net is refined, part of this energy will inevitably appear under an alias as energy of the large-scale flow, i.e., as an error of observation. This will remain true until the mesh size is reduced to the smallest eddy size permitted by viscosity. It will then obviously have become impossibly small. Thus it appears that errors of observation are inevitable even when they are not strictly instrumental. In practice, instrumental errors will be appreciable and will have to be reckoned with (they, too, are related to the existence of turbulence).

The question of predictability may now be asked in a more realistic manner. Given the inevitable small errors, will these remain small or will they grow, and, if they grow, how fast will they grow? How long will it be before the error has grown beyond acceptable bounds? These questions were asked by Lorenz[1] who related them to the question of the stability of a dynamical system with a finite number of degrees of freedom. If the system is represented by a point in a phase space and occupies a bounded volume in this space, it must pass arbitrarily close to the same point on more than one occasion. If the system is stable, in the sense that a small perturbation of the system in the phase space will remain small, it is easily seen that it must be periodic or almost periodic. Conversely, if it is not periodic it must be unstable. Figure 1, taken from Lorenz's article, illustrates this situation. Lorenz also showed that if a solution is nonperiodic, it is not only unstable but the neighboring solutions must eventually become as far separated as two randomly chosen solutions. He carried out numerical experiments with a very simple atmospheric analogue containing only 28 degrees of freedom and was able to obtain steady, periodic, and nonperiodic solutions.

There is every indication that the actual atmosphere is aperiodic and therefore unstable, although it contains periodic or quasi-periodic components such as the lunar and solar tides. The question is, then, how fast will a given error, interpreted as a perturbation of the atmospheric flow, grow before the perturbed motion differs from the unperturbed motion by as much as two randomly chosen flows. To estimate the limit of predictability in this sense, a series of numerical experiments were performed by Drs. C. Leith, Y. Mintz, and J. Smagorinsky, at the Livermore Laboratory of the University of California, the University of California at Los Angeles, and the Geophysical Fluid Dynamics Laboratory of the U.S. Weather Bureau, respectively. Numerical predictions were performed with each of

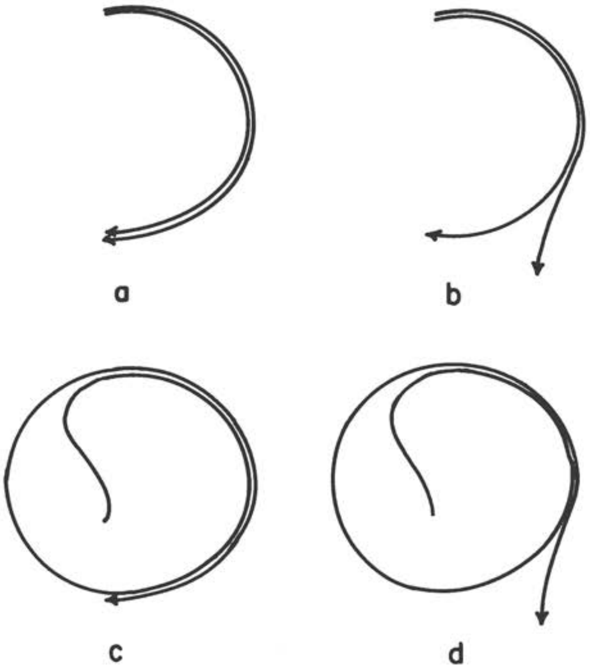

FIGURE 1. Schematic diagrams illustrating predictability.

their models for so long a period that the starting conditions had ceased to have any discernible effect. At this time a sinusoidal "error" perturbation in the temperature field was introduced and a prediction was made for at least 30 additional days. This prediction was then compared with the evolution of the unperturbed flow for the same period. The individual models will now be described.

(a) *The Leith model.*[2] This model is global in extent. The grid divides the atmosphere into six pressure levels in the vertical and covers the globe with a horizontal grid spacing of about 500 km. Heating is due to incoming solar radiation, the release of heat of condensation, and small-scale convection. Infrared radiative transfer is included by specifying a cooling rate as a function of pressure alone. The surface temperature is a fixed function of latitude and longitude, and the ground is flat. Vertical and horizontal diffusion of heat and momentum by turbulent eddies are provided for by linear diffusion laws with constant eddy coefficients. We note especially that the horizontal diffusion coefficient, D, is given the unusually large value 10^{10} cm^2 sec^{-1} in order to ensure computational stability. This results in a dissipation half-life of $L^2 \log_e 2/8\, \pi^2 D = 5.2$ days for a sinusoidal disturbance whose wavelength, L, is 6,000 km in both the zonal and meridional directions.

(b) *The Mintz-Arakawa model.*[3] This model is also global in extent. The grid divides the atmosphere into two pressure levels in the vertical and covers the globe in 9° intervals of longitude and 7° intervals of latitude, except in small regions near the poles. The heating due to incoming solar radiation is fixed in space and time; the heat of condensation is brought in parametrically and rather unrealistically only to keep the lapse-rate of temperature from exceeding the moist-adiabatic; heating by small-scale convection is allowed at the lower level; and the infrared cooling rate at both levels is given as an empirically determined function of the temperature at the lower level. The ocean temperatures are fixed, but the land temperature is permitted to vary in accordance with the temperature at the lower grid level. These features do not differ significantly from those in Leith's model except for the variable land temperature and the absence of large-scale precipitation. There are two additional features, however, in which the model does differ significantly: first, owing to the employment of a completely stable difference scheme devised by Arakawa, it was not necessary to assume so large a horizontal diffusion coefficient; and second, orographical variations are taken into account.

(c) *The Smagorinsky model.*[4] The Geophysical Fluid Dynamics Laboratory's current nine-level model could not be used in this test because of the prohibitive amount of computation that would have been required. An earlier two-level model was used instead. In this model the flow is bounded by vertical walls at the equator and at latitude 64.4°. The grid is a square net on a Mercator projection, with a mesh size varying from 555 km at the equator to 240 km at the north boundary. The earth's surface is flat and homogeneous. The thermal structure of the atmosphere is characterized by a single variable temperature at an intermediate level and a constant static stability. Diabatic heating is given as a linear function of the temperature. Surface friction is treated as a boundary layer phenomenon, and lateral eddy diffusion of momentum is assumed to take place with a coefficient of viscosity dependent on the deformation tensor, so that strong momentum diffusion occurs only when the deformation field is large.

In each of the models a temperature perturbation of the form $\Delta T \sim \sin 6\lambda \cos 11\phi$ was introduced. Here λ is the longitude and ϕ the latitude, giving six waves zonally and six from pole to pole.

Graphs showing the time variation of the root-mean-square (r.m.s.) temperature deviation,

$$\left[\frac{1}{N}\sum_{1}^{N}(\Delta T_n)^2\right]^{1/2},$$

averaged over all the grid points ($n = 1, 2, \ldots N$), are presented in Figures 2, 3, and 4 for the Leith, Mintz-Arakawa, and Smagorinsky models, respectively. The perturbation temperature amplitudes were taken to be 2.0°, 0.5°, 0.1°, and 0.02°K in the Smagorinsky model and 1°K in the others. The r.m.s. errors were calculated separately for each hemisphere and each level in the Mintz-Arakawa model, and for the whole atmosphere in the others.

The initial temperature errors were chosen so small that it was thought that they could be regarded initially as linear perturbations on the finite-amplitude time-variable flow. It was expected that they would at first grow exponentially until they reached a finite-amplitude nonlinear stage and would then grow at a decreasing rate. It

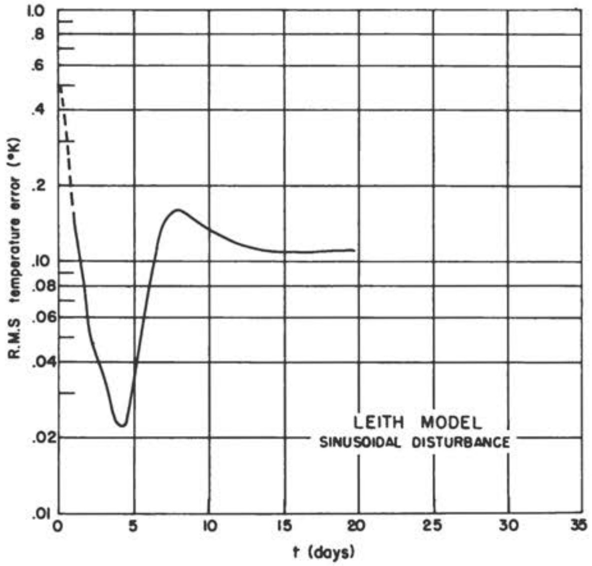

FIGURE 2. Root-mean-square temperature error in Leith model.

will be seen from the figures that this expectation was borne out only in the Mintz-Arakawa model. In the Leith model the r.m.s. error started at 0.50°K and, after undergoing a transient oscillation, leveled off at 0.11°K. The calculation was terminated after 20 days because of a computational instability associated with the condensation process. The flow at the upper levels became nearly a constantly

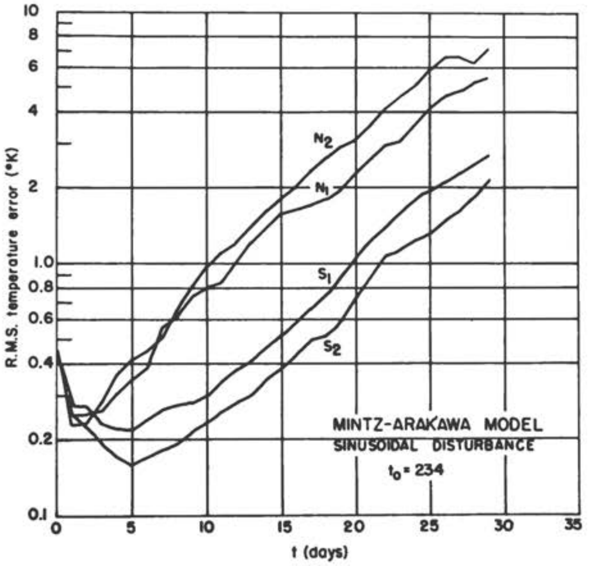

FIGURE 3. Root-mean-square temperature error in Mintz-Arakawa model.

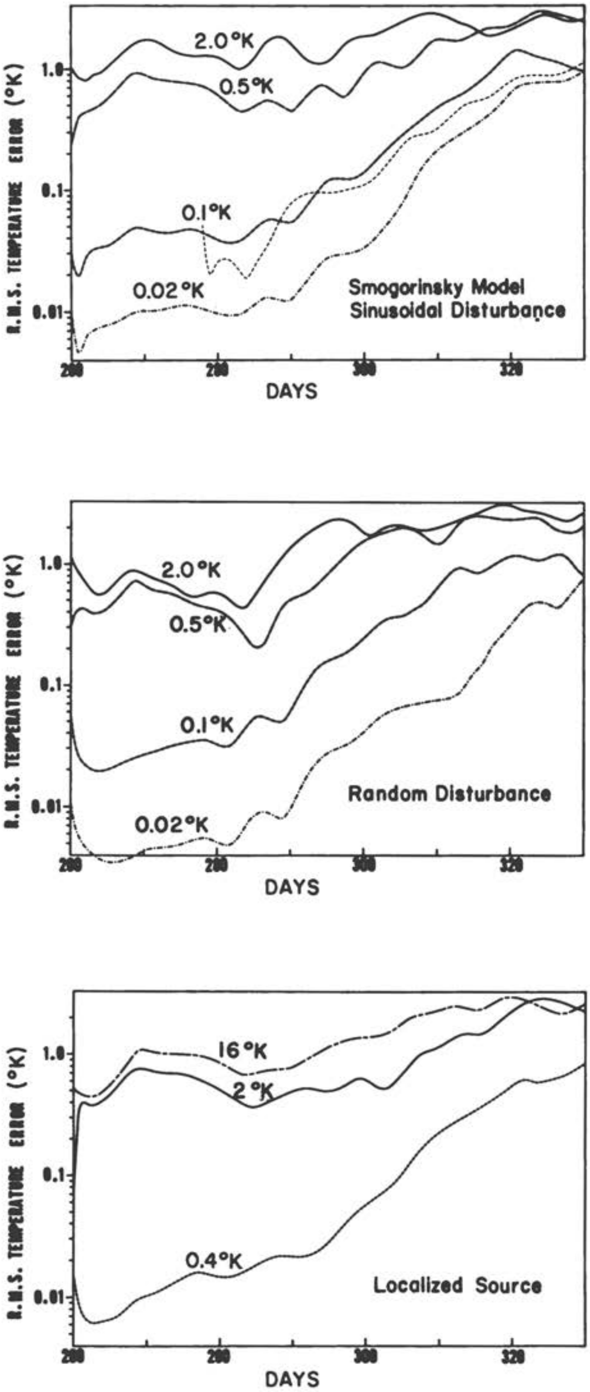

FIGURE 4. Root-mean-square temperature error in Smagorinsky model.

translating wave pattern of small amplitude. The cause of this upper-level stability is probably the excessive eddy viscosity and the weak coupling with the surface.

In the Smagorinsky model the temperature amplitude of the unperturbed flow was, in the first calculation, no greater in order of magnitude than the imposed perturbation of 2°K. This placed the perturbation immediately in the nonlinear range. However, even when the amplitude was reduced to 0.5°K the error growth exhibited a similar behavior. In both cases it will be seen from Figure 4 that the r.m.s. error varies in a quasi-periodic fashion with a period of about 2 weeks and a slowly increasing mean value. The variations parallel each other for about 30 days and then begin to depart. The smaller error disturbances, of amplitude 0.1°K and 0.02°K, show a slow but continuous growth until after about 30 days, when the doubling time reaches the value of 6 or 7 days. An examination of the actual flow patterns revealed that the motion was primarily periodic, with a small aperiodic component. In accordance with what has been said about the stability of dynamical systems, it might have been expected that the instability would appear as a slow growth superimposed on a periodic fluctuation. After about 30 days the vacillating regime changed to a more aperiodic behavior, and at that time the error grew more rapidly with a doubling time of 6 or 7 days. This behavior does not resemble very well the usual condition of the atmosphere in which strong instabilities appear always to exist.

The only model exhibiting the strongly aperiodic behavior of the atmosphere was the one of Mintz and Arakawa. Integrations had been performed with this model for upwards of 284 days with the sun constantly at the Northern Hemisphere winter solstice. A sequence of sea-level pressure charts at 2-day intervals for days 229–243 are shown in Figures 5, 6, 7, and 8. It will be seen that the flows are realistic at middle and high latitudes, with the traveling disturbances and the quasi-permanent centers having typical locations and intensities. The zonally and time-averaged temperature distributions shown in Figure 9 are also seen to correspond well with observations for the winter season. We may therefore be justified in assuming that the statistical properties of the error growth will be realistic.

The primary deficiency of the model is its unrealistic treatment of the condensation process; this deficiency is indicated most markedly in the tropics by too broad a low-pressure trough and the absence

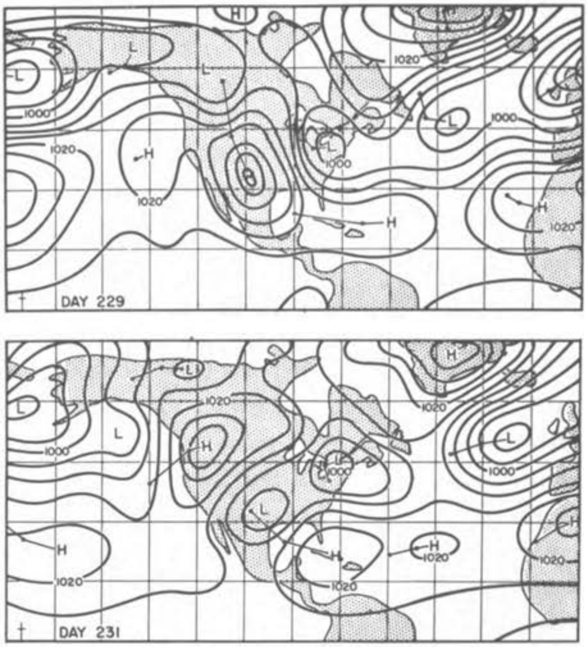

Figure 5. Sea-level-pressure maps as computed for days 229 and 231. The isobars are at 5-mb intervals and the small circles, connected by thin lines, show the positions of the low and high centers in the preceding two days.

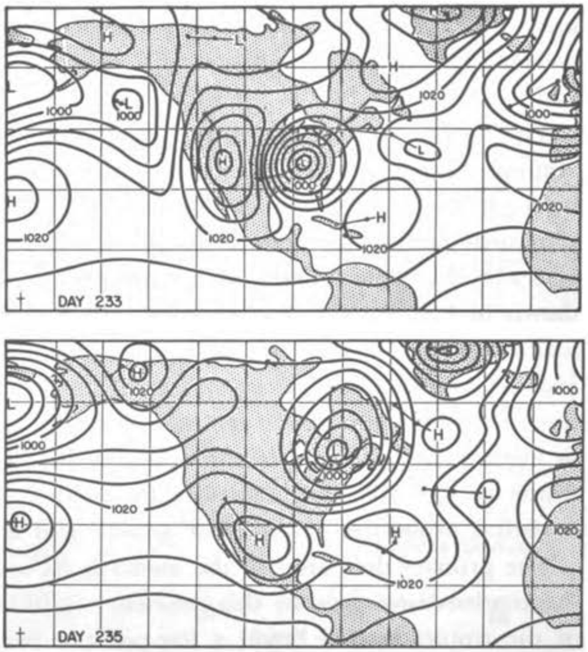

Figure 6. Sea-level-pressure maps as computed for days 233 and 235.

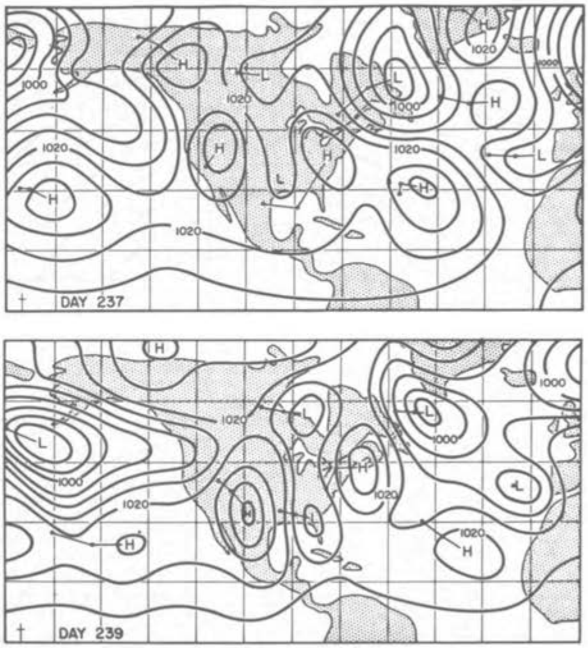

Figure 7. Sea-level-pressure maps as computed for days 237 and 239.

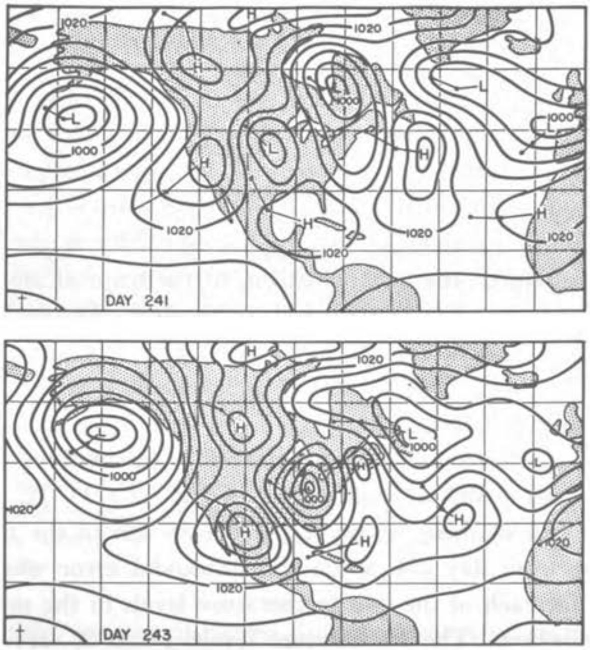

Figure 8. Sea-level-pressure maps as computed for days 241 and 243.

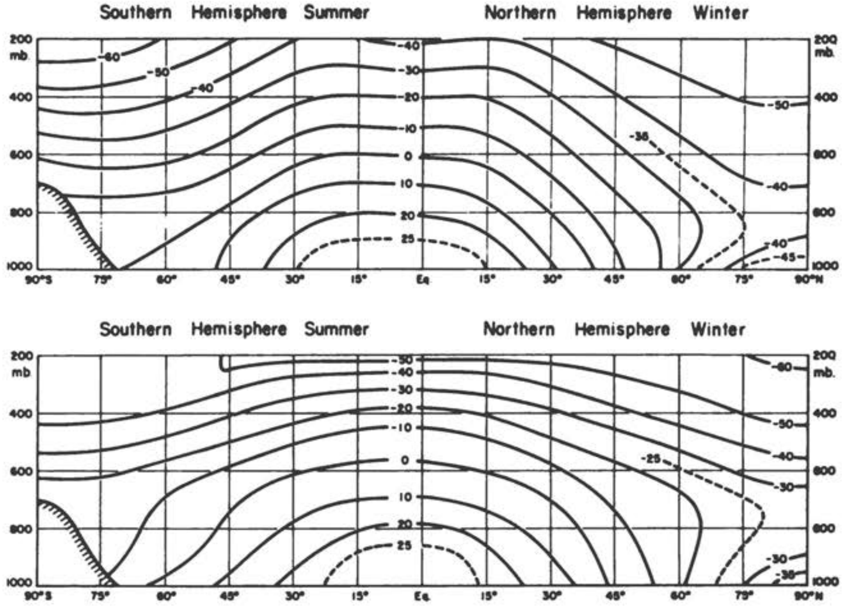

FIGURE 9. Meridional cross sections of the zonally averaged and time-averaged temperature, in degrees centigrade, for Northern Hemisphere winter and Southern Hemisphere summer. The upper figure is the 30-day mean (from day 256 to 285) computed in the numerical experiment. For representational purposes, the zonally averaged surface temperature is shown at the 1,000-mb level, except over Antarctica. The lower figure shows the observed field, according to Burdecki (1955).

of the normal tropical disturbances, as well as in a distortion of the subtropical high-pressure pattern. This is shown in Figure 10. However, the principal error growths are associated with strong middle-latitude cyclogenesis, and since cyclogenesis is far less frequent and usually less intense in the tropics, especially in the Northern Hemisphere winter, the lack of realism in the tropical motions cannot have affected the statistical results significantly. The lack of condensation in the extratropical developments is probably more serious, but since it is not the primary cause of cyclogenesis, it is not thought to have a dominating effect.

The results of the predictability calculations with the Mintz-Arakawa model are summarized in Figures 3, 11, 12, 13, 14, 15, and 16. The first of these figures shows the growth of the r.m.s. temperature error from day 234, when the sinusoidal error was inserted, to day 264 for each of the two temperature levels in the model and for each hemisphere. The temperature levels, 1 and 2, vary somewhat in elevation and have means of 400 and 800 mb, respectively.

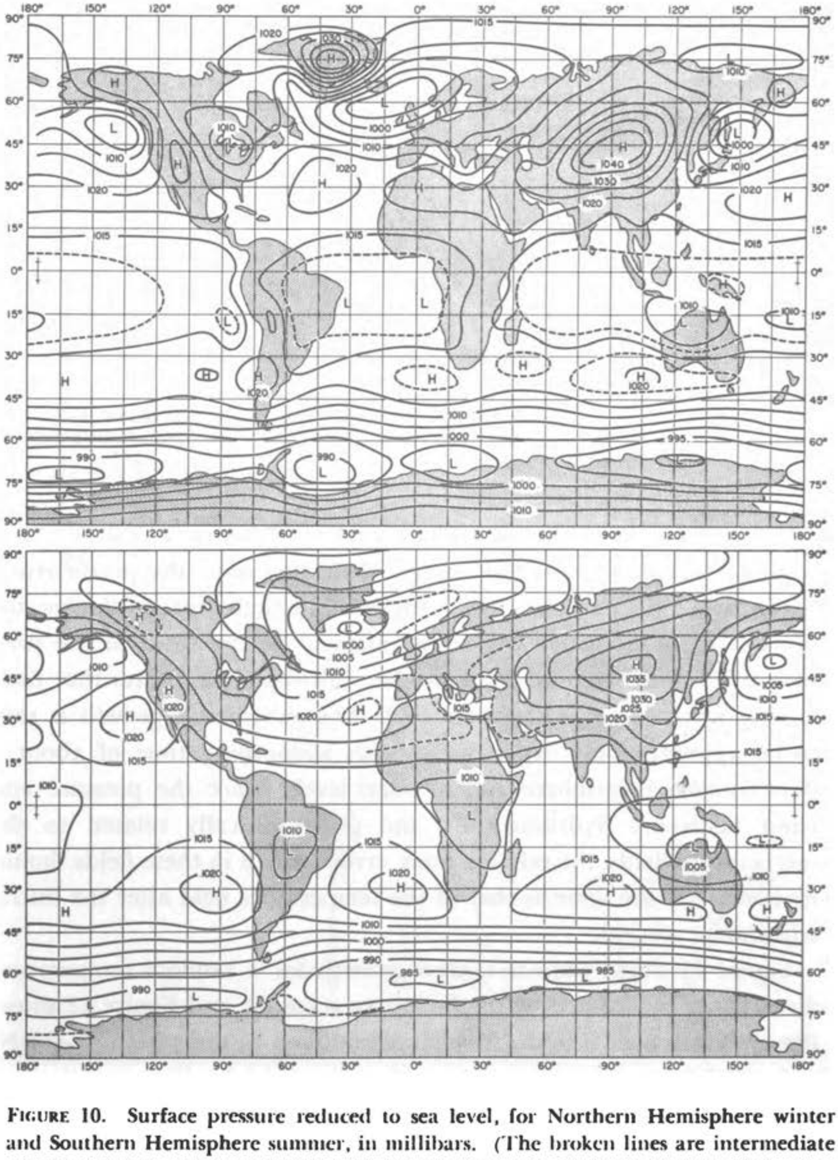

FIGURE 10. Surface pressure reduced to sea level, for Northern Hemisphere winter and Southern Hemisphere summer, in millibars. (The broken lines are intermediate 2.5-mb isobars.) The upper figure is the 30-day mean (from day 256 to 285) computed in the numerical experiment. The surface pressure was reduced to sea level using the computed surface temperature and a subterranean temperature lapse rate of 6°C/km. The lower figure shows the normal January sea-level pressure, according to O'Conner (1961), 90°N–15°N; Riehl (1954), 45°N–45°S; and van Loon (1961), 15°S–90°S.

Since the wind field was not disturbed initially, the initial decrease in the r.m.s. temperature error most likely represents a transformation

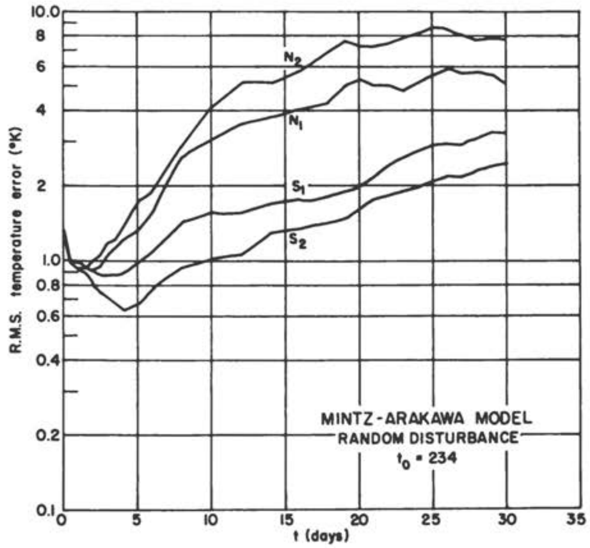

FIGURE 11. Root-mean-square temperature error in Mintz-Arakawa model.

from perturbation potential energy, associated with the perturbation temperature fluctuations, to perturbation kinetic energy during the process of the quasi-geostrophic adjustment of the wind to the pressure field. The evidence from another calculation indicates that little gravity wave energy was generated.* The subsequent growth is seen to be approximately exponential, with a doubling time of about 5 days in each hemisphere and at each level. Since the pressure and wind fields are hydrostatically and geostrophically related to the temperature fields, the relative r.m.s. error growth in these fields should be essentially the same as that of the temperature field after the initial adjustment period.

Figure 11 shows the r.m.s. error growth for a random temperature disturbance modulated by the factor cos ø cos 6ø, and Figure 12 shows the growth for an initial disturbance confined to the region 21–63°N, 157–203°W. Again, we see that after the initial adjustment period the growth becomes near-exponential with a doubling time of about 5 days.† In the former case the initial error is large, and the nonlinear range is reached sooner. In this range the growth rate first

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* It may be seen from Figure 12 that the gravitational wave energy generated by a perturbation placed initially in the Northern Hemisphere invades the Southern Hemisphere within a day or two, and that at this stage it is three orders of magnitude smaller than the initial energy.

† A similar doubling time for an initially random disturbance in a two-level model was obtained theoretically by Thompson.[5]

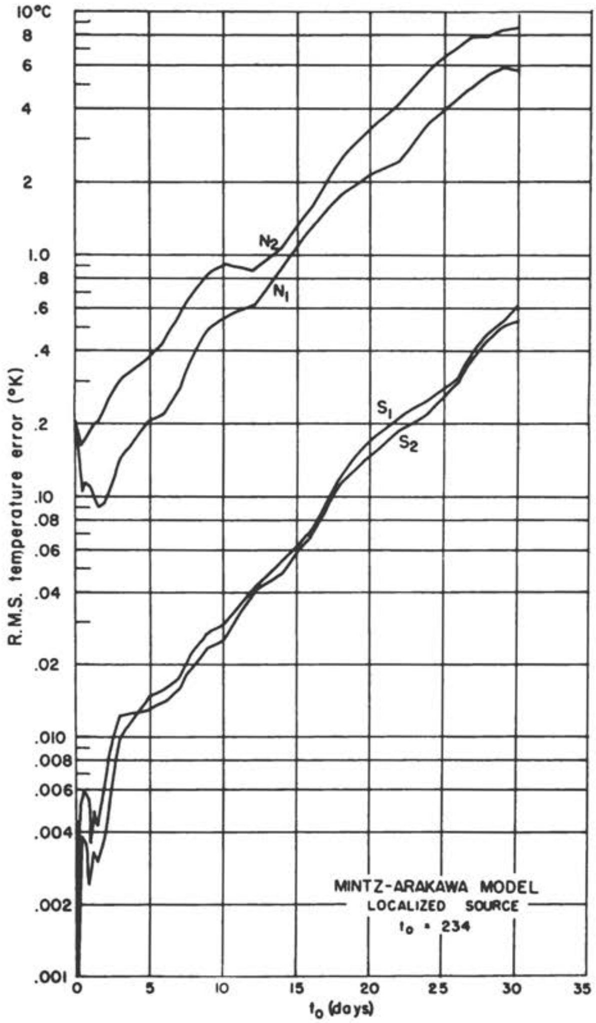

FIGURE 12. Root-mean-square temperature error in Mintz-Arakawa model.

diminishes and then levels off to an irregular fluctuation, at which time the perturbed flow ceases altogether to resemble the unperturbed flow. All deterministic predictability is lost when the r.m.s. errors become comparable to those obtained by differencing two random flows. Estimates of these magnitudes were obtained by differencing temperatures for the days 261 and 260, 262 and 259, 263 and 258, etc. The resulting r.m.s. temperature differences are shown in Figures 13 and 14 as functions of the time-difference in days. It will be seen that beyond 3 days the resemblances are so weak that the pairs may be considered essentially random. (Three days is therefore the upper

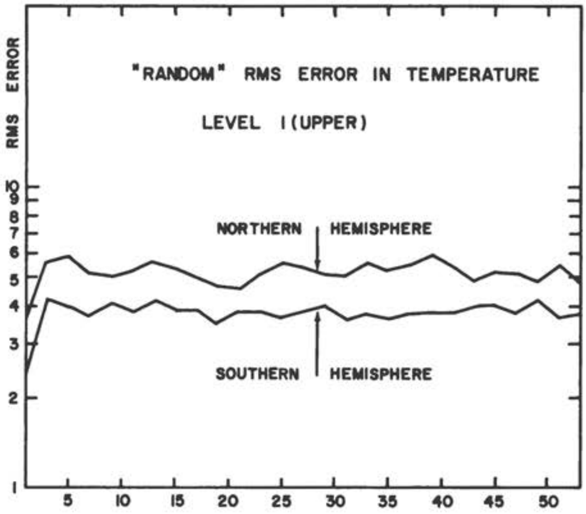

FIGURE 13. "Random" error in temperature as a function of days of separation. Upper level.

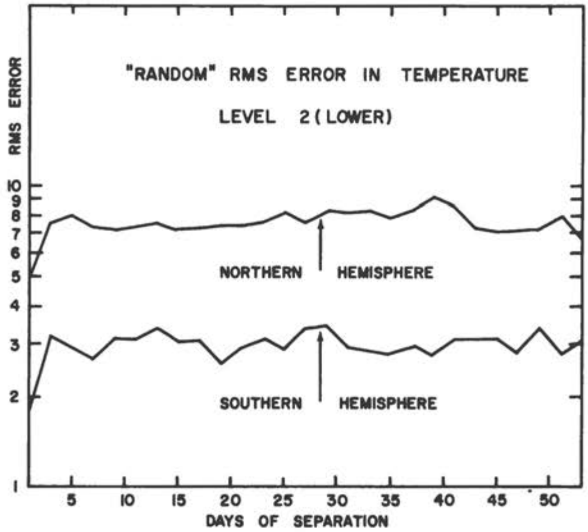

FIGURE 14. "Random" error in temperature as a function of days of separation. Lower level.

limit for a "persistence" forecast.) Referring to Figures 13 and 14 and Figures 3, 11, and 12, we note that all predictability in the Northern Hemisphere is lost at 26 days for the wave perturbation, 19 days for the random perturbation, and 29 days for the localized perturbation.

We note from Figure 4 that the behavior of the random and localized disturbances in the Smagorinsky model resembles that of the Mintz-Arakawa model after the first 25 days, but with a slightly lower growth rate.

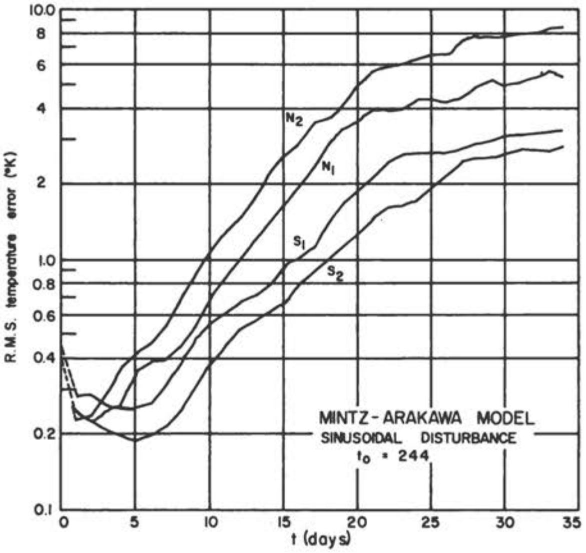

FIGURE 15. Root-mean-square temperature error in Mintz-Arakawa model.

It may seem at first surprising that the logarithmic rate of growth of the r.m.s. error is approximately independent of the nature of the initial error. An explanation of this phenomenon is suggested by Fourier analyses of the error along zones of latitude at middle latitudes. One finds for the case of the sinusoidal wave perturbation, whose wavelength corresponds roughly to disturbances of cyclone scale,

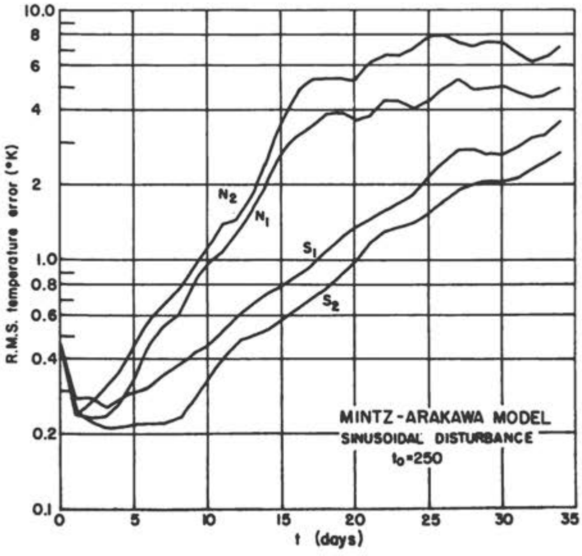

FIGURE 16. Root-mean-square temperature error in Mintz-Arakawa model.

that the spectral energy quickly spreads in such a manner that after 5 days two other peaks in the spectrum appear in the wavenumber range 1 to 4 and 8 to 12 but that the maximum energy remains near wavenumber 6. This is the spectral behavior that would characterize the interactions of the most unstable of the normal perturbation modes of the finite-amplitude time-variable flow with the finite-amplitude flow itself. It is what one would expect if the error growth were essentially a baroclinic instability appearing as cyclone development in a band centered near wavenumber 6. The first-order interactions of this *perturbation* mode with similar or larger scales of the *finite-amplitude* flow would produce the peaks of *perturbation* energy near wavenumbers 3 and 10. Since each of the error disturbances considered (and any that would be likely) has energy at either the long, intermediate, or short scales, its first-order interaction with the finite-amplitude flow will produce energy in the cyclone-scale mode, which will then dominate the development by its rapid growth and give rise to the characteristic r.m.s. growth rate.

We may infer from the correspondence of the space and time scales that the finite-amplitude irregular flow of the atmosphere is unstable in much the same way as the idealized baroclinic zonal flows which have been studied theoretically, but that, because of the irregularity of the basic flow, the unstable perturbation modes are themselves so irregular that it would require a very special initial disturbance indeed not to excite them.

An important conclusion concerning data requirements may be drawn from the above considerations. Since errors on any macroscale will ultimately grow by instability or by nonlinear interaction, one is not spared the necessity of defining the entire spectrum in the macro-range by means of the observational system. The conjecture that the need for defining the smaller scales of motion is removed by extension of the forecast range is wrong on two counts. In the first place, one cannot measure the long-wave components without measuring the shorter ones as well, for if the shorter components have appreciable energy, a large part will appear under an alias as energy of the long waves. In the second place, the errors in the neglected shorter-wave components will immediately affect the long-wave components through nonlinear interaction.

If one accepts a doubling time of 5 days as the rate of growth of the r.m.s. temperature difference and (from Figure 14) 8°K as the r.m.s. temperature difference between randomly chosen flows at 800 mb in the Northern Hemisphere winter, then a flow whose temperatures are determined within an r.m.s. error of 1°K will remain deterministically predictable for about $5 \log_2 8$ or 15 days. If the error were random with an amplitude of 1°K its r.m.s. value would be $1/\sqrt{3}$, and the flow would remain predictable for some 4 days longer. An indication of how the rate of error growth varies with the synoptic situation was obtained by inserting the initial sinusoidal error perturbation at days 244 and 250 (see Figures 15 and 16). The integrations show doubling rates which vary from 4 to 5 days in the early stages of the prediction in the Northern Hemisphere winter and which decrease in the later stages, just as for the first case where the initial time was day 234. In the Southern Hemisphere summer the rates are somewhat less: the doubling time varies from 5 to 7 days at r.m.s. amplitudes below 1°K, and may be as long as 15 days at r.m.s. amplitudes about 1°K.

CONCLUSIONS

We may summarize our results in the statement that, based on the most realistic of the general circulation models available, the limit of deterministic predictability for the atmosphere is about 2 weeks in the winter and somewhat longer in the summer. We have assumed that the observational system defines the initial state of the atmosphere globally and that the temperature error is random and not greater than, say, $\sqrt{3}°$K, with the errors in pressure and wind having hydrostatically and geostrophically corresponding values in middle and high latitudes. Observational systems of the kind contemplated in this report can be expected to determine temperatures to within this error.

Finally, it should be stated that, in principle, prediction of certain statistical quantities might be made for longer periods. It remains to be seen whether there are predictable statistical quantities which vary significantly and yet more slowly than the individual dynamical parameters. Surface interactions due to heat storage in the mixed layers of the oceans, variable snow cover, etc., may act as governors regulating these changes. However, it would appear from the rapid growth rates due to the basic instability of the atmosphere that the slower surface interactions will not appreciably change the limit of deterministic predictability, i.e., the limit of predictability of the individual motions.

CHAPTER TWO

REGIONAL OBSERVATIONS

THE PROBLEM: SMALL-SCALE ATMOSPHERIC MOTIONS

In the development of techniques of middle- and long-range forecasting, and the formulation of mathematical models of the atmosphere suitable for the successful analysis of problems of large-scale weather and climatic modification, smaller-scale processes must be incorporated into our theory of atmospheric motions. These processes include not only the turbulent exchange between the atmosphere and the underlying surface of such quantities as momentum, heat, and water vapor, but also the redistribution of these quantities within the atmosphere itself due to turbulent motions on the meso- and microscale. At present, only crude quantitative estimates of turbulent exchange resulting from smaller-scale motions are available. This represents an important deficiency in our knowledge of large-scale weather prediction and modification.

Present studies of smaller-scale exchange processes are primarily devoted to taking local measurements and to clarifying the nature of the physical system. This method of attack yields fundamental information which may ultimately be of great value in our understanding of the behavior of the atmosphere. It will not, however, provide us with the quantitative information we require for substantially extending the time range of weather forecasts. For such purposes it will be necessary to relate the mean value of the various exchange rates, averaged over appropriate intervals of space and time, to synoptically observed macro-scale variables such as those described in the previous section. In this way, self-contained dynamically determinate prediction systems can be formulated.

THE OBSERVATIONAL REQUIREMENTS

Small-scale exchange processes fall naturally into two major categories. In the first are processes which take place at the surface of the earth and in the turbulent boundary layer. Quantities to be measured here include the momentum transfer due to friction with underlying surfaces, the exchange of energy in various forms (including sensible heat and net radiation), and the net exchange of water vapor. Macro-variables to which the exchange processes must be related include such parameters as surface pressure gradient, the atmospheric stability, the incoming solar radiation, a roughness parameter or parameters descriptive of smaller-scale surface variation (closely related vegetation type), and a macro-scale surface roughness (related to the two-dimensional variance spectrum of the topography). Also, especially for water-vapor exchange, the temperature of the soil, a measure of soil-moisture content, and a dew point or specific humidity characteristic of the free atmosphere will be needed. It remains to be seen whether additional parameters related to the variation of macro-scale variables in space and time will also be required in the establishment of suitable empirical relations.

In the second category are exchange processes internal to the atmosphere. The magnitude of internal exchange due to meso- and micro-scale turbulence is even more poorly known. The internal exchange problem is closely related to the transformation of energy from one form to another by condensation and radiative processes. Thus, for example, the local release of latent heat due to condensation may be thought of as a heat "source" in the thermodynamic energy equation, and as a mass "sink" in the continuity equation for water vapor.

The macro-scale variables with which internal exchange and energy-transformation processes are to be related have yet to be formulated. Quantities to be examined will obviously include the field of mean vertical motion, and macro-scale variations of temperature, water vapor, and wind with height. The use of satellite information on cloud distribution and incoming and outgoing radiation will provide valuable information required to establish the validity of empirical relationships. Radar measurements of condensation processes will also be usfeul.

SURFACE-FLUX RESEARCH

RELATION TO PREDICTION PROBLEM

For time periods greater than about 3 days the atmosphere is influenced significantly by energy transformations occurring within it through radiation, evaporation or condensation, by turbulent dissipation, and also by boundary fluxes which transfer energy, momentum, and water vapor to (or from) the atmosphere. Therefore, the usefulness of the global observing system for extended prediction will be limited by our ability to specify the distribution of sources and sinks of energy, momentum, and matter and, most critically, by our ability to specify the global distribution of boundary fluxes. To do this the series of research investigations described below will be required.

Boundary fluxes must be obtained which are compatible with the macro-scale observing system, that is, which are representative of areas of about 250,000 km^2 and of time intervals of 3 to 12 hr. The primary objective of the research investigations must be to relate the boundary fluxes to the macro-scale observations. The most fruitful approach is likely to be both to extend fundamental understanding of the physics of the transfer processes and to develop empirical relations between the global observations and average fluxes. Fundamental understanding and derivation of empirical relations can be sought simultaneously through a carefully planned program in which a variety of independent methods are used to compute the vertical fluxes.

METHODS OF MEASUREMENT

1. *Reynolds flux*

The vertical fluxes of momentum, heat and water vapor can be directly computed from the co-spectra of fluctuations of the velocity components, temperature, and humidity. The required instruments are sophisticated and the data processing expensive, and only a few successful sets of measurements have been made in Australia, the Soviet Union, and at several institutions in this country.

Measurements can be made at fixed points a few meters above the land or ocean surface, and in aircraft flying about 100 m above the surface. Fixed-point measurements are feasible for the important spectral range between about 0.5 and 100 sec, but the sampling problem presented by the use of point measurements as representative of area averages is a serious one. Aircraft measurements reduce the sampling problem, but there may be significant inaccuracies associated with limited spectral range on the high-frequency side. Therefore, fixed-point and aircraft measurements should be made simultaneously.

2. *Profile methods*

The aerodynamic theory of flow over homogeneous rigid surfaces may be successfully applied to the calculation of boundary fluxes over land in a limited number of situations. Extension to calculation over water surfaces appears reasonable, but there are special difficulties due to the following: incomplete theory associated with water surfaces and with stability effects, smaller vertical gradients over water than over land, motion of floating platforms, and the general unfriendliness of the sea to field investigations.

3. *Conservation (or budget) methods*

The principles of conservation of mass, energy, and momentum may be applied to appropriate volumes of the atmosphere and of the land or water in order to calculate vertical boundary fluxes. Thus, there are six conservation equations available, though usually fewer than all six can be successfully applied in individual cases. Land or sea areas may be chosen to be compatible with the synoptic scale of the global observing system.

In general, to achieve useful resolution, averages must be taken over large areas and/or over extended time periods. Resolution is proportional to the magnitude of the boundary fluxes, so that in comparing fluxes determined by several methods it is important to choose areas and situations of large flux. A great variety of observing and measuring techniques may be used, including: aircraft, standard surface and upper-air stations, radar, streamflow, precipitation, ship, tower, and buoy observations. For comparison with other methods aircraft probably provide the most critical capability. The minimum time unit to which conservation methods can be successfully applied is probably determined by the time required for observing aircraft to complete a circuit of a test area of, perhaps, 250,000 km^2, and in most cases averages should be taken over several such time units. Thus, plans for comparisons of the several methods should be based on periods of the order of 12 hr. For longer time periods routine observations become more useful, and it will be important to carry out studies employing a range of time periods up to a month or even longer.

LAND TEST AREAS

The preceding discussion has emphasized the need for instrument and platform development and testing as well as for comparison of independent methods of measurement. To aid in these essential activities, two land test areas are proposed. The first area should be horizontally homogeneous and should be accessible to measurements using both fixed facilities and portable facilities. It should occupy several hundred square kilometers and should be extendable for certain purposes to a much larger area. Boundary fluxes should be measured at a number of sites distributed over the area, and efforts should be made to develop instrumental standards. The test area should be used in comparison and evaluation of the independent methods described above. The second test area should be in a mountainous region of greater extent than the homogeneous area, with boundary fluxes determined by the budget method. Responsibility for operation of test areas should be undertaken by a single laboratory or institution, but cooperation with other laboratories and institutions should be arranged. It is estimated that this research would cost approximately $6 million for a 5-year program.

LAKE AND OCEAN EXPERIMENTS

Instruments and techniques are already far enough advanced that carefully designed observational programs over water can be profitably undertaken. As has been emphasized in the National Academy of Sciences report, *Interaction between the Atmosphere and the Oceans* (NAS-NRC Publication 983, 1962), one of the Great Lakes offers advantages of accessibility, relatively protected environment, and the simultaneous use of water and atmosphere conservation equations. Other observational programs will be needed over portions of the ocean such as the Gulf of Mexico and over limited portions of the open ocean. The persistent and severe problems associated with corrosion, fouling, and wave and current forces require that platforms and instruments be tested under realistic conditions in the open sea and that development programs include these tests.

Experience has been acquired by many individuals and institutions in separate studies of boundary fluxes over water, conducted in Australia, Canada, the United Kingdom, Germany, Japan, the United States, and the Soviet Union. Relevant experience in comparisons of various methods has been acquired in the study of Lake Hefner conducted under Navy sponsorship in 1950 and 1951 and in studies in the Indian Ocean near Bombay conducted jointly by the University of Washington, the Woods Hole Oceanographic Institution, and the Weather Bureau in 1964.

Successful planning and execution of field programs of the sort described here require the coordinated effort of a considerable number of capable and experienced scientists, engineers, and technicians. Central planning and logistic management is important to success, and this has been lacking in the past. The recent establishment of the Sea Air Interaction Laboratory (SAIL) in the Department of Commerce is an encouraging development, and it may be appropriate to assign to SAIL the chief responsibility for coordination of the studies proposed here. It is estimated that this research would cost in the neighborhood of $7.5 million for a 5-year program.

THE TROPICS

SPECIAL STUDY NEEDS

In spite of the general inadequacy of data, research on the tropical atmosphere suggests that its structure and behavior may be more complex than in high latitudes. As in the higher latitudes, we can identify macro- and synoptic-scale tropical systems (such as subtropical anticyclones, the equatorial trough, and tropical cyclones), as well as meso-scale systems (such as the organized cloud patterns apparent on many satellite photographs) and micro-scale systems (ranging from individual cumulus clouds to turbulence elements important in boundary-layer exchanges). In contrast to the situation at higher latitudes, there is evidence to support the contention that local energy sources, particularly of latent and sensible heat, play an important role even in the largest-scale systems such as the trades and the equatorial trough, as well as in synoptic-scale systems. Since this energy is supplied by the earth's surface and is transported and convected by micro- and meso-scale systems, these processes must be described and understood. The outstanding example is the importance of the internal addition of latent and sensible heat energy in hurricanes, which accounts for the fact that these storms form only over the oceans.

In view of the above, it is impractical, if not impossible, to establish an operational data network adequately describing all scales with proper time resolution throughout the tropics. In the past, several special data-collecting programs have been carried out in low latitudes and have contributed much to our present knowledge. However, these programs are typically concentrated on only one scale of motion. Ultimately it is clear that some way must be found to express the influences of meso- and micro-scale systems in terms of synoptic and general-circulation-scale parameters. Hopefully, it will be possible to do this, but only after the energy fluxes and conversions on all scales and their interactions have been investigated quantitatively with adequate data.

IMMEDIATE VALUE OF THE GLOBAL OBSERVATION NETWORK

First, the network will increase the density of observations over the tropics by an order of magnitude and cover many large areas so far completely devoid of observations. This will make it possible to arrive at a definitive description of the tropical general circulation structure and of the mechanisms of latitudinal exchange of such properties as heat and momentum.

Second, the network will permit computations of variations of the mean meridional circulation and its role in the coupling between low and high latitudes.

Third, the question of whether there is an interrelation between the westerly belts of both hemispheres across the equator can be answered. The mechanisms of such coupling, its variations and influence on long-range weather anomalies in both extratropical zones, as well as in the tropics, can be studied.

Fourth, the network will be capable of giving a gross quantitative description of synoptic weather disturbances in the tropics, possible up to now only through comparison of numerous cases. Numerical models may then be developed for predicting the motion and intensification of tropical disturbances on the scale of several days.

Fifth, from budget calculations, it should be possible to make a close estimate of the residual functions to be performed by motions on scales smaller than those defined by the global network.

PROBLEMS REQUIRING ADDITIONAL RESEARCH

Irrespective of the foregoing, it is recognized that studies involving the several scales of motion must be carried out, if only to demonstrate that macro-scale motions govern the behavior of the atmosphere on smaller scales. This is not completely obvious *a priori*. Following are some of the problems on which further research is needed:

(1) Formulation of the proper form of the dynamical equations under conditions of widely varying gravitational stability for application to tropical disturbances.

(2) Understanding of the energy transformations in situations where the energy of motion is derived largely (and possibly by devious ways) from condensation heating in an atmosphere that is nearly moist adiabatic. It must be postulated that the surroundings do work by means of pressure forces on the precipitation area, permitting the latter to remain in existence. Recent calculations indicate that tropical synoptic disturbances with such cold cores can be maintained from energy released by the primary general circulation.

(3) Adequate formulation of the thermodynamic transformations in convective situations where important vertical and lateral mixing occur on small scales, so that conservation of entropy cannot be required of individual small masses of air.

(4) Because heat of condensation is important, the micro-physics of clouds and rain cannot be rejected out-of-hand as factors of little importance. For instance, the total count of condensation nuclei may determine the efficiency of warm clouds as precipitation producers. Cloud-physics measurements should be made and related to the synoptic structure of the atmosphere.

(5) Under strong wind conditions, the immediate air–sea interactions assume great importance for the growth of storms; no direct measurement of such interaction has ever been made at gale force winds or higher.

(6) The tropical disturbances are usually open systems with respect to extratropical and perhaps also cross-equatorial interactions, quantitatively unexplored and probably of highly nonlinear character.

(7) Interactions between meso- and synoptic-scales of disturbances have recently been found to be far more varied and complex than had previously been thought. In waves in the easterlies alone, no less than four distinct types of thermal and cloud patterns have been observed. Simultaneous observations on both the meso- and synoptic-scales must be made to ascertain the nature of these interactions.

DEVELOPMENT OF A DETAILED OBSERVATION PROGRAM

At least two experiments are needed: one over a continental area such as Africa, the other over an oceanic body such as the Caribbean. Because of the great diversity of tropical synoptic-scale disturbance in different geographical areas, it would be highly desirable to carry out additional experiments in the western Pacific and in the region of the Marshall and Gilbert Islands.

In the detailed observational program, it must be possible to make measurements over the entire extent of the active parts of a tropical weather system. Heavy augmentation of the superpressure balloon release, plus aircraft observations at various levels, are visualized as the principal tools of observation, in addition to such satellite capability as may be available. Some of the measurements, however, can be executed from platforms, such as oceanographic vessels and weather ships, where the use of stationary barrage balloons and kitoons is recommended, in addition to other forms of measurement, for observation of detailed time trends in the free atmosphere. It is further suggested that a portion of the observations proposed in the chapter on Ocean-Surface Observations be concentrated at these installations, so that the interaction between all scales of motion can be observed and analyzed.

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II

Technical Considerations

CHAPTER THREE

INTRODUCTORY REMARKS

INADEQUACY OF PRESENT NETWORK

Studies undertaken by the World Meteorological Organization (WMO) indicate that 90 percent of the surface of the earth has an inadequate number of upper-air observing stations. A division of the globe into 100 equal areas shows 11 areas with adequate upper-air observational coverage (20 or more stations), 10 areas with marginal coverage (10–19 stations), 29 with less than minimum coverage (3–9 stations), and 50 with totally inadequate coverage (less than 3 stations). The WMO Executive Committee Working Group on World-wide Meteorological Networks has proposed the addition of 53 upper-air stations. This will provide one or two additional stations in areas that, at present, have no coverage or only one or two observing points. The situation is somewhat less desperate as far as surface observations are concerned, although still far from satisfactory.

The inadequacy of the Northern Hemisphere network may be illustrated in another way. Mashkovitch[1] has calculated the errors of interpolation of the geopotential of three selected isobaric surfaces from the existing aerological stations to a uniform array of grid points dividing the hemisphere into equal squares on a polar stereographic projection. The interpolation is performed by a method that minimizes the mean-square error. The relative errors of interpolation, ϵ, expressed as the ratio of the mean-square error to the mean-square deviation from the climatic mean, are shown in Figure 17. The location of the aerological stations regularly reporting observations at present are shown in Figure 18.

If one takes $\epsilon < 0.02$ as representing a reasonable criterion to be fulfilled by an observational system, one obtains a relative r.m.s. error of $(0.02)^{1/2} \times 100 = 14$ percent. Since the r.m.s. deviation of the geopotential from its climatic average is in the range of 100 to 200 m, $\epsilon < 0.02$ represents an upper bound of 14 to 28 m on the error in the geopotential. It will then be seen from Figure 18 that only about 20 percent of the Northern Hemisphere is adequately covered by observations. Since the Southern Hemisphere network is almost entirely inadequate, one again obtains 10 percent as approximately the fraction of the earth adequately covered by upper-air observations.

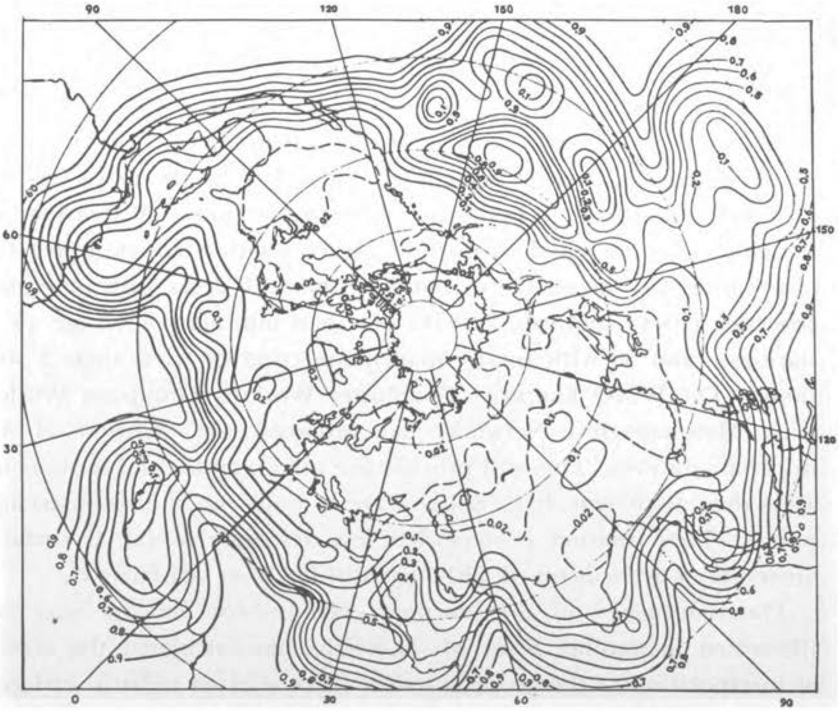

FIGURE 17. Errors ϵ of interpolation corresponding to the distribution of stations shown in Figure 18.

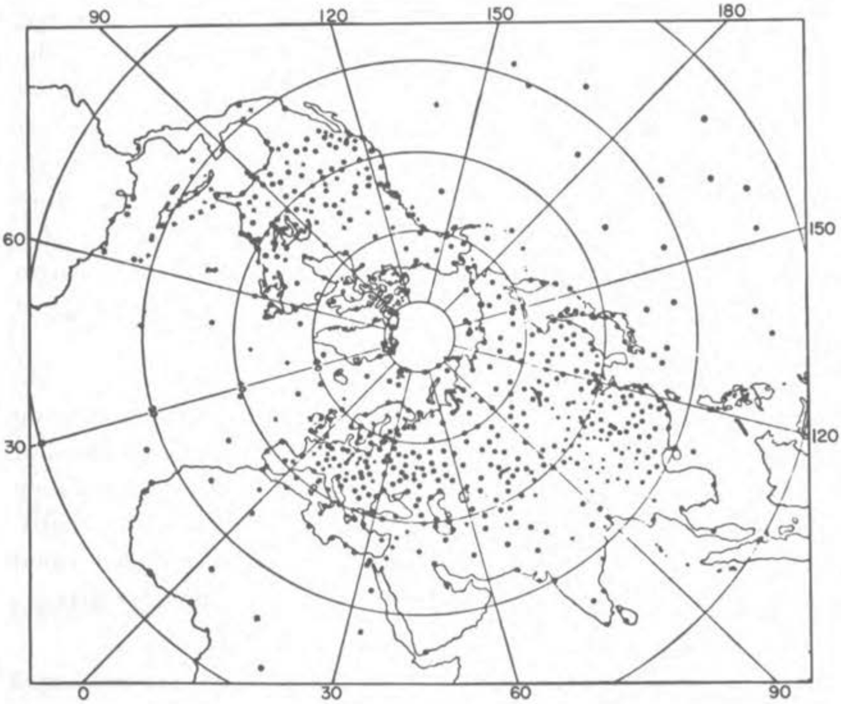

FIGURE 18. Location of aerological stations regularly reporting observations at present.

ALTERNATE OBSERVATIONAL SYSTEMS

It appears that the extension of conventional radiosonde networks would, at present, be a prohibitively expensive method for obtaining the global upper-air data. Acquisition of data by aircraft using direct-sensing techniques or dropsondes can provide additional capability. However, this means of acquiring data is also expensive, although well suited for special problems. Fixed ocean weather ships can be used in a supplementary way as gap fillers to obtain information but their cost is warranted only in critical areas. Commercial ships appear to offer better possibilities. These can be staffed with trained observers and supplied with radiosonde equipment for upper-air observations of pressure, temperature, and humidity. The measurement of upper winds presents greater but not insuperable difficulties. Although such a system has inherent limitations in cost, reliability, and coverage, there is every evidence that the observations would constitute a valuable adjunct to the existing system. However, neither this nor any of the other more conventional means of acquiring observational data over the oceans can be expected to provide a complete global description of the macro-state of the atmosphere at a reasonable cost. Ships and aircraft will continue to be expensive aerological observing platforms (or sensors), lacking the flexibility and potentiality of a system consisting of light, neutrally buoyant, unmanned floats interrogated by satellites.

Satellite technology now provides us with a surveillance and communications system in which unmanned devices, fixed or free-floating in the atmosphere or the oceans, can be interrogated for geophysical information. In addition, satellites provide a means of obtaining information about the state of the atmosphere through direct radiation measurements. We are able already to observe global cloud distributions and to generate crude temperature and moisture data.

FREE ATMOSPHERE MEASUREMENTS

One of the promising developments in the field of unmanned sensing devices is the superpressure balloon. This platform makes it possible to obtain continuous measurements of wind, temperature, density, pressure, water vapor, and ozone. The present technology in balloon development makes it possible for balloons weighing approximately 1 kg to remain aloft for periods of several months, floating at constant density-altitudes in the middle and upper atmosphere. These unballasted balloons, with associated thin-film or miniaturized electronics, can in principle be built so that they constitute no significant hazard to aircraft. Under the continuous surveillance of satellites, their location can be determined at suitable intervals to compute their rate and direction of motion, thus providing wind information. The temperature, water content, and other parameters can be relayed by telemetry to the satellite for readout at ground stations.

These balloons can be flown at altitudes ranging from 850 to 10 mb (higher if necessary), and it appears that approximately 4,000–8,000 balloons in each hemisphere will provide complete global coverage at a sufficient number of key altitudes. The balloons at the lower levels will have a shorter useful lifetime than those at the higher levels.

Direct measurements from satellites are already providing information on radiation balance and cloudiness, and crude information about temperature and moisture structure. The possibilities for the future dwarf present accomplishments. Instrumentation already under development may yield more detailed and accurate descriptions of the vertical distribution of temperature and moisture, as well as the delineation of areas of rainfall and intense convective activity.

However, neither satellites nor the horizontal balloon observing systems will eliminate the need for more conventional vertical soundings. Such soundings will still provide a standard against which other techniques will be measured. The desirability of increasing the frequency of standard radiosonde observations should be examined as a means of substituting information in the time domain for information in the space domain.

SURFACE OBSERVATIONS

Expansion and augmentation of the surface observing network will also be required. Here again, satellites may be useful both as vehicles to carry sensors and as interrogation and communication devices. For the land areas of the world that are inaccessible, fixed unmanned sensing stations that can be interrogated by satellites are well within technological capability. For the ocean areas of the world, either fixed or floating buoys that also can be interrogated by satellites can provide the density of surface weather data required for the studies outlined in this report. This aspect of the problem is discussed in the chapter on Ocean-Surface Observations.

Insofar as the properties of the frictional boundary layer in the atmosphere are determinable from the properties of the underlying surface and of the free atmosphere above the boundary layer, one can dispense with measurements within the layer itself; i.e., it should, in theory, be possible to dispense with surface measurements of such properties as velocity and temperature and moisture in the surface boundary layer of the atmosphere and in the wind-stirred upper layer of the oceans. In practice, however, no existing boundary-layer theory has the required accuracy and completeness, and surface measurements will remain necessary.

USE OF SATELLITES FOR LOCATION, INTERROGATION, AND COMMUNICATION

Several satellite systems have been proposed to perform the functions of location, interrogation, and communication. These are (a) the IRL system of the U.S. National Aeronautics and Space Administration, (b) The EOLE system of the French National Center of Space Studies, and (c) the GHOST system described in the present report. Each of these systems has been planned to satisfy a somewhat different set of design criteria, and each, therefore, has certain advantages and disadvantages with respect to the others. The following is a brief description of the IRL and EOLE systems.

THE IRL SYSTEM

The IRL (Interrogation, Recording, and Location) system is designed to collect data from a number of automatic unmanned stations. It has the capability of locating moving stations such as balloons and free-floating buoys. An experiment using the Nimbus B satellite is planned for 1967. This experiment should provide a most useful test of the feasibility of determining accurate location. A technical description of the IRLS experiment is given in Appendix B.

THE EOLE SYSTEM

France is planning a major test program (Project EOLE) of a balloon–satellite weather-data-gathering system for 1968 in the Southern Hemisphere. The system to be used is similar in many respects to the GHOST and IRLS configurations (Appendixes A and B, respectively). However, it has been designed for satellite simplicity, and no effort will be made to program new address codes on each orbit. Consequently, the experiment is limited to 512 balloons, the maximum number that may be sequentially coded.

A number of excellent electronic features have been introduced in the French system, which might be used in modifications of the IRLS or in the eventual GHOST systems. A technical description of the EOLE system presented in an IUGG report by Blamont[2] is reproduced as Appendix C.

It is desirable at this point to describe some of the differences between the IRLS and GHOST systems. Since the IRL system has been designed for an early test with a variety of observation platforms, the emphasis has been placed on versatility and reliability rather than on compatibility with the balloon system. In contrast, the GHOST system to be described takes cognizance of the need for satellite communication with balloons, which, for safety and economy, are required to have minimal size, weight, and cost. Such a system is in a sense optimal, but it is recognized that a considerable engineering development program is required before it can be realized.

CHAPTER FOUR

THE GLOBAL HORIZONTAL-SOUNDING TECHNIQUE

INTRODUCTION

The observational system to be described here is an instance of a fully integrated balloon–satellite system that is deemed to be operationally feasible. It is the product of the efforts of a study group that was asked to investigate the feasibility of a balloon–satellite system for measuring the synoptic-scale motions of the entire lower atmosphere. The basic observations were to be pressure, temperature, humidity, and wind at levels from 850 to 10 mb.

The study group has defined its objective within the framework of its charter to *establish the feasibility, capability, and practicality of a Global Horizontal-Sounding Technique* (GHOST) *from an engineering standpoint*. In addition it has presented a best estimate of an orderly development program leading to a system serving both operational and research needs.

The report provides a history of work in the acquiring of weather observations from horizontal floating balloons, defines a useful system, describes the present state of the art required to produce such a system, and delineates necessary developments. A system that will meet the requirements that have been defined is then described, and an implementation program outlined.

HISTORY

THE SYSTEM CONCEPT

The first horizontal-sounding system was introduced by the Japanese in 1944 with the Fugo balloon-bomb. In a period of 5 months, 9,300 balloons were launched against the United States. Many of the balloons were equipped with radio beacons to permit the Japanese to determine the trajectories of the balloons, forecast the expected trajectories for future flights, and verify their original estimates of the wind patterns at the 10-km level. It might be well to remember when we consider the economic feasibility of GHOST that a single nation, as a diversionary tactic, launched more than 60 large balloon systems a day in time of war.

The first large-scale attempt to obtain exclusively meteorological data using horizontal-sounding balloons was an Air Force project called Project Moby Dick.[3] Flights were made at altitudes of 15 to 22 km over the United States from 1950 to 1952, with tracking provided by radio direction finding. The primary intent of these flights was to obtain stratospheric wind data above the altitudes then achieved by radiosondes.

The U.S. Navy embarked on a development program in 1951 to obtain meteorological data over ocean areas. An operational system called Transosonde[4] was flown in 1957, and a limited-scale flight program was conducted over a period of 2 years. A 12-m-diameter plastic balloon carried an instrument gondola equipped with sufficient ballast for 5-day flights. Tracking was accomplished by FCC and Navy radio direction-finding stations. The combined weight of balloon, instruments, and initial ballast was about 300 kg. This system was the first to provide data inputs to the operational weather teletype circuits. Flights were made at 250 mb. With the advent of jet aircraft operations over the Pacific, flights were discontinued.

The Navy has since developed a light-weight (5-kg) version of the Transosonde system using superpressure balloons,[5, 6] but work was discontinued after a limited flight-test program.

In June 1957, the American delegate to the Commission on Aerology of the World Meteorological Organization described a proposed horizontal sounding system and invited all nations to contribute to a program to develop the system. The Commission recommended (CAe-II/Doc. 79-E, Annex II) "that research in the creation and development of horizontal-sounding techniques be encouraged." The basic program, which was given the title of GHOST, was described in detail by Haig and Lally[7] in 1958. At this time it was made evident that a useful system must fly at aircraft altitudes and must therefore not constitute a hazard to aircraft. The concept of filmed electronics mated to the superpressure balloons to provide a global data-gathering system was introduced. In 1959, Lally proposed[8] that the superpressure balloon, thin-film electronics, and the communications satellite could be bound together to constitute the most efficient atmospheric data-collection system.

The Air Force Cambridge Research Laboratories proposed a test program[9] in the Northern Hemisphere, employing the FCC High Frequency Direction Finding Network to track superpressure balloons across the Pacific. In the last 3 years, efforts at AFCRL have been concentrated on development of large superpressure spheres for carrying heavy loads to high altitudes. Flights of 30 days' duration have been achieved with balloon performance still adequate at termination.

In 1962, a report was prepared by the Joint Meteorological Satellite Advisory Group to the National Aeronautics and Space Administration describing a balloon–satellite system that had the added capability of locating emergencies. The planned system was called STROBE,[10] and it represents the most complete description of a practical system to date. However, no work has been done to test the basic design concepts.

The National Aeronautics and Space Administration has proceeded with the development of a communication system to permit interrogation, location, and readout of land stations, floating platforms, and balloons. As previously mentioned, this system is called IRLS (Interrogation, Recording, Locating System), and is planned for test as an experiment on the Nimbus B satellite scheduled for launch in 1967. This data-collection system, by updating addresses on each orbit, has a capability of interrogating several thousand platforms. It also has a capability of readout of a large number of data points from each platform.

Sylvania has made a study for the National Aeronautics and Space Administration[11] of a data-collection satellite that will recover data from balloons, free-floating and fixed buoys, and fixed ground weather stations. The assumption is made that there will be 300 balloons and 900 fixed and floating buoys and fixed ground stations. This assumption biases much of the analysis. However, the report does provide much useful data on position-location errors as a function of balloon motion and displacement from the orbital path.

Stanford Research Institute[12] has made an analysis of the applications of a data-collection satellite having position-locating facilities. The study was concerned with collecting and collating the views of interested parties to determine the geophysical uses of such a satellite.

The students in a graduate engineering course at Stanford University, under the direction of Dr. William Bollay, carried out an analysis and preliminary design study for a global meteorological satellite data-collection system. The report* found that "the use of a satellite system to collect worldwide meteorological data could not be excelled by any other method in terms of global coverage, speed, reliability, and cost."

BALLOONS

The large plastic balloons presently used for scientific experiments are called "zero-pressure" balloons, since the balloon has an open appendix to permit the exhaust of excess gas that otherwise would cause the balloon to burst. During the sunlit hours, the balloon film, usually polyethylene, is heated, and transmits this heat to the lifting gas. At sunset the gas cools and the balloon loses lift. To maintain the balloon at altitude, ballast must be dropped—from 5 to 10 percent of the gross system weight. The Moby Dick balloons carried sufficient ballast for 3 days. The Transosonde balloons carried sufficient ballast for 5-day flights. The balloons were necessarily large to permit the carrying of the required ballast. Such ballasted systems become completely unreasonable in weight for flights in excess of 2 weeks. A system with sufficient ballast for even 1 night provides

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* SWAMI (Stanford Worldwide Acquisition of Meteorological Information) Report No. 213, issued June 1964 by the Stanford University Department of Aeronautics and Astronautics.

a hazard if it is at aircraft altitudes, and our weather data are most urgently needed in the altitude region inhabited by aircraft.

The Office of Naval Research sponsored the development of cylinder balloons and, later, small spherical balloons made of Mylar between 1957 and 1960 to permit the development of a light-weight Transosonde system with a payload of 12 lb in two 6-lb segments. (This remains the maximum load that can be flown on a balloon without falling under FAA regulations.) The balloons were made without any appendix, so that the free lift introduced on the ground was converted to superpressure at flight altitude. If we assume that the balloon is tight and unyielding, the overpressure equals free lift plus superheat. When the gas cools, the overpressure decreases but remains positive. Since mass and volume are unchanged, the balloon continues to float at a constant density–altitude without ballast.

The Navy-sponsored program provided no outstanding flights, but much was learned on problems of seals, pinholes, and the necessary overpressures required to overcome day–night and infrared-radiation fluctuations.

The Air Force Cambridge Research Laboratories has sponsored since 1957 a continuing program in the development of superpressure balloons.[13] However, in recent years the emphasis has been on large balloons for heavy-load-carrying capability. No flights of the small light-weight systems required for operation in the airlanes have been made. In May and June 1962, AFCRL flew a 34-ft Mylar sphere with a 40-lb payload for 19 days with command cut-down and a second sphere for 30 days with timer cut-down. Later a 54-ft balloon was flown for 28 days with an 80-lb payload. Flights are now being made with the 120-ft balloons carrying 300 lb of payload. Although these balloons are much larger than those planned for the GHOST system, the flights indicate the potential of the superpressure balloon. The basic advances that made these flights possible were the development of strong "bi-tape" seals on both sides of the balloon gore and the use of bilaminated Mylar film to eliminate leaks caused by small pinholes in the cast film.

In April and May 1964, 13 balloons designed to float at 200 mb were launched by NCAR from Japan. The balloons were equipped with a sun-angle detector, transmitter, and cut-down timer. Only four of the balloons stayed aloft for the scheduled time of 6 to 10 days, indicating a need for careful inspection and leakage test just prior to launch to detect pinhole leaks introduced in packing and shipping.

COMMUNICATIONS LINK

Since the basic objective of a constant-level balloon program is to obtain weather data in remote and inaccessible areas, the communications link, prior to Sputnik, was always considered as a high-frequency radio link. A number of receivers at widely separated sites obtain directional bearings on the signal, and a fix is obtained from bearing intersections. The highly skilled crews of the Federal Communications Commission (FCC) can obtain fixes accurate to 20–30 miles over an area from the mid-Pacific to the eastern Atlantic Ocean. However, ten balloons in this area would saturate the capability of the FCC network because of the precise and time-consuming measurements and computations required.

Moby Dick and Transosonde both used the services of the FCC network, which proved adequate for limited operations. The FCC also tracked the Japan GHOST flights of 1964 to provide checkpoints for calibration of the navigation device.

The NCAR GHOST flights used a high-frequency transmitter that telemetered a code proportional to sun-angle. From a number of sun-angle readings, a position location is obtainable. Accuracy of fixes varied from 100 to 200 miles. Some improvement is expected in a modified model. This method does have the advantage over direction finding in that only one receiver is needed and data are obtainable even with weak signals.

The satellite offers a unique capability for obtaining accurate location and reliable coverage on a global basis. Since wind data are derived from consecutive position fixes of a balloon, accurate data require precise positioning, and the satellite promises at least an order-of-magnitude improvement in position accuracy. High-frequency direction finding, sun-angle detectors, and other interim procedures are simple compromises while we await the availability of a data-collection satellite.

BALLOON ELECTRONICS

The electronic packages for the Transosonde and Moby Dick balloon systems weighed over 50 kg. The NRL-developed light-weight Transosonde weighed 5,000 gm. The NCAR-developed package used in Japan weighed 240 gm. However, this unit did not have storage cells and operated only during daytime hours. It was constructed with no special attempts to reduce weight. An analysis of the GHOST interim electronics indicates that it could be reduced to 80 gm, using commercially available thin-film techniques.

There has been very little work on the development of thin-film electronics for balloon use. AFCRL contracted with RCA to build a light-weight 5-W transmitter that weighed 55 gm with available components and a pliable substrate. It was housed in a Styrofoam container weighing 81 gm. When fired at a velocity of 600 mph into an aircraft windshield consisting of eight laminae of glass, only the first lamina was cracked. When fired into a leading-edge wing section, the package penetrated to the first spar. Homogeneous foam-plastic plugs without electronics were fired into a similar wing section, and dimpled the skin without penetration.

The test results indicate that three-dimensional light-weight instrumentation will cause damage, although not catastrophic to the wing and windshield of an aircraft traveling at 600 mph. However, foamed masses apparently will not penetrate.

In the original concept of Haig and Lally, it was considered that electronics would be filmed on the balloon. Later the idea was modified to consider the use of thin-film modules on a separate plastic "pillow" balloon carried below the main balloon. A transmitter weighing less than 1 gm including the Mylar substrate[14] was constructed using this technique. Some work on this type of thin-film module has been continued at the G. T. Schjeldahl Co., but no major effort has begun.

During these years, however, a major revolution has occurred in the development of microminiature circuits. At least 50 companies are now qualified to make circuits (generally in three-dimensional configurations) that are so small that their mass can be considered negligible in terms of impact hazard.

A modest effort on thin-film batteries has been made at the Harry Diamond Laboratories, which indicates that there are acceptable engineering solutions.

Solar cells now in large production for space applications are light enough and inexpensive enough to provide a satisfactory energy source. The silicon cells of 1 × 2 cm weigh less than 0.3 gm per cell in conventional thickness, and cells have been made weighing less than 0.1 gm. For daytime transmission only, 50 to 100 of these cells provide an adequate energy source for a low-powered balloon electronics system.

SENSORS

1. *Wind*

The superpressure balloon, of course, moves with the wind field. Wind data may be obtained from knowledge of the position of the balloon over a time interval. The accuracy with which we can position the balloon determines the basic accuracy of the wind measurement. However, if the integration time is made large, a relatively poor location capability still can provide acceptable winds integrated over this long a period. The basic objective of the Moby Dick and Transosonde systems was to obtain wind data. Position fixes were made at periods usually of three hours. Since the balloon location was known to an accuracy of 20 to 30 miles, a typical error in the 3-hour averaged wind was 10 knots. The balloons flown from Japan using a built-in navigator could be located only to an accuracy of 100 to 200 miles. Obviously, any wind data obtained from hourly positions of these balloons would be useless. However, the plot of the balloon positions from day to day provided useful data in terms of the general circulation.

In order to obtain accurate wind data averaged over short periods of 1 to 2 hours, the balloon position must be fixed within a very few miles. Only the satellite system provides a possibility of obtaining such accurate fixes over the entire globe.

2. *Pressure*

Pressure measurements have been made on constant-level balloons using conventional aneroids. These have provided sufficient accuracy up to altitudes of 30 km. However, on those systems where Morse-coded outputs were obtained from aneroid pressure elements, the sensitivity in terms of the discrete outputs from the aneroid often has not been sufficient to give a good indication of the vertical motion of the balloon. Since the superpressure balloon flies at a constant density–altitude, it does not appear necessary to measure pressure:

a knowledge of density and temperature would provide pressure data. However, the light-weight Transosonde flights revealed pressure variations that could not be correlated with temperature changes. Pressure measurements are planned at least on the first experimental flights of superpressure balloon systems to determine whether the pressure element is needed in the final operational system.

3. *Temperature*

The measurement of temperature from a balloon floating in the air mass requires great care. The lack of ventilation introduces radiation errors during both daytime and nighttime hours. The conventional radiosonde thermistor element is black in the infrared and if not ventilated, suffers errors in excess of 1°C due to variation in the infrared environment. In its normal use it is ventilated by the ascending balloon at a rate of 5 to 6 m per sec. Tests made by Ney[15] and by Wagner show that a small metallized bead thermistor or a thin wire will have a negligible radiation error whether ventilated or not. However, the small bead suffers from self-heating when placed in a measurement circuit, and the thin wire requires elaborate electronic circuitry to permit accurate telemetry. Mastenbrook used a small bead thermistor on his most recent Transosonde flights, and apparently was able to measure temperature within 1°C with the use of a sophisticated electronic circuit that minimized self-heating. If the existing radiosonde element is mounted vertically, the error from solar radiation below 30 mb will not exceed 1°C. A knowledge of sun-angle can reduce this error to less than 0.5°C. The infrared error is large and more difficult to correct with the present element. A metallized version, however, will reduce this error to less than 0.5°C for altitudes below 30 mb.

4. *Humidity*

Since the constant-level balloons, both zero-pressure and superpressure, that have been flown to date have been flown at altitudes above 100 mb, there has been no attempt to obtain humidity measurements. At the lower altitudes where humidity would be a significant parameter, it appears that conventional techniques for measuring humidity will be completely adequate. The biggest difficulty in humidity-sensing on radiosonde systems has been to obtain high speed of response. The humidity-sensor on the superpressure balloon will be maintained in its environment for many, many hours, and the reading that it provides can be an integration of the basic moisture in this particular air mass. With the removal of the requirement for fast speed of response, we have a large number of attractive humidity-transducers to select from.

5. *Overpressure*

Superpressure balloons have been outfitted with overpressure measurement devices in order to monitor balloon performance. These devices themselves, however, indicate the radiation environment of the balloon and may prove of use in the future in providing an additional measurement parameter. Since the balloon is essentially black in the infrared, the variations in overpressure can be attributed to changes in the radiation environment.

A USEFUL SYSTEM (SYSTEM-PERFORMANCE CRITERIA)

ALTITUDE

Superpressure balloons can be flown at any altitude up to 45 km. The cost of a balloon flying at a very high altitude is great, and the life expectancy of a balloon flying close to the surface is quite short. It would appear that balloons floating at up to six standard levels between 850 mb and 10 mb would be adequate. The desired altitudes should, of course, be specified by the meteorological community. Flight at altitudes below 500 mb will pose problems in duration, with the chance of the balloon being forced down by orographic or meteorological influences. At altitudes above 100 mb, the cost of the balloon begins to increase, although we can expect compensatory increase in the probable life of the balloon.

NUMBER OF BALLOONS

In order to provide truly global coverage at any altitude in both hemispheres, it would appear that a minimum of 1,000 balloons should be provided at each of the altitudes. If economic or other considerations force a limitation on the number of balloons to be used, then it would appear to be wiser to reduce the number of levels rather than the coverage of any one level. However, the more persistent and orderly circulation in the stratosphere would undoubtedly permit an adequate delineation at the higher levels with a smaller number of balloons. It would appear that the number of balloons required for a particular level above 100 mb could be of the order of one half of those required at lower levels. The short life-expectancy of balloons flying at 850 or 700 mb might prevent the use of as many as a thousand balloons at each of these altitudes. However, launchings would be established to provide a maximum coverage at these levels over the large ocean areas where upper-air data are presently lacking.

SENSORS AND ACCURACIES

It would be desirable to measure the wind to an accuracy of 1 or 2 knots averaged over a period as short as an hour. Such measurements would permit computation of accelerations in the wind field and accurate measurement of divergence and convergence. If such refined accuracy is not feasible, or economically justifiable, then a wind-determination to an accuracy of 2 or 3 knots, or 5 percent (whichever is greater), averaged over a period up to 2 hr, would appear to be entirely adequate and far superior to the presently achieved accuracy of wind-determination with radiosonde systems. Temperature should be measured to within 0.5°C, and the pressure altitude within 100 m. Dewpoint should be measured within 2°C for dewpoints above 0°C and within 4°C for dewpoints to –40°C. For altitudes above 300 mb, it would perhaps be best to dispense with humidity measurements and substitute ozone measurements.

It would be desirable, of course, to measure the integrated vertical wind over a long period of time to determine whether the air mass is subsiding or rising. Hopefully, measurement of the higher-frequency vertical motions could be used to determine turbulence.

LOCATION ACCURACIES

In order to determine winds averaged over a 2-hr period to an accuracy of 3 knots, the probable error in the positioning of the balloon should not exceed 4 nautical miles. This appears to be a reasonable and realizable requirement on a satellite-location system. When wind speeds are high, this accuracy of location is not required, since larger absolute errors in wind speed are permitted. Since balloon motion is one of the factors leading to error in position-determination, this error is balanced by a less restrictive requirement on absolute accuracy.

SAFETY

The safety requirement for the GHOST system is easily stated. The platform should not provide a hazard to either propeller-driven or jet aircraft at any of the altitudes at which the balloons will fly. The argument that the system will be much safer than radiosondes is not a valid one. The radiosonde is a hazard to air navigation in its present form and the low probability of a radiosonde–aircraft impact does not justify complacency. The radiosonde itself must be redeveloped as a nonhazardous airborne system, just as the GHOST balloon vehicle and electronic package must be nonhazardous. The safety of the GHOST system must be demonstrated in ground and airborne tests.

SATELLITES

A single polar-orbiting satellite at an altitude of 600 miles will provide every 12 hr a pair of readings at all points on the globe and readings on every pass in areas in the polar regions. This would appear to be a completely satisfactory capability for the initial implementation of the program. An equatorial-orbiting satellite would provide essentially continuous data readout over the entire region within 20° north and south of the Equator. Other useful configurations would be a second polar-orbiting satellite in an orthogonal orbit to the first one, which would halve the period between readings—providing 6-hr data readings in the worst cases and, in the temperate and polar regions, essentially continuous data. A third alternate might be use of a second satellite in the same plane as the first and 180° out of phase. This would permit wind measurements to be averaged over periods of the order of 50 min rather than 100 min. Such a technique is only justifiable, of course, if the accuracy of balloon location makes the shorter averaging time more attractive.

DATA PROCESSING—DATA POINTS

The satellite of the GHOST system is basically a communication device. It provides a ranging and telemetry link from the balloon and then provides a readout link to the ground. With the number of balloons indicated above, it is conceivable that up to 2,000 of these could be interrogated in a single satellite pass. The maximum readout from each balloon platform should not exceed 100 bits, so that the total readout of data from satellite to ground communication link is a modest 200,000 bits. Even if we assigned a redundancy of tenfold to the data output, the total of 2,000,000 bits is still of the same order as the data output from a single high-resolution Tiros or Nimbus picture.

In order that the satellite can efficiently interrogate large numbers of balloons on each pass, it must be programmed on each pass with the addresses and approximate times at which it should interrogate balloons during the orbit. The ground environment associated with this system is obviously complex: the data must be extracted from the satellite; the position of the satellite accurately known as a function of time; the range readings associated with a particular balloon programmed through a computation cycle to provide balloon location; and then the telemetered data printed out and associated with a particular balloon. The computation process also must feed back to the satellite the new program of times and addresses for its next cycle, based on a prediction of where the balloons will be at this later time.

With only a single satellite, some balloons will be "lost" due to error in the prediction of trajectories during the long periods between communications. To overcome this difficulty, the addresses of missing balloons can be placed in a search category and the addresses transmitted globally until they are either found or abandoned.

In the final concept of the GHOST system we can envision a computer programmed with a multilevel model of the atmosphere, which is continuously up-dated in real time as new balloon data are introduced, and the computer corrects or modifies its model in such a fashion that all data are used as soon as acquired. The problem of entering synoptic and off-time data into a computation scheme is thereby avoided, and data are not held until they can be put together with some later inputs. This computer, as it maintains and up-dates its data on its complete model of the global atmosphere, is capable of reading-out whenever required a current picture of atmospheric conditions on a global basis or, when requested, of providing a prognostic description for some future time.

STATE OF THE ART, 1964–1967

BALLOONS

Superpressure balloons can presently be made of laminated Mylar gores in sizes from 4 ft to 120 ft in diameter that will withstand stresses in excess of 10,000 psi at temperatures tested as low as —60°C. The ability to withstand these high stresses permits the design of small light-weight balloons for the carrying of modest payloads. Table 1 indicates the size and the thickness of balloons required within the existing state of the art to carry payloads to various altitudes using gored bilaminated Mylar balloons. The designs are based on a safe

TABLE 1A. *Standard Atmosphere Values Used in Computations*

Pressure, mb	850	700	500	300	200	100	30	10
Altitude, m	1,457	3,012	5,574	9,164	11,784	16,180	23,849	31,055
Temperature °K	278.7	268.6	251.9	228.6	216.6	216.6	220.5	227.7
Density, kg m^{-3}	1.062	0.908	0.692	0.457	0.321	0.160	0.0474	0.0153
Lift of He, kg m^{-3}	0.915	0.782	0.596	0.394	0.277	0.139	0.0408	0.0132

TABLE 1B. *Balloon Specifications for 300-gm Load*

Pressure Altitude (mb)	Balloon Diameter (ft)	Balloon Diameter (m)	Film Thickness (mils)	Balloon Mass (gm)	Maximum Stress[a] (psi)
850	5.0	1.52	4.0	1,290	11,600
700	5.0	1.52	3.5	1,120	10,800
500	5.0	1.52	2.5	775	10,900
300	6.0	1.83	2.0	950	9,800
200	7.0	2.13	1.6	820	9,500
100	8.0	2.44	1.0	820	8,700
30	13.0	3.97	0.5	1,080	8,500
10	34.0	10.35	0.5	7,460	7,400

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[a] Stress at 25 *percent* over pressure.

balloon stress level for overpressures of 25 percent of atmospheric pressure at float altitude. It is not expected that overpressures will exceed these amounts at any of the designated altitudes. Not enough is known as yet on the maximum overpressure that will be realized by balloons floating at the several altitudes to provide final design data. NCAR plans to make a number of flights in 1965 at all these levels, with appropriate telemetry to provide adequate design data.

The present method of making balloons from many gores is an inefficient system resulting in excess weight and the possibility of leaks along seams. At least for balloons up to 8 ft in diameter, it would appear to be of great advantage to be able to manufacture the balloons from a much smaller number of individual sections, which would be cast in the spherical shape and assembled with a minimum of seals. The balloon not only will be much less vulnerable to leakage but also will be able to stand much greater stress because of its truly spherical shape.

The greatest problem in superpressure design is the development of leak-free balloons. Until the use of bilaminated Mylar, the reliability of small superpressure balloons was completely unsatisfactory. The bilamination technique eliminates problems of pinholes in the basic Mylar material. It does nothing, however, to prevent the introduction of pinholes during the manufacturing and packaging processes. Leakage through the balloon film because of defects of various kinds constitutes the basic limitation on flight duration. Figure 19 is a graph of diffusion through a spherical Mylar balloon as a function of temperature. The tabulation accompanying Figure 19 shows the percentage of loss of gas per day through typical balloons of 5-, 7-, and 13-ft diameter at temperatures which would be encountered at the float altitude. If we design the balloon with sufficient overpressure that only after a 6 percent loss will the balloon lose its superpressure under adverse conditions of radiation, the table indicates that a 7-ft-diameter balloon flying at a skin temperature of −30°C at 200 mb will maintain adequate overpressure for 2 years. Even a small 5-ft-diameter balloon flying at an average temperature of −10°C at 500 mb will hold adequate pressure for more than 6 months before diffusion of gas reduces the superpressure by 6 percent.

A Mylar balloon can now be manufactured that will survive in the atmospheric environment for a period in excess of several months with

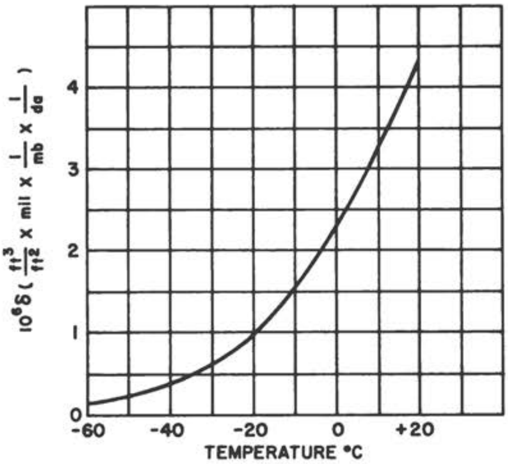

FIGURE 19. Diffusion through a 300-gm load spherical balloon as listed in Table 1B.

$$\text{LOSS PER DAY} = \frac{4\pi r^2 \times P \times \delta}{t}$$

$$\text{\% VOLUME LOSS PER DAY} = \frac{\text{Loss/Day}}{4/3\,\pi r^3} \times 100 = \frac{300\Delta P\delta}{rt}$$

Balloon Type	% Loss/Day
700	0.10
500	0.03
200	0.008
30	0.002

adequate structural integrity and with no problem with respect to molecular diffusion through the balloon film. At this time, however, we have no assurance that balloons with no leakage through pinholes or defective seams can be made with present manufacturing techniques. Large balloons have been flown for periods up to 30 days; small balloons have been flown for periods in excess of 2 weeks. It is necessary to provide an adequate test facility to measure the existing capabilities of manufacturers to make leak-free balloons. NCAR has built a facility that is being used for balloon testing. Balloons in several sizes have been procured from all qualified manufacturers, and careful leakage tests are being performed. The validity of the leakage tests will be tested in Southern Hemisphere flights during 1965 and 1966. It is planned to set up a similar test facility in the Southern Hemisphere so that balloons can be tested prior to flight, and then flown immediately without any deflating, refolding, repacking, or any handling of the balloon that might introduce defects subsequent to the test.

We are sanguine that the next year will prove conclusively the ability of small superpressure balloons to survive in the atmosphere for periods of many months. However, a reasonable investment in the development of a balloon-fabrication technology over the next few years is required to ensure that small superpressure balloons can be made reliably and at reasonable cost. Materials such as polypropylene, which may be formed more satisfactorily than Mylar, certainly should be investigated.

BALLOON INSTRUMENTATION-ELECTRONICS

The electronics industry has passed by the original concept of providing thin-film evaporated electronic components on a plastic substrate. It may well be that the small three-dimensional integrated circuits can be made so small that there will be no need of filming the electronics over large surface areas. However, the integrated circuits that are presently commercially available have been made for relatively high-speed operations with no major attempt to reduce the power consumption within the individual circuit elements. An independent development program is required to produce nonhazardous GHOST electronics. This program can either take the form of a modification of existing integrated circuit techniques to reduce the mass required for rugged encapsulation for extreme environmental capabilities—or, as a more primitive alternative, to carry on the development of reliable thin-film circuits that will be evaporated on a thin plastic film substrate. In either case, emphasis should be placed on the development of low-power consumption circuits operating at extremely slow speeds. The bit rates required for telemetry and command in the GHOST system concept are extremely low, and the necessary transmission bandwidths are very narrow. There is, therefore, no need for the high-speed high-power consumption circuits currently being manufactured by all the electronic firms concerned with development of micro-miniature circuits.

POWER SUPPLY

Solar cells provide the only acceptable existing power source for the GHOST system. Silicon solar cells of efficiency approaching 12 percent are presently available. If we assume an average power requirement of 200 mW, 100 such cells would provide this power during most daylight hours. The total weight of the cells would be less than 20 gm. These cells currently cost about $2.50 apiece, although rejects for satellite application that are still completely satisfactory for balloon operations can be purchased for considerably less.

If we have to provide power to operate the balloon electronics on a nighttime as well as daytime basis, 100 cells would still suffice to provide an adequate capability for storage in most areas. During the winter months in polar regions, at least twice this number of cells would be required. The cell cost and cell weight now approach numbers that may be of concern. A number of cells are being developed that will be considerably less efficient than the silicon cell, but which promise much lower costs and can be made by processes that permit essentially a thin-film solar-cell capability. General Electric is presently manufacturing on an experimental basis cadmium telluride cells of 4 percent efficiency, which weigh 30 mg/cm^2 of surface, including the substrate. The thickness of the cell material is approximately 1 mil and there appears to be no reason why the cell could not be made upon a thinner substrate, if required.

There is no existing storage cell that could be considered thin film in structure or nonhazardous for balloon operations. There is no reason why thin-film storage cells could not be manufactured. The requirements on the cell itself, however, are quite severe, since the storage cell should operate at temperatures down to $-60°C$ and should be capable of recycling many hundreds of times. A single thin-film nickel–cadmium storage cell that exhibited superior temperature performance to conventional nickel–cadmium cells and was recycled many times has been built at the Harry Diamond Laboratories. It is clear, however, that a major development effort must be undertaken to provide a storage capability adequate for the nonhazardous electronics requirement of the GHOST system. Since there is no assurance that such a storage cell will be developed within the next three years to an operational capability, even with the investment of major funds, it would seem appropriate at this time to plan for initial operation of the GHOST system in such fashion that the balloon can be interrogated only during daytime hours, with power supplied from solar cells and with a modest storage capability to take care of peak power requirements during the few seconds per day of transmission.

SENSORS

No sensors designed in the appropriate configuration for use with the superpressure balloon are currently available. A modification of the existing radiosonde thermistor, providing a metallized coating as a substitute for the present lead carbonate coating, should provide a sensor accurate to 0.5°C for all altitudes up to 30 mb.[15]

During test flights of the GHOST system, it is considered advisable to use accurate aneroid pressure sensors on initial flights to determine whether the balloon is flying stably enough at its constant density–altitude to permit the determination of pressure from the known values of density and temperature. If experiment indicates that a pressure element should be a basic transducer on an operational system, then a development program is required to engineer an accurate pressure element of minimum mass. Since the variation in pressure on any balloon flight will not deviate by more than 10 percent at most flight levels, then the problem of developing an accurate minimum-mass aneroid element is much less severe than the development of an equivalent radiosonde element that must operate over a range of two orders of magnitude. No difficulty is seen in providing such a sensor if required.

The development of an adequate humidity sensor for lower-altitude GHOST flights may well prove to consist of a literature survey of elements that have been developed in the past for radiosonde and other uses and which have been rejected because of poor time constant. The carbon and aluminum oxide elements look particularly attractive for this application, although there may be other elements with much inferior response times that will provide a greater stability over their lifetime with less temperature sensitivity. It will take a major development program to obtain useful humidity sensors for altitudes above 500 mb.

One of the most intriguing possibilities with respect to the superpressure meteorological measurement system is the possibility that the device may be used for measuring clear-air turbulence. A black bead heated by the sun will show variations in its resistance as it is cooled by slight wind motions with respect to the balloon. These variations may well be interpreted as small-scale turbulent phenomena that can be correlated with large-scale turbulence. The only difficulty envisioned in such a measurement is that the satellite will interrogate the balloon only at infrequent intervals and will read out telemetered data as it exists at the moment. Any sensor that requires readout of a history of variation in the element to be measured poses a serious problem in telemetering.

COMMUNICATION

No basic engineering breakthrough is required to communicate the command address from a satellite to a balloon and to provide the response from the balloon to the satellite. The one difficulty within the present state of the art in communicating from balloon to satellite lies in the frequency to be used. Frequencies for communication must be in the VHF or UHF region, and the assignment of VHF channels for a single service appears to be difficult to obtain at this time. This leads to the assignment of UHF channels, which are completely acceptable for most applications. However, the balloon system must be developed with minimal weight, size, and complexity of electronics, which in turn dictates a solid-state system. Within the current state of the art there are no adequate, efficient, solid-state transmitters operating in the frequency range above 400 mc/sec. There is reason for optimism that within the next 3 years such capabilities will be available. VHF communication will permit narrower bandwidth not only because of the greater ease of holding frequency drift within narrow limits, but also because Doppler shift will cause a smaller absolute effect at VHF than at UHF frequencies. In addition, the capture area of a simple antenna structure will be greater at VHF. However, advances in higher-frequency solid-state devices are coming so rapidly that UHF systems may soon be competitive.

SATELLITE COMMUNICATIONS

The communication of instructions from the ground to the satellite and the readout of data from the satellite to the ground produce no difficulty with the contemplated system. Instructions from ground to satellite are merely new programmed addresses that the satellite will then call out at assigned times in its orbit. The total number of bits required for communication from ground to satellite and associated satellite storage for the most complicated imaginable orbital program would not exceed 2,000 addresses and associated times. The total storage would certainly not exceed 50,000 bits of nonredundant data. This corresponds to a few feet of magnetic-tape storage, or, if so desired, a reasonable core-storage capability within the satellite. The readout data from satellite to ground for storage certainly would not exceed 2,000,000 bits even with the most redundant techniques for data transformation. This, of course, implies a certain amount of data processing on the satellite of the data received from the individual balloons, to minimize storage. However, the techniques of converting analog data telemetered from the balloon back to the satellite into stored digital data are well within present comfortable state of the art.

DESCRIPTION OF THE SYSTEM

The system described below is not intended to be a detailed description of the final configuration of the GHOST system. A number of questions are still to be answered both in the evaluation of capabilities of the components and in the completion of a full system-design study. It does, however, provide a workable and realistic capability that will meet the requirements described earlier, and it does provide a description of a system that is within the state of the electronics and satellite art as we know it today. This is true not only because of the difficulty of building a satisfactory electronic system weighing only a few hundred grams that will survive for many months in the atmosphere, but also in consideration of the numbers of balloons involved. We are dealing with one or two ground stations, one or two satellites, tens of fixed ground stations, hundreds of free-floating weather buoys, and thousands of balloons. The maximum intelligence must be placed in the ground environment; the next order of complexity assigned to the satellite; and the most simpleminded of solutions provided for the balloon platform. Other platforms may then be designed into the system as add-ons, if appropriate.

BALLOON PLATFORM

1. *Payload*

The balloon design is critical with payload. In Table 1, the size and weight of balloons required to carry a 300-gm payload at a given altitude was shown. As a general rule, doubling the payload to be carried by a balloon doubles the required weight of the balloon. For reasons of balloon economy, as well as for reasons of aircraft safety, payload should be kept to the absolute minimum. The major contribution to weight in the balloon payload will be the storage cell that is required to provide 24-hr capability for the balloon system. There appears to be no difficulty in providing a transmitter, receiver, and electronics capability as well as adequate solar-cell power in a package weighing 300 gm. In the section on power supply below, the problem of construction of a thin-film storage cell is described, and estimates made of weight. At this time, our best estimate of an adequate storage-cell capability would add 300 gm to the payload.

2. *Altitude*

The altitudes at which the GHOST balloons are to be flown should be determined by the meteorological community. For this particular system analysis, we have defined the altitudes to be used as 850, 700, 500, 300, 200, 100, and 30 mb. These are, of course, somewhat arbitrary choices and it should be remembered that the balloon itself flies at a constant density–altitude and not at a constant pressure–altitude. Flight at the 10-mb density–altitude is perfectly reasonable and feasible. The larger and more costly balloons would undoubtedly be compensated at this altitude by the longer expected life duration. In addition, the greater persistence of the circulation in the stratosphere would undoubtedly permit a much smaller number of balloons to be used at either the 30-mb or the 10-mb surface.

For purposes of cost analysis, we have assigned 2,000 balloons to the 850-, 700-, 500-, 300-, 200-, and 100-mb surfaces, and 1,000 balloons to the 30-mb surface. In the section on costs, an analysis is given of the expected life duration at each of these altitudes, tied in with the cost of the individual system.

It may be possible to fly balloons successfully at density–altitude levels as low as 850 mb. However, such balloons will be useful only over the great ocean areas. Certainly there is little reason to expect them to survive for any appreciable period of time over land areas. Topography, precipitation, and strong vertical currents would doom such balloons to short life. Test flights must be conducted over the ocean areas to come up with reasonable estimates of the expected life of balloons at 850 and 700 mb before we can place confidence in the cost estimates for these levels.

3. *Sensors*

The basic sensor proposed for the GHOST system in its initial implementation would be air temperature and pressure. Telemetry channels should be made available for the addition of at least three sensors assigned for special research purposes. Eventually, some or all of these channels might be taken over for use in measurement of humidity, ozone, and radiation.

4. *Launch sites*

Total replacement of balloons flying between 500 and 30 mb probably would be of the order of 20 to 30 per day with an additional replacement of the order of 15 per day required at 700 mb. Since the 700-mb balloons will be used primarily to obtain data over the great ocean areas, launch sites would in general be set up along the coast lines of the continents so that the prevailing winds of the season would take the balloons out over the ocean areas on the longest possible trajectories. It would appear that between 25 and 50 launch sites would be adequate on a worldwide basis to permit reseeding of balloons at all levels as instructed by the main computation facility. Each site would be committed, on the average, to only one or two launches a day. Since the system must be accepted as a completely international system so that flights will be permitted in both Southern and Northern Hemispheres, it would appear worthwhile to set up launch sites in as many countries as desire to participate in the program. This might provide an excess over the number of sites required, but would not necessarily increase the basic costs of the program. It would, of course, be feasible to set up for most of the balloons an air-launch capability to inject at the best place at the right time. However, this would be a costly capability and would in a sense subvert the goal of complete international cooperation.

Launch sites for the sea-level floating-balloon systems would best be from ships at sea. Logistics problems of getting such floating balloons to the right place at the right time appear much more formidable than the problems of launching the superpressure balloons.

5. *Launch checkout*

The superpressure balloon, at least at this time, is a delicate device that suffers from handling, folding, and packaging. It appears that a leakage check must be made on each balloon prior to flight. A simple leakage-check procedure has been developed that involves accurately weighing-off the balloon with an amount of gas slightly less than that required to superpressure the balloon. This weigh-off is performed in a cold room where temperature is accurately controlled. The balloon is then moved to a warmer room where temperature is controlled and pressure monitored. The balloon pressure rises to a known superpressure and is kept in the second room for a period of the order of a day. When returned to the first room the balloon is then reweighed and any loss in life assigned to leakage. Under extremely careful control, it appears reasonable that leakage as low as 0.01 percent per day can be detected by this technique. Such a check-out chamber has been built at NCAR at a cost of $15,000.

Once the balloon has successfully passed its leakage test the excess gas is removed and the balloon can then be flown. It should never be repackaged, refolded, or handled. It is believed that with this technique we will be able to obtain reliable flight for extended periods.

ELECTRONIC SYSTEM

1. *Balloon electronics*

The balloon electronics, of course, must be kept as simple as possible with minimum power consumption. The principal functions to be performed by the balloon electronics are as follows:

(a) To recognize and respond to an address when interrogated by the satellite.

(b) To transmit some form of information that can be then interpreted as a range by the satellite system.

(c) To telemeter back to the satellite three or four meteorological parameters to an accuracy of the order of 1 percent.

Appendix A provides one approach to the balloon and satellite electronics. It is not represented as the only or best solution. It is a workable concept within the current state of the art; and it is designed with the point in mind of absolute simplicity for the balloon-electronic system. The multiplication by a factor in excess of 10,000 of any cost element assigned to the balloon, required the shifting of complex functions to the satellite or to the ground.

No detailing is included on the transmitter or receiver. We can only reiterate at this time that every effort should be made to use VHF frequencies rather than UHF. Such an assignment will provide substantial cost, power, and weight reductions on the balloon vehicle.

2. *Satellite electronics*

A concept of satellite electronics that is compatible with the balloon electronics and well within the present state of the art is included in Appendix A. All processing that can be performed on the ground is transferred to the ground, except that analog inputs from the balloon are digitized prior to storage and transmission to the ground. This straightforward digitizing reduces storage requirements and permits rapid, error-free transmission to the ground environment.

3. *Ground programming and readout*

The ground system to serve the balloon-satellite system will comprise the most complex and most expensive aspect of the enterprise. It will consist of a basic computer capability and a communication link both to and from the satellite. A block diagram of the ground system is shown in Figure 20. Information on the location of every balloon must be stored within the computer-programmer capability and there must be a capability to predict the probable position of the balloon on the next satellite pass. Programming instructions must be transferred to the satellite, providing addresses to be called out as a function of time on the orbit so that the satellite will address the balloon as it approaches and as it withdraws from the balloon. This program must be revised on each pass of the satellite. It should be noted that the satellite capability for storage here is not sophisticated; it is simply the storage of an address code that will be read out as a function of time. The data transmitted from the satellite back to the ground will consist of the addresses of each of the balloons interrogated, digital outputs that will be a function of the phase comparison of the two subcarriers, and a digital ranging output in terms of the delay in arrival time of the returned ranging signal; this plus three or four digital outputs of no more than seven bits in terms of meteorological parameters. For each balloon the amount of information transmitted should not exceed 100 bits. Of course, there will be two readouts from each balloon as it is interrogated on approach and withdrawal of the satellite. With only two range readings* there will be an ambiguity in the position of the balloon so that the position will be either to the left or to the right of the satellite. The ground

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* The assumption is made that two range readings are sufficient. The data obtained from the IRL system on Nimbus B can be used to determine whether two or three range readings should be taken in each pass.

system can make an assumption on which is the more probable location. On a satellite that passes directly over a balloon or quite close to it, of course, the ambiguity in reading will not be resolvable by the ground environment.

In this case a particular reading is not used and the readings from the previous pass and the next pass will be used in deriving wind data. The balloon will be interrogated by the satellite on three successive passes whenever the second pass is over or close to the balloon.

POWER SUPPLY

In the "STROBE" report the receiver-power requirement is indicated as 150 mW. The NASA IRLS receiver calls for 1.5 W of continuous power. The Sylvania report estimates a 250-mW requirement. The real requirement cannot be known until the system is initially designed and frequencies assigned. The conservative estimate of a UHF receiver and associated address decoder would appear to be 200 mW. A VHF system would require less power—perhaps as little as 100 mW. Since the duty cycle of the transmitter will be less than 0.1 percent, a 10-W power requirement during transmission will increase average power consumption only to 210 mW.

The total power requirement for 24-hr operation becomes 5 W-hr. If we assume the use of existing solar cells of 12 percent efficiency, we may compute the requirements for 24-hr use:

Solar cells mounted horizontally
Solar input at balloon level = 1,000 W/m^2
Sunlight for 10 hr
Average incidence equal to 0.3 of normal
Charging efficiency of 0.8
Energy available per day per m^2 = $0.12 \times 1{,}000 \times 10 \times 0.3 \times 0.8$
= 288 W-hr
Solar-cell area required = 5/288 m^2 = 173 cm^2
Number of 1×2 cm cells required = 87.

If we assume a 14-hr night, a storage battery must provide 3 W-hr of storage capacity. With a 50 percent discharge, the capacity must be 6 W-hr. On the assumption that a high-efficiency storage cell can be fabricated with close to optimum capacity to weight ratio, a nickel–cadmium thin-film battery would weigh about 300 gm. A silver oxide–cadmium battery might weigh as little as 100 gm.

Until a satisfactory storage cell with adequate low-temperature (—60°C) characteristics is available, it may be necessary to restrict operations to sunlit hours. The same number of solar cells, 87, would provide acceptable operation for all sun angles above 6° over the horizon. A storage capacity of less than 0.01 W-hr would be required to provide peak transmission requirements.

A summary of power-supply weights and cost for 24-hr and daytime-only use is estimated below.

	24-hr Capability	*Daytime Only*
Solar cells (1 × 2 cm)	87	87
Solar-cell weight	17 gm	17 gm
Solar-cell assembly weight	35 gm	35 gm
Solar-cell cost per balloon	$100.00*	$100.00*
Thin-film battery weight	300 gm	—
Peak-power battery weight	—	10 gm
Estimated battery cost	$50.00	$5.00

The development of a thin-film battery for 24-hr operation is a necessary element of the complete GHOST system. This development should be pursued as a first-priority item in the program.

SATELLITE SYSTEM

In the initial system, a single polar-orbiting satellite will provide adequate data coverage, permitting a minimum of two paired sets of observations per day. With a satellite orbit of 600 miles, the paired readings would be about 110 min apart. Each set would be separated by 12 hr. At high latitudes, either three or four observations would be possible during each 12-hr period. There is no requirement that data be collected simultaneously with a picture-taking satellite. On the other hand the planned Nimbus polar orbit at 600 miles provides a completely acceptable configuration.

In the ultimate system, the preferred configuration might be two satellites in the same orbital plane spaced 180° apart. Each balloon would be interrogated at 55-min intervals, providing an almost ideal averaging of the wind field. Such a configuration can be justified

* Silicon solar cells are presently available on surplus market at $0.20 to $1.00 per cell.

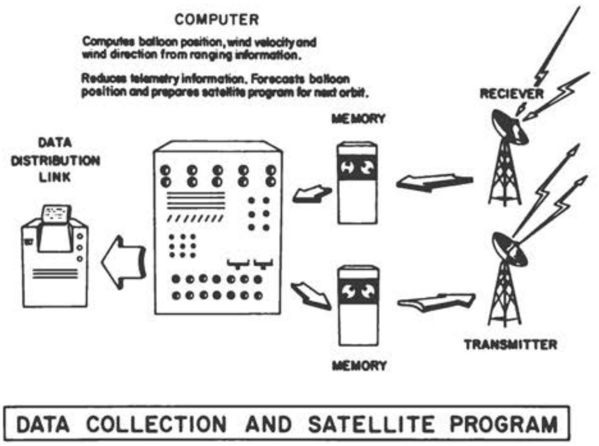

FIGURE 20. Schematic diagram of ground station.

only if the satellite system is capable of locating the balloon within one or two nautical miles.

No attempt is made in this study to describe satellite design. The satellite is basically a simple device of less complexity than a TIROS system. Storage and readout can be in tape form as TIROS and NIMBUS, or it can be a two- or three-dimensional core of film storage as proposed for IRLS.

GROUND ENVIRONMENT

The GHOST system will increase by severalfold the world's output of atmospheric data in the troposphere and lower stratosphere. The ground data-handling system that accepts these data is necessarily complex, converts into a usable form for reprogramming the satellite, reduces to a useful language for numerical analysis and prediction, and provides instructions to launch-sites on the type of balloon to be launched, address to be set, and time of launch to replace dead balloons and fill gaps.

Figure 21 provides a sketch of the data-flow between ground station, satellite, and balloon. It should be noted here that there can be only one control center for a GHOST satellite. International participation may include launch-sites and data-sharing, but programming and readout must be centralized. It would be quite feasible for nations or agencies to have their own independent satellites to interrogate the shared balloons, but there can be no sharing of the control or readout of an individual satellite. The balloons can serve many

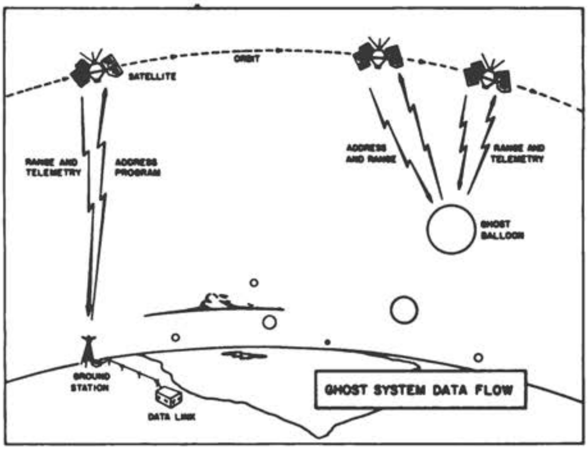

FIGURE 21. Schematic data-flow diagram.

satellite masters, but the satellite can serve only one control center. It is also quite feasible over any geographic area to set up ground interrogation stations to monitor *continuously* the location of all balloons within line-of-sight of the locating network (two or three stations). Such a network would be especially useful for research studies where continuous and precise tracking is desired. The ground interrogation would have to be suspended for a brief period during the satellite overpass to prevent jamming.

If it is desired to operate the major computer elements of the ground environment remotely, a high-quality voice link is all that is needed. Since the data readout from a satellite will not exceed 2×10^5 bits, a 10^3 bit/sec dataphone link could be used to relay the total information in three minutes. A microwave or coax link, of course, could be used to relay all data in a few seconds.

RECOMMENDED IMPLEMENTATION

MANAGEMENT CONCEPT

The development of the balloon–satellite system is a complex program involving many interrelated design decisions. Since the balloon and its associated electronics must not constitute an aircraft hazard, it may be necessary to make many compromises in optimum system capability to ensure a safe system—without compromising the over-all utility of the system as a means of obtaining adequate atmospheric data on a global basis. For example, it may be desirable to accept a daytime-only capability in the first version of the system until an adequate, safe, storage battery is developed.

The development tasks for so highly integrated a system can not be assigned to the several interested agencies on the basis of existing competence. There must be a clear assignment to a single agency to conduct the development and test program. This designated agency may then call on other competent groups for assistance on specific tasks.

SYSTEM-DESIGN STUDY

The GHOST system has been the subject of a number of design studies over the last 8 years. None of the studies has been in sufficient depth to constitute a careful system design. Several have been committee efforts that suffer from lack of depth, attempts to couple the GHOST system to other worthwhile satellite systems, or an effort to describe a broad spectrum of feasible techniques. These studies have provided a useful background literature for a detailed system-design study but are not a substitute. The design study must include sufficient experiments and tests to provide answers to the critical questions.

Competitive schemes for the addressing, ranging, and telemetry should be carefully evaluated and the most promising scheme or schemes breadboarded and tested.

The problem of aircraft safety must be honestly faced and suitable tests made to determine potential hazard.

The major problem in the system-design study is the ground environment. Computer programming should be set up to provide for the use of Lagrangian data and to permit the updating of data within the computer on a continuing basis as it is received from the satellite. Careful analysis should be made whether it is feasible to provide all the computing functions at a remote site from the data-acquisition and command station. The basic problem of balloon loss by leakage or meteorological or orographic attrition should be answered in field programs.

Concurrently with the system-design study, a component evaluation study should be conducted to provide essential data to the system-design study and to ensure that certain key long-term component-development efforts are initiated as early as possible and do not hold up the over-all system development. In the next section a number of the key component-evaluation studies and development programs are described.

COMPONENT-EVALUATION DEVELOPMENT STUDY

There are a number of electronic components for the GHOST system that have not yet been built. The principal one of these is an adequate storage battery made in thin-film form and adequate to temperatures of −60°C. This is the one component whose characteristics are still uncertain. The major development effort is a first priority item in order to produce such a power supply.

Decisions must be made during the course of the system design on the frequencies to be used for balloon receivers and balloon transmitters. A strong technical preference is indicated for VHF rather than UHF. The assignment of such clear channels on a worldwide basis will require considerable political skill. Once the basic assignments are made or there is an indication of the frequency band in which these frequencies will be assigned, development should move ahead on both transmitter and receiver for the balloon system. The basic techniques to make light-weight nonhazardous thin-film transmitters and receivers are known and within the current state of the art. However, it appears that a 1-to-2-year development program will be required to provide efficient transmitters and receivers for the balloon vehicle. If frequencies above 400 mc/sec are assigned for this application, the development effort may extend beyond 2 years. A development program should be initiated on methods of fabricating thin-film circuits specifically for the balloon application, whether the electronic circuits take the form of mist-module circuits evaporated on a basic Mylar substrate or consist of light-weight versions of existing micro-miniature circuits. In either case, a development program is needed to optimize the design of the circuits for this particular application.

To date, it has not been possible to provide reasonable tests for balloon performance for small superpressure vehicles. Before any major investment is made in the GHOST system we must have conclusive proof that small superpressure balloons will survive in the altitude ranges from 850 mb to 30 mb. The only feasible way to make such tests at this time involves the use of HF transmitters to locate the balloon and to telemeter data, and relies on the cooperation of the amateur radio operators in the Southern Hemisphere to provide data output. NCAR plans to begin flight operations in the Southern Hemisphere in late 1965, flying balloons primarily at three altitudes and testing various meteorological sensors. Primary emphasis in the initial part of the program will be in determining balloon performance and balloon parameters. If balloon performance proves to be satisfactory, emphasis will shift to provide more accurate location techniques for the balloon and experimentation with a variety of atmospheric sensors. It is hoped that this Southern Hemisphere flight program can serve as the test bed for basic component evaluation and for the testing of new and improved balloon configurations. All balloons will be carefully tested for leakage rate prior to flight, and flight results will be correlated with predicted duration based on leak tests.

The answers that it is hoped will be obtained from this flight program are: (a) the capabilities of small superpressure balloons to fly for extended periods of time, (b) the testing of temperature, pressure, overpressure, and radiation sensors on superpressure balloons, (c) the extent of clustering of balloons in particular areas, (d) the extent of cross-equatorial flow, (e) crude initial estimates of the planetary climatology of the wind circulation in the Southern Hemisphere at three altitudes, (f) the practicability of using large rugged balloons floating on the sea surface to provide wind and other meteorological data over the open ocean areas as a substitute for buoys.

GLOBAL OBSERVATION EXPERIMENT

It is essential that component development proceed during the system-design study. By the time the design study is completed, the basic questions in the components area should be answered:

(a) Expected balloon-flight duration at the several altitudes,
(b) Hazard to aircraft,
(c) Availability of thin-film battery.

Assuming the answers to these questions are sufficiently encouraging, a global observation experiment should be conducted. Major balloon launching should await the check-out of the satellite ranging and programming system with a limited number of balloons. Once this is accomplished, launches can commence—perhaps limited to a single hemisphere initially if economic and political circumstances prevent the full implementation.

SCHEDULE

A detailed schedule of development prior to a detailed system-design study is an exercise in futility. What follows is an intuitive estimate of what needs to be done, an approximate estimate of the time required, and a recognition of a necessary order of accomplishment. A slippage of 1 year is inevitable if assignment of mission responsibility is delayed.

First Year

Assignment of complete mission responsibility by the federal government to a single agency;
System-design study;
Determination of hazard problem and establishment of hazard criteria;
Southern Hemisphere balloon and sensor flight test program;
Thin-film battery development;
Development of improved balloon materials and fabrication techniques.

Second Year

System design completed;
Balloon and battery developments continued;
Southern Hemisphere tests continued;
Satellite system development;
Balloon platform electronics development;
Ground environment development.

Third Year

Battery development completed;
Decision to operate initially on a 24-hr or daytime-only basis;
Decision on lowest practical flight level;
Balloon development continued;

Southern Hemisphere tests continued;
Test of satellite–balloon ranging technique as a pick-a-back on a planned satellite.

Fourth Year

Satellite, ground environment, and balloon platform electronics developments completed.

Fifth Year

Satellite launched;
Balloons launched in global experiment.

CHAPTER FIVE

CLUSTERING OF CONSTANT-LEVEL BALLOONS

INTRODUCTION

The feasibility of the Global Horizontal Sounding Technique (GHOST) depends on the expected benefit and the cost of the system. The cost in turn depends on the number of balloons required to obtain the desired density of weather observations. If there is a pronounced tendency for the balloons to cluster in certain areas, the release of additional balloons to fill the data gaps might greatly increase the cost of the system. Three different groups, utilizing different techniques, have studied the problem of balloon clustering.

J. Angell, at the U.S. Weather Bureau in Washington, D.C., used the National Meteorological Center (NMC) historical tapes to calculate 60-day balloon trajectories at 500 mb for 24 different starting times, with the hypothetical balloons spaced initially at about 1,000-km intervals (Figure 22). These trajectories were computed with the aid of a quasi-geostrophic, three-level forecast model; the nondivergent components of the wind were derived from the balance equation and a Poisson equation was solved for the irrotational component. No forecast was involved in these calculations; the balloons were advected (in 1-hr steps) by means of spatial and temporal interpolation from

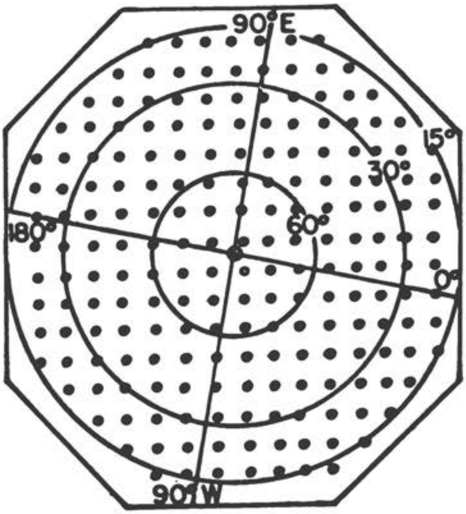

FIGURE 22. Northern Hemisphere grid points from which the hypothetical 500-mb balloon flights began (polar stereographic projection).

velocities determined from the actual 12-hr observations. When a balloon reached the equatorial limit of the NMC grid it was removed from the system; consequently there was a continuous decrease in the number of balloons.

Y. Mintz, at the University of California at Los Angeles, used the Mintz-Arakawa global, primitive-equation forecast model to determine 32-day trajectories at 800 and 400 mb for balloons initially spaced at intervals of 7° latitude and 9° longitude. The characteristics of this model have been described in Part One.

F. Mesinger, at the National Center for Atmospheric Research at Boulder, utilized a scheme similar to that of Angell, but with some improvement:* First, trajectories were computed in isopycnic surfaces, the surfaces on which a constant-volume balloon would actually move. These were chosen at $\rho = 1.012$ and 0.458 kg m^{-3}, corresponding approximately to 800 mb and 300 mb. Second, flow through the equatorial limit of the grid boundary was allowed so that the number of balloons remained essentially constant.

ANGELL'S RESULTS

In order to obtain balloon-density statistics, one may determine (a) the number of balloons within arbitrary squares or (b) the distribu-

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* A detailed description of Mesinger's results is given in Appendix D.

tion of distances between pairs of balloons or from the balloons to fixed points. (The latter techniques are theoretically preferable and have been used by Mesinger.) Angell simply counted the number of balloons within 2,000-km overlapping squares (170 such squares available).

Figure 23 shows the distribution of balloons 5 to 60 days after release on November 9, 1962 at the 200 grid points indicated in Figure 22. The isopleths show where the balloon density exceeds four and eight balloons per 2,000-km square, and the stippling represents areas where no balloons at all are to be found within a 2,000-km square. The latter areas are located mostly near the equatorward edge of the grid because of the loss of balloons to the tropics.

Diagrams similar to Figure 23 were prepared for all 24 starting times. The standard deviation of the number of balloons per 2,000-km square was evaluated, and, in order to compensate for the loss of balloons, it was divided by a factor proportional to the square root of the mean number of balloons per square. The resulting quantity is

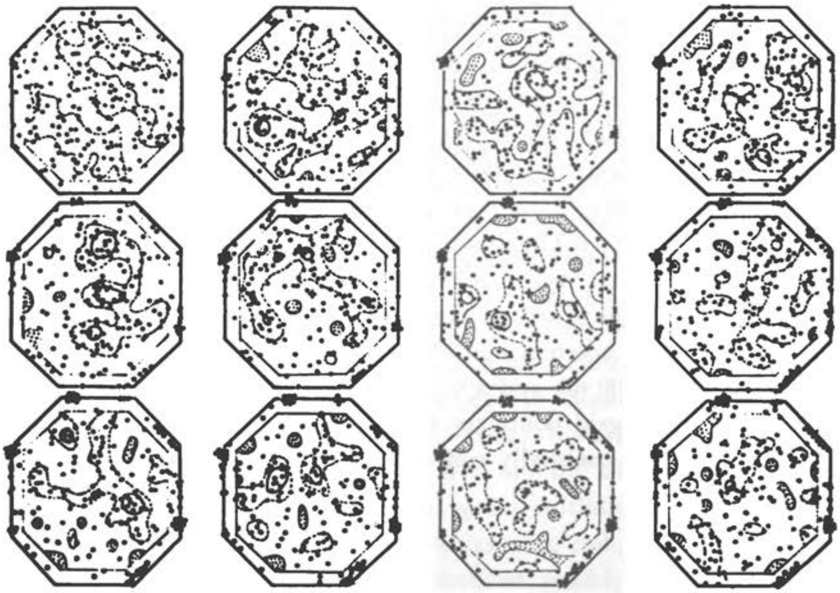


FIGURE 23. "Balloon" positions, at 5-day intervals, from 5 to 60 days (reading from left to right and then down) based upon 500-mb trajectories originating, on November 9, 1962, at the grid points indicated in Figure 1. The balloon positions on the boundary indicate where the balloons passed out of the NMC grid.

called a clustering index. Figure 24 shows the clustering index at 500 mb as a function of time after release. It will be seen that there is a wide variation in the degree of clustering with date of release and with time after release. Figure 25 gives the average clustering index at 500 mb as a function of time after release for summer and winter and the average of summer, winter, and fall. In the mean, clustering

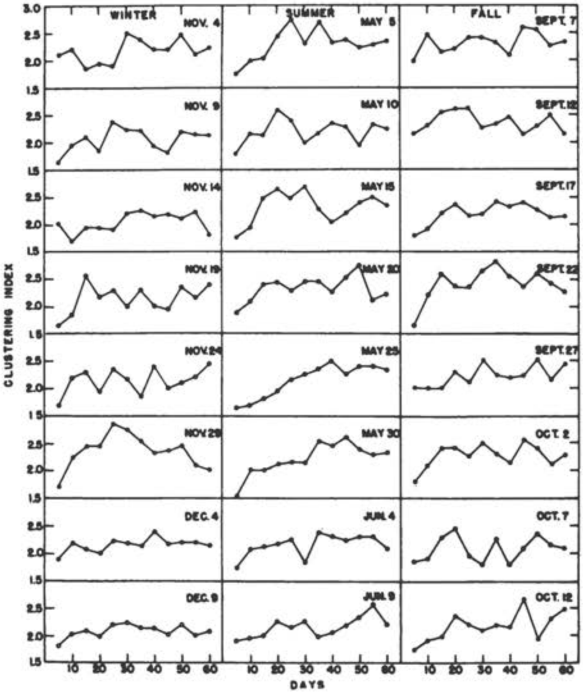


FIGURE 24. Clustering index (relative standard deviation) as a function of number of days from the given starting dates of 500-mb trajectories in 1962–1963.

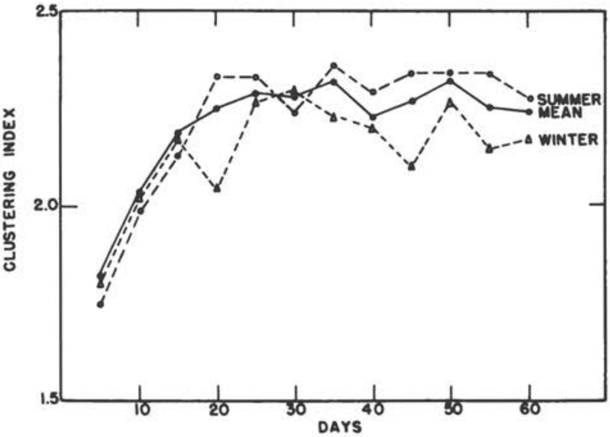


FIGURE 25. Mean seasonal and annual balloon clustering at 500 mb as a function of time since the start of the flights. (See legend for Figure 24.)

becomes more pronounced for the first 25 days after release and thereafter remains essentially constant. Apparently the clustering effect of negative divergence comes into equilibrium with the declustering effect of positive divergence, these being progressive phase phenomena. The tendency shown in Figure 25 for greater clustering in summer than in winter may thus be due to the slower progression of the divergence waves through the fluid.

Since the above analysis indicates no pronounced tendency for the clustering to increase after about 25 days, it is possible to estimate the degree of clustering that one might expect at an arbitrary time. Table 2 shows the percentage area of the hemisphere over which, on the average, the balloon density would be expected to exceed the initial density by the factor *F*.

TABLE 2. *Areal percentage of the Northern Hemisphere (north of 20°N) over which the 500-mb balloon density would be expected to exceed the initial balloon density by the factor* F

F	Winter	Summer
0.25	91.2	90.6
0.50	80.1	79.0
0.75	62.4	62.3
1.00	42.4	44.7
1.25	24.9	29.2
1.50	13.4	17.7
1.75	6.5	9.0
2.00	2.8	3.9

We find that the clustering is more severe on certain dates, as might have been expected from the peaks in the diagrams for November 4–24 in Figure 24. If the clustering index is averaged by date, and the clustering periodicity estimated by the time it takes the pertinent autocorrelation coefficient to fall to zero (multiplied by 4), it is found that the clustering period is 24.4 days in fall, 26.8 days in winter, and 33.2 days in summer. On the average, above-normal clustering tends to occur in 4-week intervals.

MINTZ'S RESULTS

In Mintz's calculation, the initial balloon-density (per unit area) increased with latitude, as shown in the top diagram of Figure 26.

The middle and bottom diagrams of this figure show the balloon positions at 800 and 400 mb, respectively, after 32 days. The striking feature of these diagrams is the number of balloons that are swept out of the Northern Hemisphere Tropics at 800 mb and the equatorial regions at 400 mb. The letter designators—N for Northern Hemisphere, S for Southern Hemisphere, and Q for Tropics—show that at 800 mb most of the balloons initially located within the Northern Hemisphere Tropics have been displaced to a zone just south of the equator. On the other hand, at 400 mb the majority of tropical balloons appear to have been displaced to the Northern Hemisphere subtropics. Presumably, the displacement of the balloons away from the tropics is due to the presence of unrealistically strong Hadley cells in the model. Because of the oversimplification of the tropical thermodynamics in Mintz's model, particularly in his treatment of the condensation process, his results for the tropics and subtropics are not quantitatively acceptable. In order to obtain numerical estimates of the clustering, the diagrams in Figure 26 have been divided into areas of 20° latitude and 36° longitude (approximately the size of the squares used by Angell). The percentage area over which the balloon-density exceeded 0.5 and 1.5 times the initial density was evaluated and is shown in Table 3.

The 800-mb forecast trajectories for three initially adjacent balloons are plotted in the top diagram of Figure 26. The differences among the trajectories are quite striking. We note the apparent ease with which two of these trajectories crossed the equator. We note also

TABLE 3. *Areal percentage over which the balloon density exceeds 0.5 and 1.5 times the initial density in Mintz's calculation after 32 days and in Mesinger's after 30 days*

Region	Mintz		Mesinger	
	>0.5	>1.5	>0.5	>1.5
800 mb N.H.	70.0	13.3	74.5	22.4
800 mb S.H.	96.7	30.0		
400 mb N.H.	96.7	50.0		
400 mb S.H.	86.7	30.0		
300 mb N.H.			85.5	13.6

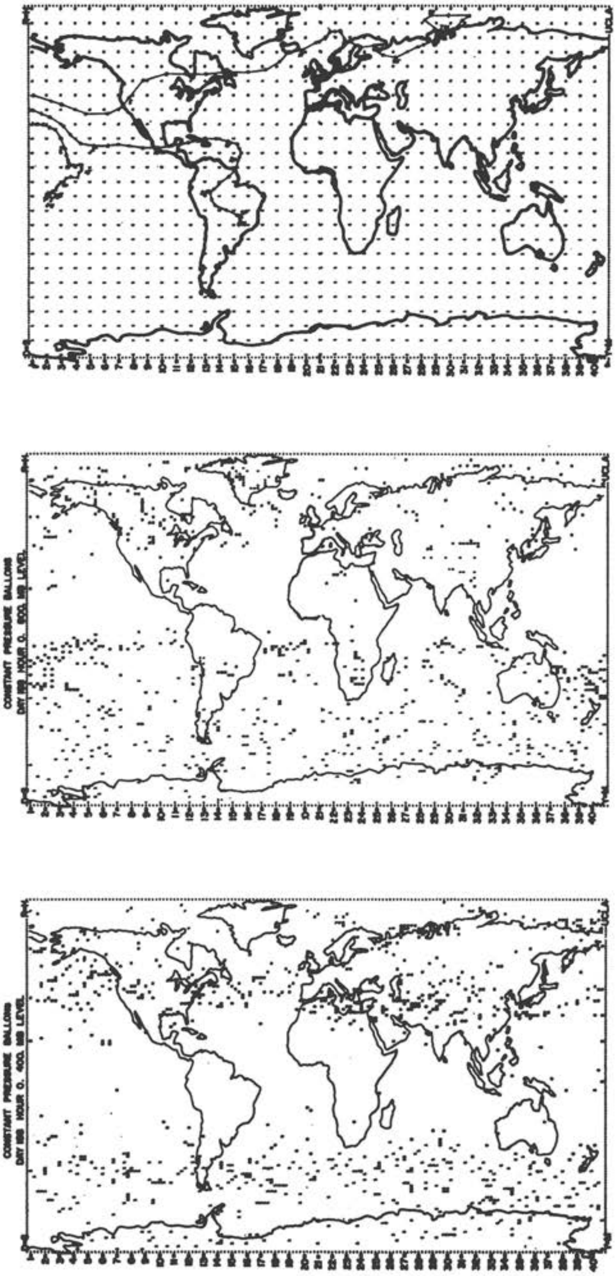


FIGURE 26. Initial distribution of balloons on June 4, 1964 (top), the distribution after 32 days at 800 mb (middle) and at 400 mb (bottom), based upon the Mintz-Arakawa global forecast model. The asterisks and plus signs at 800 mb show where the balloons have been "trapped" by the topography.

that, after 32 days at 800 mb, approximately 10 percent of Mintz's balloons were trapped by mountains—chiefly by the Himalayas, Greenland, and the Andes. No balloons were trapped by the Rocky Mountains because the smoothed land elevations in the model were below 800 mb. In reality, of course, a large number of balloons at 800 mb would be trapped by these mountains.

MESINGER'S RESULTS

Mesinger has also calculated trajectories for the month of December 1962. A summary of his results is given in Appendix D. His analysis gives the variation with time of the distribution of distances of 1,750 fixed points, randomly placed within the NMC grid, to the nearest balloon. Table 3 shows that 30 days after balloon release the clustering is considerably greater at 800 than at 300 mb. According to Mesinger, this difference is not the result of differences in the intensities of the divergence fields at the two levels, which are comparable, but are due to differences in the intensities of the nondivergent motions that tend to destroy spatial differences in the concentrations of balloons. Another explanation, however, may be that the relative speed of the divergence wave is slower at the lower level, just as it is slower in summer at a given level. Mesinger's winter data yield, at 500 mb, an interpolated value of 20.2 percent of the area of the Northern Hemisphere (north of 20°N) over which the balloon density would exceed 15 times the original density, compared with Angell's 19.9 percent. In this case the agreement obtained by the two methods is good. Mesinger also finds that the balloon concentration varies meridionally in a manner corresponding to a three-celled structure of the meridional velocity profile (see Table D1 of Appendix D).

CONCLUSION

The empirical studies of Angell and Mesinger show that, at all levels in the Northern Hemisphere north of 20°, the constant-pressure or constant-volume balloon concentrations quickly approach an equilibrium distribution such that very small values are highly unlikely. Thus, in Angell's calculations at 500 mb for both summer and winter, the concentration exceeds one fourth that of an initially uniform distribution over 90 percent of the area and one half of this value over 80 percent of the area. They also show a tendency toward greater clustering in the summer. In Mesinger's calculation for winter the concentration exceeds one half the initial density over 75 percent of the area at 800 mb and 85 percent of the area at 300 mb. His results also show appreciable latitudinal variations in concentration at low levels, with the lowest densities in the 20–30° belt. This result accords with his calculated meridional circulations, indicating an indirect Ferrel cell at middle latitudes and a Hadley cell at low latitudes producing low-level divergence in the subtropical high-pressure zone and convergence in the intertropical trough zone, and the reverse at high levels.

For the region 20°S to 20°N we have only Mintz's calculations. Although the picture is here highly exaggerated, the divergences are still not such as to demand an inordinate number of balloon replacements to maintain proper concentration; the large magnitudes of the space and time scales are mitigating factors. We may conclude, therefore, that clustering will not be a significant deterrent to the GHOST system, the occasional release of new balloons at selected locations being sufficient to maintain adequate concentration over the globe, but that additional studies must be made for the tropics if a more definitive estimate of the balloon requirements is to be obtained.

CHAPTER SIX

OCEAN-SURFACE OBSERVATIONS

INTRODUCTION

Ocean-surface observing systems must be designed (a) to provide necessary initial data for predictions of the large-scale motions, and (b) to provide the minimum data needed to estimate vertical fluxes of momentum, heat, and water vapor through the lower boundary of the atmosphere. These objectives have led us to propose a relatively simple "standard" ocean observing system, but one that will require substantial investment in a development program extending over several years. The second objective has been discussed in Part One, under *Regional Observations,* where we have proposed a series of research investigations designed to determine how to relate vertical fluxes averaged over large areas to the "standard" observations. To extend predictions beyond a few days, both the initial data at horizontal intervals of roughly 500 km and the distribution of boundary fluxes are essential. We can see no way to provide these except through the research and development programs proposed here.

General considerations of economy, technological feasibility, and methods of communication present limits to possible observing systems. In this connection we have assumed that use of the satellite for collecting data from surface stations and trasmitting to world centers will be an available ingredient of the eventual system.

The "standard" observational system proposed here will provide for average values of five or more variables at a network of points distributed more or less uniformly over the ocean surface with spacing appropriate to the synoptic scale of weather systems. Data should be reported at intervals of 4 to 12 hr depending upon other properties of the global system. A large variety of platforms are possible, and it appears likely that at least three or four different types should be used. These will include strategically located islands on which automatic or semiautomatic systems may be mounted, "ships of opportunity" that may carry semiautomatic observing equipment or more complex gear requiring a trained observer, "weather" ships, specialized towers and large floating structures, and several types of unmanned floating stations.

In order to cover the great area of ocean surface, the unmanned floating stations will number several hundred. They may be of at least three types: freely drifting buoys, buoys anchored to the deep water, and buoys anchored to the bottom. Choice of type must depend upon economic analysis, on the requirements of other users, and on local conditions of ocean currents, interference with shipping, and incidence of severe storms.

Research and development associated with establishment of the global system should provide a valuable opportunity for major extension of oceanographic observing capabilities, even though it is important that the scientific integrity of the atmospheric observing program be maintained.

STANDARD OBSERVING SYSTEM

REQUIREMENTS

The data requirements for ocean observations are set by the basic objectives of the global system: to provide the initial data needed to predict the behavior of motion systems of "cyclonic" and larger scales of motion. These considerations permit us to make the following rough specifications for the purpose of orientation.

(a) Observations should be made with a horizontal spacing of roughly 500 km, but the spacing need not be uniform or unchanging in time. If complete global coverage of this density cannot be accomplished, it may be worthwhile to accept a skeleton system south of about 30°S latitude.

(b) Observations should be made at intervals of not less than about 3 hr and not more than 12 hr, and should in some cases represent averages for the interval between observations.

(c) Data should be transmitted to weather centrals in no longer than a few tens of minutes.

(d) Reliability should be good in all but the most severe weather conditions, but failure of individual stations can be tolerated to a limited extent—perhaps 20 percent of the total number of stations.

The following minimum set of variables should be observed at all stations: atmospheric pressure to 1 mb, atmospheric temperature to 1 °C, wind speed to 20 percent, wind direction to 10°, sea temperature near surface to 1 °C.

A proper definition of the physical system should also include the temperature–salinity distribution in the wind-stirred layer of the sea, since this layer is directly coupled to the atmosphere at the time scales under consideration. In principle, the properites of this layer will be determined by those of the ocean at greater depths and at the surface—just as the properties of the friction layer in the atmosphere are supposed to be determined by the surface and free atmosphere properties. The space and time scales of the necessary observations have yet to be determined. At present they are considered only in connection with the more general set of observations described in the next paragraph.

The "standard" observing system also will serve an essential research function by permitting estimates of vertical flux on large space and time scales. These scales are too large to be incorporated in the investigations proposed in the section on surface-flux research, and it is therefore appropriate to provide for them within the standard system. For this purpose, in addition to observations of the minimum set of variables, a more general set should be observed at a few stations (probably manned). These variables include, in addition to those listed above, humidity, net radiation, characteristic properties of the wave spectrum, and the vertical distribution of temperature and salinity between the surface and the thermocline. These data, together with drift observations, should permit estimates of average stress, heat flux, and evaporation for extended periods by the conservation methods outlined in the section on surface-flux research. Provision for other specialized observations should be made for research purposes, but research data should not necessarily be communicated by the satellite system.

Upper-air observations should be made by conventional means (radiosonde and Rawin) at manned stations, and efforts should be directed at developing semi-automatic or even automatic upper-air sounding systems. These observations will represent extensions of the present system, but they will be needed even after the satellite–balloon–buoy system is developed in order to provide vertical resolution and to ensure consistency in the analysis of balloon observations.

SYSTEM TYPES

The requirements described above can be met most economically by combining several subsystems into the total observing system. Subsystems fall into two categories—manned and unmanned. For economic reasons, primary reliance must be placed on unmanned stations, but manned stations of greater observing capability will continue to play an essential role in the total system as far into the future as can now be visualized. The general properties of these subsystems are described below, but more specific properties and the optimum proportions of each subsystem can be determined only after development and testing have provided hard data on subsystem reliability and on procurement operating costs.

1. *Unmanned island stations*

About 120 remote desolate islands can be used as platforms for automatic observing stations. For this purpose, as well as for use in floating stations, a sensing and communicating package should be developed that is capable of transmitting to the satellite the minimum data upon interrogation.

In designing this unit, emphasis should be placed on simplicity, low power drain, and reliability.

2. *Unmanned anchored stations*

Considerable effort over the last two decades has gone into development of anchored platforms, primarily for oceanographic purposes. It is clear that no existing platform will adequately serve the meteorological requirements, and that further development to meet meteorological specifications is needed. Two buoys of contrasting type may be useful in providing starting points for this work; these are the NOMAD, a 12-ton buoy of boat-hull type, and the 40-ft "discus" buoy developed by Convair.

Unmanned anchored stations will be especially needed in regions of onshore currents or in regions of strong horizontal divergence. Experience suggests that a range of sizes will be required to provide desired longevity with reasonable cost. The larger, more rugged buoys will have power and space adequate for mounting sensors for specialized research as well as for the general set of observations listed in the *Introduction* to this report. The specialized data probably should be transmitted by high-frequency radio telemetry and should not be tied to the satellite communication system.

Where deep currents are weak, unmanned buoys may be anchored to the deep water (1,000–3,000 m) rather than to the bottom. These buoys would in many areas travel at rates no greater than a few centimeters per second.

3. *Unmanned drifting stations*

Small, inexpensive, "expendable" drifting buoys carrying the automatic sensing and communicating package are likely to form a most important part of the "standard" observing system. In comparison with anchored buoys, they could be made at lower cost, with better stability characteristics and probably with greater longevity in severe weather. However, existing buoys of this general type are not entirely satisfactory, so that development is needed. In addition, studies should be made of launching costs and of the numbers required to maintain the minimum required spacing.

Two types of drifting buoys have been considered—a rugged steel spar-buoy with a light mast for antenna and anemometer mounting, and a light sphere floating like a beachball on the ocean surface. The spar-buoy could be expected to weigh 500 to 1,000 lb, including sensing and communicating package, and to be rugged enough to be launched by air or by ship and survive severe weather. It would be expected to drift with the current near the surface and should have an average useful life of perhaps four months. Development of an accurate, rugged, wind-measuring system may be the principal difficulty.

The "beachball" concept has received slight attention, but has the following advantages: a wind-measurement system free of the limitations of cup anemometers and vanes, an internal antenna, economy, and ruggedness. Wind measurement might be accomplished by attaching the ball (perhaps made of gas-filled plastic) to a light sea anchor and measuring the stress exerted on the anchor by the ball. Or, the ball could drag a propeller through the water, with wind speed determined as a function of propeller revolutions through calibration. In either case, the probability of entanglement with seaweed or floating debris is relatively high, but this might be tolerable if procurement and launching costs are low enough. Another variation on this scheme would be the use of a large rugged balloon partially filled with helium so that it would be almost buoyant in the air. As a result, its surface friction would be very low, and it should skip across the water following the surface wind field. A 6-m-diameter balloon should follow the 3-m average wind speed. The balloon could be equipped with a heavy-weight version of the GHOST electronics described earlier and its position on successive satellite passes used to determine surface winds. The "beach-ball" buoy is described here as one example that should be evaluated along with others before final decisions are made on procurement of unmanned drifting stations.

4. *Ships of opportunity*

Ships should be used as platforms for ocean-surface observations where available. The sensing and communicating package provided for unmanned stations can be utilized, and upper-air and other observations should be made where appropriate. In this connection, development of a simple, automatic, balloon-tracking equipment would make feasible upper-wind observations on selected ships by semiskilled men. All equipment should be movable from one ship to another so that adequate area coverage could be provided with a minimum number of units.

5. *Manned floating stations and towers*

Platforms being developed for purposes other than meteorological (manned spar-buoys, defense radar towers, navigation buoys, missile- and satellite-tracking ships, etc.) may also be used for ocean-surface and upper-air observations. Included here also are weather ships and ocean research vessels. Such stations will provide ample power and skilled personnel; they therefore can be used for research purposes as well as for making "standard" observations.

EXAMPLE OF THE TOTAL SYSTEM

Decisions as to sensors, platforms, launching and servicing facilities, etc., can be wisely made only after further feasibility studies and further development are completed. Nevertheless, it may be useful to outline an example of one possible total observing system chosen on the basis of present limited knowledge. (See Table 4.) This is intended to provide the minimum set of surface data at 1,200 stations, the general set of surface observations at 90 stations, observations of the surface mixed layer of the ocean at 150 stations, upper-air observations at 90 stations, and to provide the opportunity for specialized research observations at 190 stations.

TABLE 4. *Sample System*

Station		Number
a. Unmanned island		120
b. Unmanned anchored		100
c. Unmanned drifting		730
d. Ships of opportunity (general set)		40
Ships of opportunity (minimum set)		160
e. Manned stations		50
	Total	1,200

CONCLUSION

The proposed "standard" ocean-surface observing system is feasible, based on current technology and on reasonable extrapolations of budget and manpower.

Research activities beyond a 5-year period are difficult to predict, but we wish to emphasize that the need for research will not end with creation of a global observing system. Rather, research will be further stimulated by the system; and if the earlier research proposed here has been successful, creation of the global system will open the door to new research problems concerned with interactions over long time periods and large space scales.

CHAPTER SEVEN

RADIOMETRIC MEASUREMENTS FROM METEOROLOGICAL SATELLITES

INTRODUCTION

The reflection of solar radiation from the earth and atmosphere and the emission of thermal radiation determine the basic energy available for driving atmospheric motions. In addition, the spectral detail of these fluxes can yield information on the physical state of the atmosphere. Both types of information are fundamental to proper understanding of the meteorology of the lower atmosphere.

In design of satellite radiometers the two most important design parameters are angular and spectral resolution; the former is determined by the extent of the system under observation, whether it be a cloud or a cyclone; the latter by the choice between measuring energy fluxes integrated over large spectral intervals, or recording narrow spectral bands or lines to exploit the rapid variation of photon mean-free-path as a remote probe for the atmosphere.

RADIOMETERS ALREADY CARRIED BY SATELLITES

Starting with the Vanguard II satellite,[16] radiometers have been carried on most meteorological satellites. The first completely successful instrument was carried by Explorer VII.[17] This simple radiometer, devised by Suomi, consists of a pair of spherical receivers with thermisters as detecting elements. One sphere is painted black to absorb both solar and emitted thermal radiation. The other is painted white to reflect solar radiation and absorb thermal radiation. The former has the minimum spectral resolution in meteorological terms, absorbing from the ultraviolet to the far infrared, while the latter has a better spectral resolution by virtue of its rejection of solar wavelengths and its absorption of the earth's thermal flux in the infrared; the angular resolution of these radiometers is given by the subtend of the earth's disk and, when in sunlight, the solar disk. Similar radiometers have been carried on several of the TIROS meteorological satellites.

The second TIROS satellite carried a different radiometer,[18,19] with five separate channels. Two were of the broad-band type, one designed for solar radiation (0.2 to 5 μ) and the other for thermal radiation (7 to 30 μ). A third channel covered the same spectral region as the vidicon cameras (0.55 to 0.75 μ), a fourth, the 6.3-μ band of water vapor (5.5 to 7 μ), and a fifth, the window region (8 to 12 μ). The areal resolution was about 30 miles when the radiometers were viewing vertically, and areal coverage was achieved by the rotation of the satellite in orbit. This radiometer and its measurements have been extensively described in the literature.[20–23,46,47]

The recent Nimbus satellite carried a radiometer of medium spectral resolution and relatively high angular resolution.[24] It viewed the region between about 3.5 and 4 μ, and its areal resolution in vertical view was about 8 miles. Its scan was achieved by motion perpendicular to the orbital motion, the images being built up by the forward motion of the satellite.

Plans for radiometers to be carried on future Nimbus satellites include, in addition to the above-mentioned radiometer of high angular resolution, a new five-channel scanning radiometer covering about the same spectral intervals as those carried on the TIROS satellites; this radiometer has been built and thoroughly tested. Another type of radiometer is the vidicon television camera. It has a spectral resolution of 0.5 to 0.75 μ, and very high angular resolution (1 mile at the surface). However, unlike the other radiometers, its intensity information is only qualitative.

The quantitative radiometers can achieve several objectives. The broad-spectral-band detectors give information on the heat balance of the earth. The medium-spectral-resolution instruments give information on cloud cover at night (8- to 12-μ or 3.5- to 4-μ radiometers). Special objectives have been achieved by other detectors, such as the 14- to 16-μ channel in TIROS VII, which was designed to test this spectral region for purposes of horizon detection in stabilization systems.

RADIOMETERS PLANNED FOR THE FUTURE

In contrast to the radiometers described in the previous section, most of those planned for future satellites are of an essentially different character. They are of high resolution and are designed to determine state parameters of the atmosphere.

The first radiometers of this class were flown in the United Kingdom II satellite experiment conducted by Frith.[25] These were intended to determine ozone concentration in the upper stratosphere. The satellite carried two instruments, one a broad-band photomultiplier, and the other a spectrometer. The spectrometer system failed shortly after launch, and the other instrument has not yet yielded definite results. These experiments are mentioned because of their similarity to others being considered for the future. Friedman *et al.*[48] have also flown a radiometer of the broad-band photomultiplier type, sensitive in the range 2,500–2,900 Å approximately.

Since 1959, the U.S. Weather Bureau has been developing a satellite-borne spectrometer that can determine the vertical temperature profile in the atmosphere. This instrument will observe the infrared radiance of the atmosphere in six channels, each of 5 cm^{-1} width in the 15-μ CO_2 band, and in a seventh channel of 7 cm^{-1} width at 11.1 μ in the so-called water-vapor window. It is anticipated that the results will give vertical temperature profiles from the surface or cloud tops to about 30 or 35 km.

A "breadboard" model of this instrument[26,27] has demonstrated the possibility of measuring radiance to an accuracy of about 1 percent, the accuracy required for temperature determination. A successful balloon flight was conducted in September 1964; its results will be discussed in a later section.

An interferometer of the Michelson type is now being considered for one of the Nimbus satellites.[35] In principle, such instruments are superior in performance to spectrometers; they are smaller and consume less power. However, the spectrometer has the advantage of being much more advanced in its development, and it is improbable that interferometers could at this time meet the very stringent requirements for vertical temperature determination. The instrument described earlier[35] is in an advanced state of construction,[49] and will probably be flown on the same satellite as the spectrometer.

Another experiment, somewhat different from Frith's, has been proposed to measure the radiance of the scattered light in the stratosphere, and from this to deduce the ozone concentration in the upper atmosphere.[28–31] Work will begin soon on experimental instruments of this general type. It is hoped that within 1 or 2 years a clear indication of the feasibility of such measurements will emerge.

Still another radiometer is being designed to measure the heights of cloud tops from the satellite by determining the absorption in the $0.76\text{-}\mu$ oxygen band.[32–34] Comparison of radiance inside and outside the band determines the absorption by the atmosphere, and hence the height of the clouds. The instrument does not yet qualify as a satellite instrument, but much preliminary work has been done, and it is expected that a hand-held spectrograph will be carried by one of the early Gemini astronauts.

APPLICATIONS TO METEOROLOGY

Past and future radiometric measurements made for synoptic purposes have been discussed at length in the literature, and need not be considered further in the present discussion. The more immediate unfulfilled requirements of the meteorologist are for the dynamical parameters, such as wind, temperature, and pressure.

Surface temperature may be determined in cloud-free areas.[36] However, when clouds, even thin cirrus, are present, temperatures derived from infrared satellite radiation measurements will be seriously in error. Since a large part of the earth has cloudiness to some degree, continuous large-scale infrared observations of surface temperature cannot be made from a satellite. This also is true for the microwave region because of a lack of information on microwave emissivity of the surface.

The determination of surface winds from meteorological satellites is within the realm of possibility only for the microwave region, but the indirect methods that might be used have yet to be evaluated. At present we do not know the relation between the microwave emissivity of a water surface and the wind at the surface or at some standard height, such as two meters above the surface. If a unique relation exists, then wind measurement from a satellite is a genuine possibility.

The vertical pressure profile may, in theory, be deduced from satellite measurements.[37] However, preliminary estimates of the probable errors indicate that the uncertainty in the deduced pressure would perhaps be greater than the uncertainty of indirect inference from cloud patterns and climatology. However, some possibilities do exist for deducing surface pressure, as shown by Fischbach.[52]

The most likely candidate for an important role in a meteorological observation system is the experiment to determine the vertical temperature profile of the atmosphere. Since observations in the infrared region are limited to the region above the clouds, one can obtain information over the earth only in the upper 500 mb or so of the atmosphere. In some areas where clouds are high and thick, even this is not possible. However, over these regions at least, cloud heights can be derived and information obtained on the atmospheric temperature above the clouds. From the discussion that follows it will become apparent that useful synoptic-scale temperature profiles can be obtained from meteorological satellites.

MEASUREMENTS OF THE VERTICAL TEMPERATURE PROFILE IN THE INFRARED

The experiment under consideration was originally proposed by Kaplan,[50] and was recommended by a group of infrared experts who met in Washington to discuss satellite measurements in the infrared. In 1960 the U.S. Weather Bureau, in cooperation with NASA, embarked on an instrumentation program that led to the production of a "breadboard" instrument.[26] This instrument is shown in Figure 27. It is a Fastie-Ebert spectrometer approximately 16 in. in diameter with a 5-in. grating. Chopping between earth and space provides an alternating signal that is detected by a set of thermistor bolometers. The original instruments had four detectors in the 15-μ carbon dioxide band (shown in Figure 28) and one in the 11.1-μ window. These

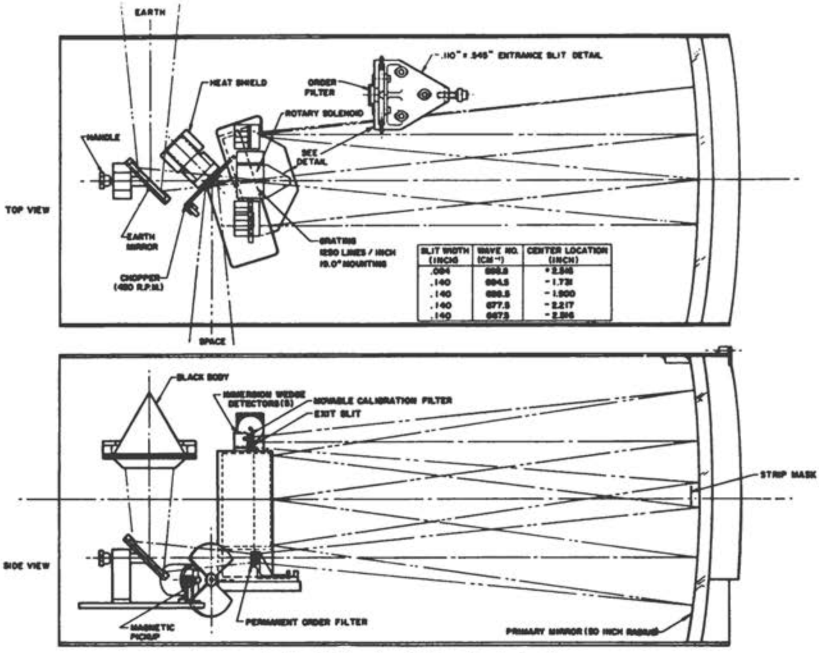


Fig. 1. Satellite meteorological spectrometer layout.

FIGURE 27. The "breadboard" model of the satellite infrared spectrometer. The chopped signal passes through the entrance slit below the grating; the dispersed beam is focused on the detectors above the grating. Top, top view; bottom, side view.

were subjected to exhaustive examination by calibration and testing and by a series of measurements of the atmosphere. The results of these measurements, as yet unpublished, demonstrated the ability of the instruments to provide the information necessary to obtain the vertical temperature profile.

After the successful ground tests, and in anticipation of the eventual satellite experiment, three advanced models were built for balloonborne tests. Each carries six channels in the carbon dioxide band, two additional channels being added for redundancy and extension of the measurements to the surface, so that with clear skies the entire temperature profile can be obtained.

The radiance of the atmosphere as seen by a single channel of the satellite instrument arises from a layer of the atmosphere approximately 12 km thick. This radiance can be expressed by the integral equation

$$I(\nu) = \int B[\nu, T(t)] \frac{d\tau(\nu, t)}{dt} dt \tag{1}$$

where B is the Planck (blackbody) radiance, ν is the frequency of the center of a narrow spectral interval, T is temperature, τ is the transmittance between any level and the top of the amtosphere, and t is the independent variable (pressure, height, etc.). The integrand on the right involves two terms: the unknown Planck radiance as a function of the temperature (which, in the atmosphere, is a function of the independent variable t) and frequency, and the derivative of the transmittance, which is known.

Figure 29 shows the derivative of the transmittance to space for each of the six 5-cm^{-1} intervals used in this instrument. These are the weighting functions for the Planck radiance (Eq. 1). If each of the weighting functions were independent (if they did not overlap), the solutions would be trivial. On the other hand, if the layers overlap to a considerable extent, one finds an instability due to the ill-conditioning of the matrix of the linear system derived by linearizing the Planck radiance in the set of six equations (Eq. 1), selecting an appropriate functional form for the solution, and integrating the

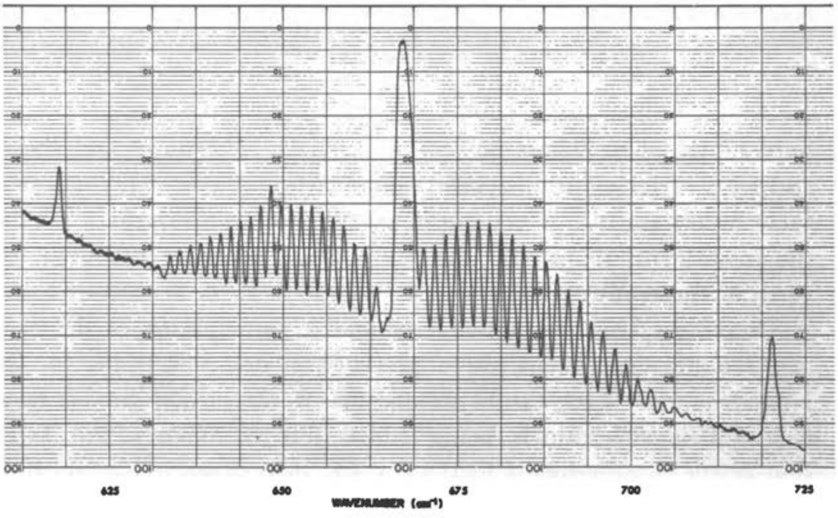


FIGURE 28. Spectrum of the 15-μ carbon dioxide band, showing the strong Q-branch at 667.4 cm^{-1} and the individual lines of the P- and R-branches to the left and right, respectively. The Q-branches of two weaker bands appear at each side. The 5 cm^{-1} intervals of the infrared satellite spectrometer are centered at 669.0, 677.5, 691.0, 703.0, and 709.0 cm^{-1}. (From Reference 42.)

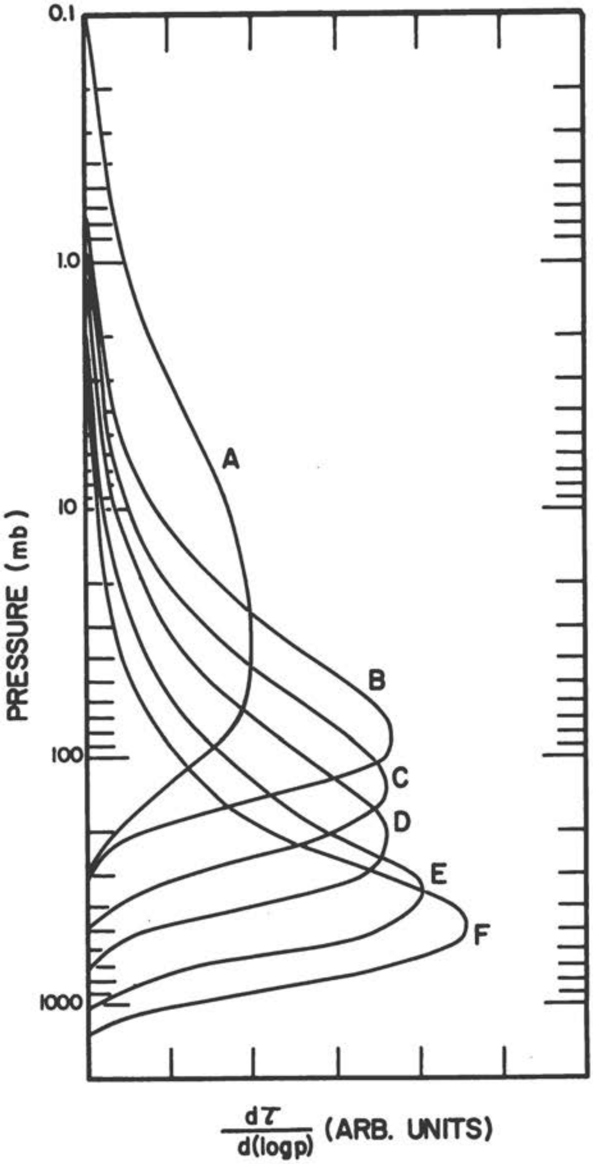


FIGURE 29. Radiance weighting functions. Derivative of the transmittance with respect to log *p* for the six spectral intervals of the satellite infrared spectrometer. (From Reference 42.)

kernel function in Eq. 1 by numerical quadrature. However, methods that circumvent this instability have been developed by introducing a smoothing criterion that eliminates the wild oscillations in the solution while retaining the essential character of the profile. Figure 30 shows a temperature profile from which radiance values have been calculated and used to solve for the temperature profile. The test assumed that the observations were exact. A series of line segments

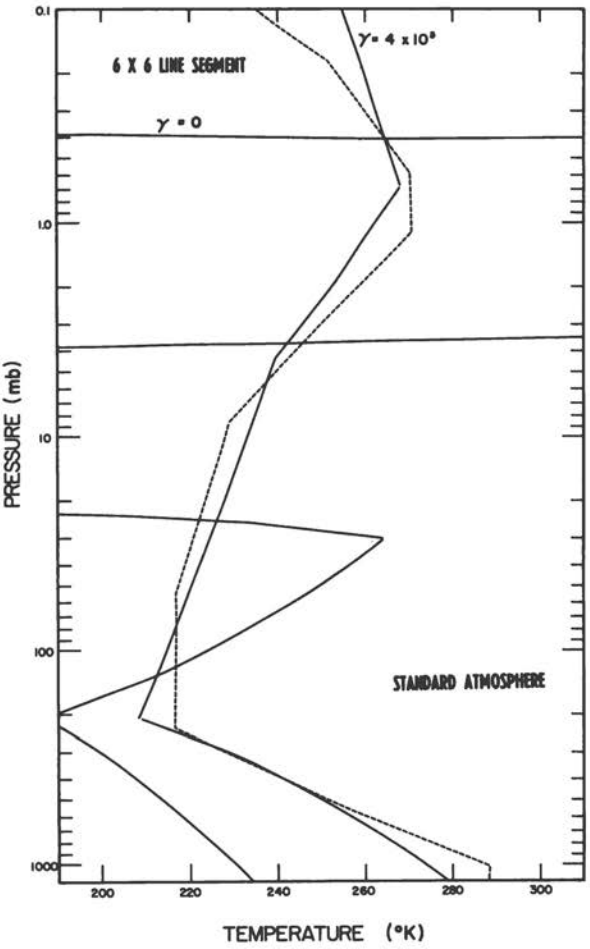


FIGURE 30. Comparison of inversion techniques. Standard atmosphere profile (dashed line) and the direct ($\gamma = 0$) and smoothed ($\gamma = 4 \times 10^{-5}$) line segment solutions. (From Reference 42.)

was used to approximate the vertical profile. In Figure 30 the solution marked $\gamma = 0$ is the direct solution of a set of linear simultaneous equations. It is obvious that this solution, which oscillates off the graph, is entirely unsuitable. However, when smoothing is applied to the solution, one finds the result shown by the series of straight lines that approximate the true solution. This series is marked $\gamma = 4 \times 10^{-5}$.

King,[37, 38] Fow,[39] Yamamoto,[40] Wark,[41, 43] Kaplan,[51] and others have each adopted a somewhat different method of solution. Each of these methods is in itself valid. However, the method that best reproduces the temperature sounding is to be preferred. Recent investigations have shown that the use of empirical orthogonal functions is optimal.

In September 1964, the U.S. Weather Bureau flew one of the advanced spectrometers from the Balloon Flight Station of NCAR at Palestine, Texas.[53] The balloon floated at approximately 100,000 feet (10 mb) for 7.5 hr. It viewed straight down through an "earth" port, and viewed a blackbody at liquid-nitrogen temperature (essentially zero energy) through a "space" port. The gondola carried equipment for measuring air temperature and radiative flux, as well as two cameras.

During the early part of the flight no clouds were present, so that surface temperatures and data for deduction of the entire temperature profile of the atmosphere were obtained. Cumulus clouds developed as the day progressed, so that a view directly to the surface was seldom obtained. At one time the balloon passed over a squall line in which the tops penetrated to about 250 mb (34,000 ft), as deduced from radiosonde data and the 11.1-μ channel measurement. As expected, channels C, D, E, F, and G were affected by the clouds, but channels A and B, in the center of the 15-μ band, continued to give almost unaltered recordings (Table 5). The *Q*-branch channel (A) had some minor electronic problems that became obvious only after an exhaustive examination of the calibration data. *Q*-branch data were therefore omitted from the preliminary analysis. Since this is the most absorbing channel, poorer results near the top of the sounding are to be expected.

TABLE 5. *Balloon Flight, Measured Radiances* (erg cm^{-1} sec^{-1})

Channel	Wavenumber, cm^{-1}	Clear	Overcast
A	669.0	49.6	49.4
B	677.5	42.4	42.0
C	691.0	40.1	39.2
D	697.0	43.6	40.9
E	703.0	52.2	44.4
F	709.0	64.9	47.4
G[a]	900.0	115.6	33.7

[a] The two-channel G radiances (atmospheric window) correspond to surface and cloud-top temperatures of 298.8°K and 232.9°K, respectively.

By techniques already mentioned, the five radiance values for the clear and cloudy cases in Table 5 were used to solve for the temperature profiles. The results shown in Figure 31 (a) are for the clear case.

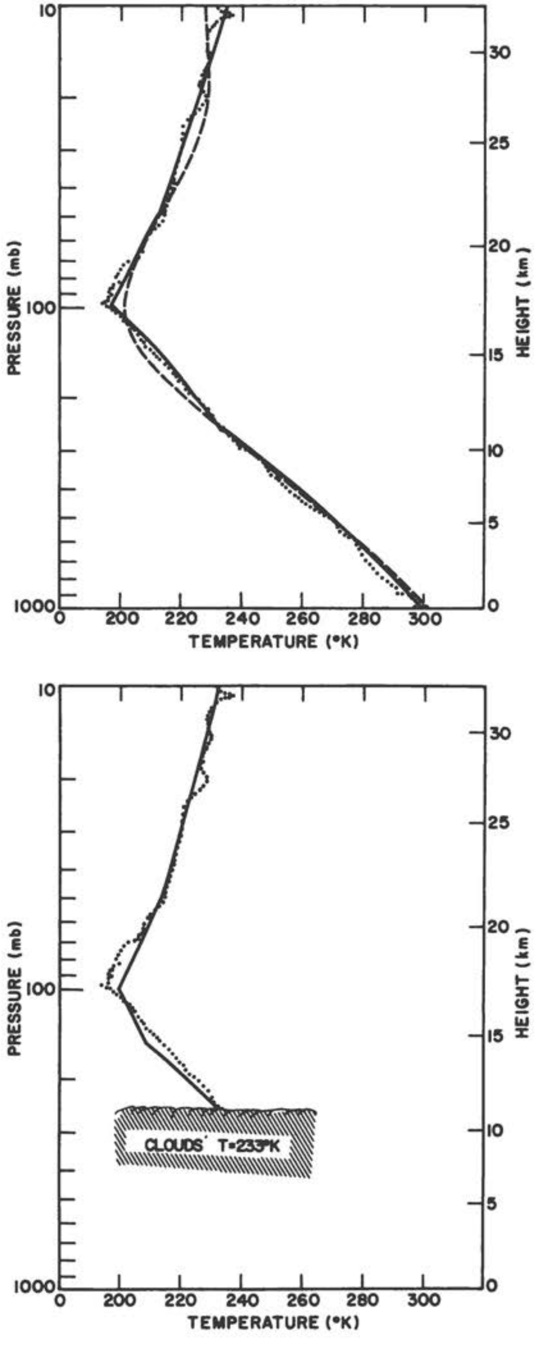


Figure 31. Observed and deduced temperature profiles: temperature versus pressure as deduced from channels B through F data derived from balloon measurements. (a) Clear skies. The dotted line is the true profile; the dashed and solid lines are the deduced profiles using a sine series and line segments, respectively. (b) Overcast sky, tops at 250 mb. The true and deduced (line segments) profiles are the dotted and solid lines, respectively.

They are compared with the sounding obtained during the ascent of the balloon. The Planck radiance profile was approximated by a sine series and by connected line segments. Figure 31 (b) shows the solution for the cloudy case obtained with line segments and, using an interative procedure, to force agreement with channel G at the cloud top. There is an excellent over-all fit in the clear case, although the agreement at the top in the sine series solution is fortuitous in view of the absence of the *Q*-branch channel. The agreement is not quite so good in the cloudy case, but the reason for this is now understood and the error can be reduced.

The effect of random errors of measurement on deduced soundings is small for errors of less than 1 percent. However, at about 3 to 5 percent, solutions usually blow up completely, and no technique is capable of retrieving the temperature profile. Systematic errors are not so serious. In the balloon measurements used for Figure 31, there was systematic error of +0.6 erg, which shows up as a high mean temperature for the atmosphere. The deviation about this systematic shift was roughly the same as the instrumental noise (~0.35 erg).

The U.S. Weather Bureau, in cooperation with NASA, is now embarked upon a program to produce a satellite model of the spectrometer. It is expected to be flown on the Nimbus B satellite. The measurements will be experimental, and therefore not designed for optimum coverage. The instrument will view in the vertical and record data only along the north-south subsatellite paths of successive orbits. These paths will be approximately 1,500 miles apart at the equator, 1,000 miles at 45°, and overlapping in polar regions.

In a routine global observation system the coverage could be greatly enhanced by viewing at several nadir angles at right angles to the direction of motion of the satellite. By means of a movable mirror arrangement the instrument could be pointed approximately 12° and 30° to each side of the orbital plane. It would have to remain in each position for about one minute to allow time for the instrument to reach equilibrium, the delay being required by the 6-sec circuit time constant and the need for some redundancy. In this way, areas 150–200 miles across and spaced 250 miles apart would be examined. The satellite would have moved 250 miles from one scan to the next. A somewhat closer mesh is possible, but the time between observations cannot be reduced to a small fraction of a minute without creating questions concerning the validity of the results.

An interferometer or microwave radiometer would probably have similar angular resolutions and time constants, so that the data coverage would be similar in nature with the observations being separated by roughly the angle of view of the instrument.

This is now a proven experiment. Improvements in inversion techniques, determination of systematic errors by comparison of satellite data with calculations from radiosonde data, and improvements in instrument design will add to the accuracy of the satellite experiment.

MICROWAVE MEASUREMENTS

As originally proposed by Smith[43] and by Meeks and Lilley,[44] one can make use of the 5-mm molecular-oxygen band in much the same way as the 15-μ carbon dioxide band is used to derive the temperature profile of the atmosphere. Molecular oxygen, like carbon dioxide, is uniformly mixed up to the ionosphere.

The microwave region has two potential advantages over the infrared, one natural and one instrumental. First, microwave radiation can pass freely through most clouds because the droplets are small compared to the wavelength. Many clouds, however, contain large water drops, hail, or snow, which being of the size of the radiation wavelength, are efficient scatterers, and any inference of the temperature profile within or below such clouds will suffer from the same shortcomings as in the infrared, namely, that the cloud is opaque or of unknown transmittance. But, on a large scale, the restrictions are much less severe than for the infrared spectrum.

The other advantage of the microwave region is the wavelength resolution resulting from the use of a coherent detector. It is possi-

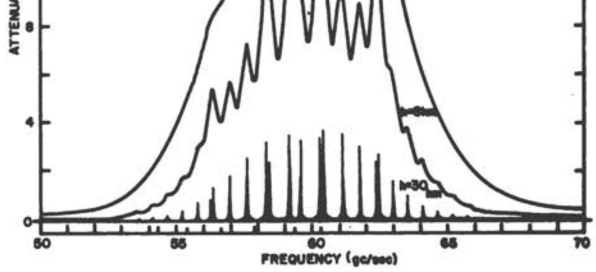


FIGURE 32. Computed spectrum of the oxygen 0.5-mb band. Attenuation per km is shown for three heights. The marks in the lower scale indicate the frequencies of the intervals shown in Figure 7. (From Reference 45.)

ble in the microwave spectrum to have a resolution narrower than the width of the line. Hence one can observe the line profile and the large opacities at line centers, and thereby one can determine temperature to greater heights and with somewhat better vertical resolution.

Figure 32 shows the spectrum of the oxygen band at 5 mm (Meeks and Lilley[44]). Spectral intervals can be selected that will permit a set of weighing functions reasonably distributed over the atmosphere (see Eq. 1). These intervals are marked in the scale at the bottom of Figure 32, and the weighting functions are shown in Figure

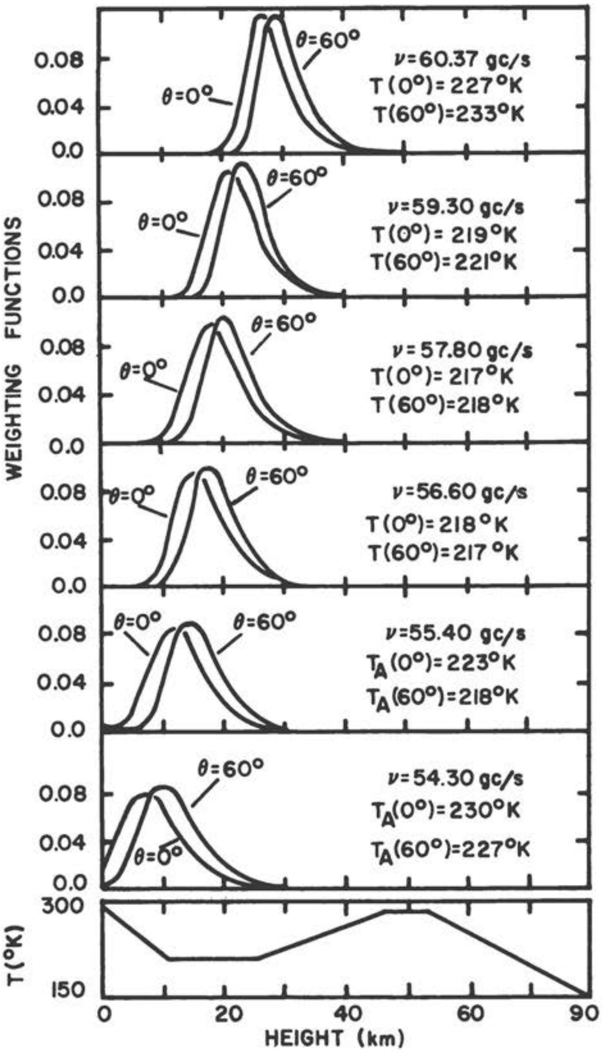
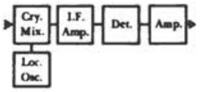


FIGURE 33. Weighting functions. For six spectral intervals in the oxygen 0.5-mm band. (From Reference 45.)

33. A recent analysis by Thaddeus has shown that the existing instruments cannot view a region that is substantially higher in the atmosphere than the carbon dioxide channels shown in Figure 29, but there is a probability of significant improvements in technique.

TABLE 6. *Microwave-Radiometer Characteristics*

	Crystal Video	Tunnel Diode	Superheterodyne
Simplified diagram			
Present wavelength region (mm)	8–100	≥ 20	Klystron, <10 Solid state, >10
Bandwidth capability (mc/sec)	large, 2,000–3,000	$\leq 1{,}000$	200–1,000
Approximate time constant (sec)	10	1–3	5
r.m.s. temperature resolution (°C)	5	0.1	1
Weight (lb)	10	20–25	Very heavy
Power requirement (W)	5–10	4–10	Very large
Characteristic	Simplicity	Simplicity	Complexity
Remarks	Carried on Mariner II	JPL has 30-mm radiometer	

Microwave-radiometer development has been concentrated mostly at wavelengths greater than 1 cm. For example, the radiometer on Mariner II[30] had two channels, one at 1.35 cm and the other at about 1.9 cm. This radiometer was a crystal video. From the simplified diagram in Table 6 it is seen to be the least complicated of present radiometers, but it is inadequate for temperature-profile determination since its band width is large and the resulting temperature resolution is considered to be too poor for the solution of Eq. 1.

The tunnel diode shown in Table 6 is also inadequate for the temperature-profile determination. Although it meets most of the requirements, the presently accessible wavelength region is beyond 2 cm and therefore not suitable for the oxygen wavelengths at 5 mm.

The only microwave radiometer now potentially suited to the oxygen-temperature-profile experiment is the superheterodyne type, shown in Table 6. This has a temperature resolution of 1°, a time constant of 5 sec, and a bandwidth of less than 1,000 mc/sec. The difficulty is that the local oscillator for this radiometer would have to be a klystron at this time, since solid-state oscillators have not been developed to operate in the region of the 5-mm band. There are current developments underway which would suggest that solid-state local oscillators qualified for space use will be available in the next few years. A klystron makes heavy demands upon the energy available aboard a satellite, requiring about 25 W of continuous power per channel. This radiometer is heavy, large, and complex. Nevertheless, it would be possible to carry approximately two to three channels on a Nimbus-type satellite, if these would materially supplement the carbon dioxide experiment. As already stated, however, it is not likely that this can be done at the present time.

In addition to the 5-mm band, there are other regions of the microwave spectrum that might permit inferences from radiometric measurements that would be useful to meteorology. Table 7 shows a number

TABLE 7. *Possible Meteorological Measurements in the Microwave Region*

(1) Free-air temperature. Present technology barely adequate. Should have development of a solid-state local oscillator, which would be very expensive.

(2) Water vapor. Present devices are capable of measuring total water vapor over the sea in the 1.35-cm line. Measuring the vertical distribution would be more difficult.

(3) Clouds and precipitation. Probably can be measured.

(4) Surface temperature and emissivity. It is possible to measure the signal at different local zenith angles to get these separately. This is a necessary input into (1) above.

(5) Sea-surface properties. Measurements at 2–3 cm can provide information as in (4) above. Relation between wind and surface emissivity not well known.

(6) Snow and moisture effects at the surface. Situation similar to (5) above.

of possible uses of microwave-radiometric measurements. Determination of (1) the free-air temperature has already been discussed. However, it is possible to measure other meteorological parameters such as (2) water vapor, (3) clouds and precipitation, (4) surface temperature and/or surface emissivity, (5) sea-surface properties and/or surface wind, and (6) snow and moisture on the ground. As one progresses down the list, the feasibility of obtaining useful meteorological information appears to increase. There is a possibility of measuring the total amount of water vapor, although some problems of sea emissivity still remain to be solved. To the degree that liquid or solid water causes difficulty with the temperature measurement, its presence in the atmosphere can be recorded. Determination of the distribution of water vapor is difficult, although a possibility exists in measurement of the 1.35-cm line. The product of surface temperature and surface emissivity can also be determined from microwave measurements. Inasmuch as the surface temperature can be determined reasonably well over the surface of the earth by other means, this knowledge may lead to the determination of surface emissivity and thereby to the possibility of wind-velocity and even wind-direction determination over the ocean areas. It has even been suggested that a simple experiment at, say, 3 cm might permit both the emissivity and temperature to be determined separately by measuring the radiance at different local zenith angles from a satellite. This would be a desirable input to the temperature-profile determination and would also be independently useful as a scientific experiment. Such a temperature determination, however, requires a knowledge of the dependence of emissivity on wavelength.

We are thus brought to the question of surface emissivity as an important datum for the proper interpretation of any of the radiometric measurements made from a satellite. Measurements using a microwave radiometer to determine sea-surface and land emissivities at 1.9 cm have been conducted by Hyatt.[54] The results of these measurements, though of a preliminary nature, provided sea-surface data that were in good agreement with calculations based on routine atmosphere soundings. The data from flights over land were somewhat less successful yet the results are sufficiently promising in both instances to deserve further attention and study. Any final decision made concerning the advisibility of making such measurements from a satellite will depend upon continuing studies of this sort.

It is now planned that a microwave-radiometer experiment proposed and executed by Thaddeus will be carried on a Nimbus satellite. The radiometer will be a one-channel device, centered at 1.6 cm and with a bandwidth of about 300 mc/sec. It is expected that many of the questions mentioned in the preceding discussion, concerning surface emissivity, wind, and cloud opacity at this wavelength will be answered by interpretation of the data to be accumulated.

GENERAL DISCUSSION

As already mentioned, many technical developments and observational tests are required in the microwave region before full meteorological applications can be made of satelliteborne experiments. There are many current activities potentially of direct relevance to the meteorological problem. Douglas Aircraft has conducted a series of measurements of the radiance of sea surfaces with an airborne 1.9-cm radiometer with a medium bandwidth in order to determine emissivity. Falco and others at Space General have been conducting an extensive project to measure radiances of water surfaces in tanks, of natural terrain, and of the sky; reports of some of their work are available. Barrett and his associates at MIT have conducted extensive measurements of the 1.35-cm water-vapor line from the surface, and of the 5-mm oxygen spectrum from balloons; reports of some of this work are available. The Air Force Cambridge Research Laboratory is considering flying a 5-mm radiometer in a satellite; no published information is now available on this experiment. Bridges of Illinois Institute of Technology has been engaged in a project to measure sky radiances in the 5-mm region; no reports are available. In addition, the following are known to have engaged in theoretical or observational work of interest to this report: AVCO Corporation, General Electric (Smith in Santa Barbara), and Radiation Systems, Inc.

Although much useful information can be derived from the above work, special studies directed toward specific meteorological goals will be required before satellite microwave measurements can be applied directly to scientific or operational use in meteorology. A program involving global meteorological observations cannot depend wholly upon accidental contributions by other research activities. This is also true of instrumental development. If the meteorological community is to tap the potential of microwave measurements, it must be prepared to give strong financial and technical support to a specifically meteorological program.

RECOMMENDATIONS

Radiometric measurements from satellites of the type that may now be considered as routine, such as the broad-band solar and infrared measurements, are a necessary and important input to the study of the radiative heat balance of the atmosphere and should be continued on this account. With respect to numerical-model studies of the general circulation and long-range prediction, it should be pointed out that the net incoming radiation is *determined* by the state of the atmosphere, including the distribution of water substance, and therefore is not an independent input, as is solar radiation. However, broad-band radiation measurements will be useful as *controls* to check the accuracy with which the models reproduce the observed patterns of net incoming radiation. This must be done with some accuracy if long-range prediction is to be possible. In addition, empirical studies of the fluctuations in space and time of the outgoing radiation in conjunction with the flow patterns may well provide insights into the mechanisms of long-period variations of the atmospheric circulation.

Measurements with low spectral and high angular resolution can also provide valuable information, on a synoptic scale, of cloud coverage, sea ice, soil moisture, etc., and therefore should also be continued. The cloud information is of special value in tropical studies.

The most important of the radiometric measurements from the standpoint of the global observation system is the determination of the vertical temperature profile. This program is now in the experimental stage and, if it proves successful on a Nimbus satellite, it should be continued in one form or another as a regular observing tool.

The development of an interferometer is a definite requirement. The comparatively modest development cost could result in eventual large savings, and could make an important contribution to scientific instrumentation methods. An interferometer that can match the radiometric performance of the spectrometer would be the preferred instrument for observations from a satellite.

In the microwave region, greater emphasis should be given to the development of sensitive radiometers in the 5-mm oxygen band. This may prove to be an unjustifiably expensive undertaking, but this portion of the spectrum has such great potential use that serious consideration should be given to the support of such a program. A continuing reassessment of the microwave instrumental capabilities should be undertaken in view of the rapid rate of development.

Other radiometric measurements, whether in the infrared, visible, ultraviolet, or microwave regions, should be encouraged on an experimental basis. These include ozone determination and emissivity characteristics of the surface in the microwave region.

It should be emphasized that a coherent developmental program among all U.S. agencies is necessary for the success of a radiometric instrumentation program.

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RADIOMETRIC MEASUREMENTS FROM METEOROLOGICAL SATELLITES

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Appendixes

APPENDIX A

Satellite-Balloon Electronics

The typical balloon–satellite interchange would be as follows: The satellite initiates the interchange by sending out a coded address signal. All the balloons that are in radio range of the satellite analyze the address signals but only the balloon whose address is called responds to the satellite. The proper balloon responds by turning on its dormant circuits, including its transmitter. The satellite then initiates a ranging sequence by modulating the transmitted carrier with a subcarrier. The ranging signal is received by the balloon and then retransmitted back to the satellite at a different carrier frequency. The satellite measures the time delay between the leading edge of the transmitted signal and the leading edge of the returned signal. This gives a rough range estimate between the balloon and the satellite. Next, the satellite makes a phase comparison between the transmitted and received subcarriers. This is used to improve the accuracy of the range measurement. The satellite now shifts to a high subcarrier frequency and phase measurements are again made to provide a vernier or finer-range measurement. The satellite now digitizes the range measurement and stores it in its memory. It also stores in its memory the address of the balloon and the time of the interrogation. After the completion of the ranging sequence the balloon switches to a telemetry mode and transmits to the satellite the meteorological parameters measured by the balloon. The satellite digitizes the telemetered information and adds this to the stored memory.

BALLOON ELECTRONICS

The two-way interchange of information between the balloon and satellite requires a two-way radio link, an address decoder, a data encoder, and circuitry for time sequencing and switching on board the balloon. Figure A1 is a block diagram of the balloonborne electronics system. The received address is analyzed by the address decoder shown in Figure A1. If the proper address is received, the decoder turns on the time sequencer which, in turn, turns on the rest of the system, and switches the output of the receiver directly into the transmitter. This is the proper connection for ranging. After completion of the ranging sequence, the output from the data encoder is switched into the transmitter and the time sequencer switches Sensor 1 into the data encoder, followed by Sensor 2, followed by the remaining sensors. After completion of the telemetry sequence, the sequencer turns off all the circuits except the receiver and decoder and the balloon is semidormant until it is interrogated again. Figure A2 is a more detailed diagram of the balloon system.

RADIO LINK BETWEEN BALLOON AND SATELLITE

The optimum frequency for the radio link is between 100 and 200 mc/sec. The lower limit of 100 mc/sec is determined by the minimum frequency that will penetrate the ionosphere without excessive attenuation. The upper limit is determined by several factors, for example, 200 mc/sec is about the region where lumped parameter tuning elements such as inductors and condensers are no longer usable. Above

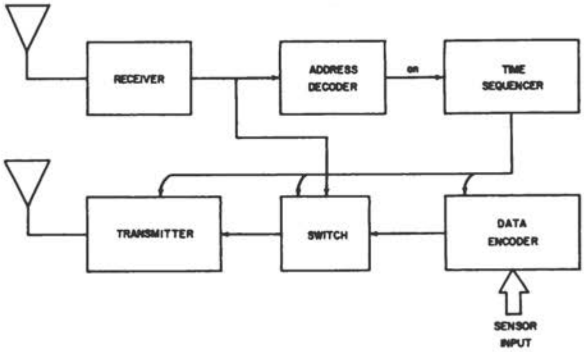

FIGURE A1. Block diagram—balloon electronics.

this frequency strip lines and tuned cavities are coming into use. These, of course, require structures with dimensional stability and mass which are not compatible with the lightweight frangible concept. Also, the efficiency of transistors used in the transmitter decrease rapidly with increasing frequency. At the present time, the transistor is not a practical device for use as a power amplifier at 400 mc/sec. In fact, at frequencies above 200 mc/sec, varactor multipliers are currently used instead of transistors. The varactor multiplier is a device that can convert power from one frequency to power at a higher frequency. However, there is a power loss in the transfer. Several of the reports that deal with the global horizontal sounding concept state that frequencies between 100 and 500 mc/sec are feasible. 100 mc/sec is indicated as the most practical as far as the balloon platform is concerned. However, the assumption is then made that the 400-mc/sec region is where the system will operate because of existing meteorological assignments in that region. At this point in time it should not be conceded that the system will operate at 400 mc/sec because the engineering aspects definitely indicate the advantages of using frequencies between 100 and 200 mc/sec. The balloonborne receiver and transmitter should operate with a frequency separation of about 400 mc/sec. This is to ensure that the transmitted power will not interfere with the receiver operation. A 40-mc/sec spread would allow a simple bandpass filter to be used in the front end of the receiver. Included in Figure A2 in the upper left-hand portion of the

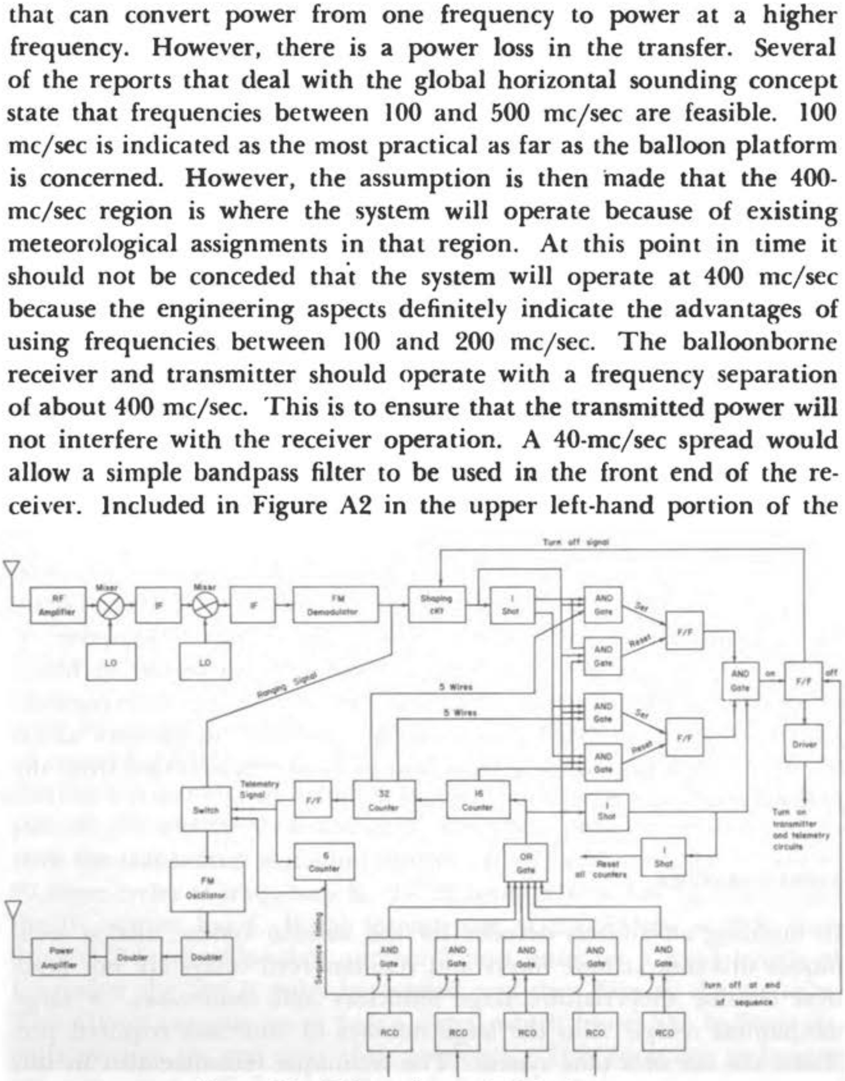

FIGURE A2. Balloon-electronics logic diagram.

diagram is a block diagram of a receiver that could be used on board the balloon. This receiver is a double-conversion superhetrodyne FM receiver. It might be advisable to build the receiver as a triple- or even quadruple-conversion receiver. The reason for many conversions is to separate the gain of the receiver so that the gain is divided among several frequencies. This would allow the designer to build a thin-film receiver that does not require mechanical structures for RF and IF shielding. The Sylvania report indicates that an IF bandwidth of 55 Kc is required to locate the balloon with a 0.1-mile accuracy using a 400-mc/sec carrier. However, if a 100-mc/sec carrier is used and the ranging accuracy is reduced to 3 nautical miles, then the required IF bandwidth reduces to 11 Kc. Sylvania calculations show that 10 W of transmitted power would be sufficient for communication between the balloon and satellite at a 55-Kc bandwidth. If, however, we are able to reduce the bandwidth to 11 Kc the transmitted power required would reduce to 2 W. At 400 mc/sec the frequency uncertainty to the Doppler shift and crystal instability is plus and minus 12.2 Kc. At 100 mc/sec the uncertainty reduces to about 3 Kc.

The use of a phase-locked receiver on board the balloon would make it possible to reduce IF bandwidth still further. However, this would require that a search mode be included in the interrogation sequence. This would consist of turning on the transmitter in the satellite and slowly changing the frequency. This would allow the phase-lock receiver to lock on to the transmitter carrier. After lock-on the receiver would automatically tune out the Doppler shift and the frequency drift. Since 2 W of power is already a very nominal power requirement for the satellite there is no need to incorporate the phase-lock receiver feature on board the balloon. However, it might be advisable to incorporate a phase-locked receiver on board the satellite and to include a tuning operation in the interrogation sequence. It is estimated that a tuning sequence would take about 0.4 sec. This would allow a reduction in power transmitted from the balloon to about 1 W.

ADDRESS DECODER

In building an address decoder for the balloon system, analog techniques utilizing LC-tone filters and resonant-reed relays are not practical because they require large inductors and condensors, or large mechanical relays. Also the large number of addresses required precludes the use of a tone system. The technique recommended in this presentation is the use of digital circuits for address decoding. The

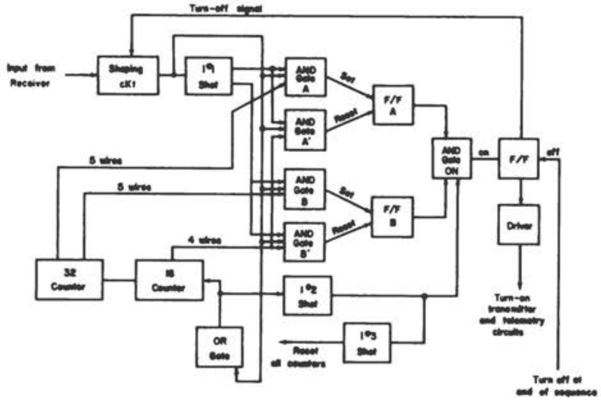

FIGURE A3. Address-decoder logic diagram.

logical diagram of an address decoder is shown in Figure A3. The logical diagram for a digital address decoder is more complex than for an analog system. However, the individual elements that make up the logic are very small and do not require much power.

The shaping circuit shown in the upper left of Figure A3 takes a sine wave output from the receiver and shapes it to a square wave. The positive-going leading edge of each cycle triggers the one-shot, and the output of the one-shot goes positive for a fixed length of time. As a result, the frequency of the signal from the receiver determines the symmetry of the one-shot output. If F_f is the frequency that will cause the one-shot output to be symmetrical then a frequency a little higher than F_f will cause asymmetry in a positive sense (output positive longer than negative). This is called frequency A. A frequency lower than F_s will cause asymmetry in a negative sense; call this frequency B. The shift in symmetry as a function of frequency provides a digital means of discriminating between the two frequencies.

The ranging sequence consists of first sending a fixed number of cycles at frequency A: for example, 328 cycles. The 328 A cycles go from the shaping circuit through an OR gate into a 16 counter. The 16 counter divides 328 by 16 to send 20 counts on to the 32 counter, leaving a remainder of 8 counts in the 16 counter. If 20A is the first part of the address then AND gate A sends a pulse to set flip-flop A. Now the transmitter shifts to frequency B and and sends, for example, 80 more cycles at frequency B; the 32 counter now has 32 counts and the 16 counter has 8. If the second part of the address is 25B, then flip-flop B is set. One-shot number 2 now waits for a fixed length of time after the last B pulse has passed and then flips to the set state. This allows AND-gate-ON to pass a signal which causes the balloon circuits to turn on and start their sequence. This counting technique allows an error of plus or minus 8 cycles. For example, the A part of the address would have accepted 328 cycles to 336 cycles. However, if 337 cycles or more had been received, AND gate A′ would have reset flip-flop A. In a similar manner flip-flop B would have been reset if there had been an excess of B counts either of which have nullified the address code. This type of address coding allows more than 1,000 different addresses to be used at the same time.

DATA ENCODER

A logic diagram of the balloonborne data encoder is shown in Figure A4. The meteorological data that is to be encoded is converted to a frequency by the resistance controlled oscillators (RCO) and the voltage controlled oscillator (VCO). These appear at the bottom of Figure A4. Resistance controlled oscillators are used since the inputs will come from sensors such as thermistors for temperature and a humidity indicator—both of which give a variable resistance as an output. A VCO is shown in the diagram to indicate that voltage inputs would also be acceptable. The RCO's are simple unijunction circuits that use an RC time constant to determine the frequency of oscillation. The R is the resistance of the sensor and the C is a fixed condenser. The RCO outputs are gated through an AND gate one at a time. From the AND gate the signal goes through an OR gate to a string of counters. The counter string contains the same 16 and 32 counter that was used in the address decoder system. In addition there is one more flip-flop stage resulting in a total count down of 1,024. The output of the final flip-flop goes to a 6 counter that controls the AND gates. The result is that RCO No. 1 sends out 1,024 pulses. On the last pulse the 6 counter closes AND gate No. 1 and opens gate No. 2. RCO No. 2 sends out 1,024 pulses and the circuit shifts on to RCO No. 3. The resulting signal out of the flip-flop circuit is a rectangular wave form where the period of 1 cycle is proportional to the RCO frequency (Fig-

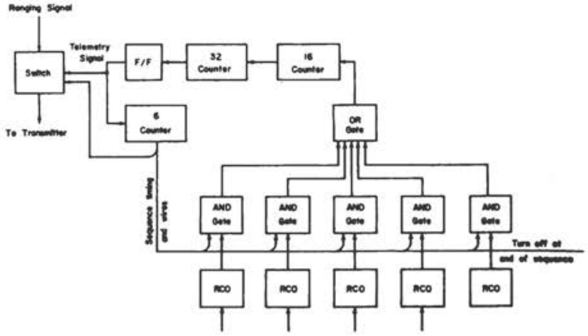

FIGURE A4. Data-encoder logic diagram.

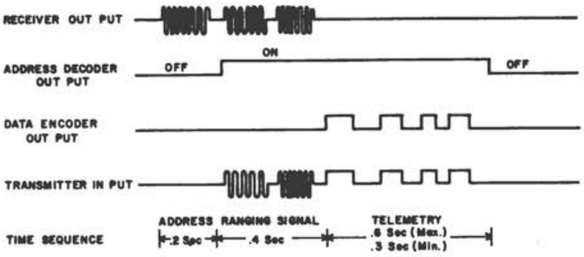

FIGURE A5. Balloon-electronics phase-relation chart.

ure A5). The rectangular waveform is used to modulate the transmitter.

When the address decoder turns the balloon circuitry on, the AND gate to the far right (Figure A4) is the one that is open. This gate allows pulses from the block marked clock to be counted first. The purpose of this circuit is to provide a time during which ranging can take place. After the ranging period each RCO or VCO is sequenced. After the last sequence the 6 counter sends out a signal that turns off the balloon circuits.

Figure A5 shows the time phase relationship between the operations on board the balloon.

SATELLITE ELECTRONICS

Figure A6 is a block diagram of the satellite electronics system. The left-hand portion of the diagram contains the receiver and transmitter for communicating with the ground readout station. On each orbit the ground station transmits to the satellite the program for the next orbit. The program consists of the address of the balloons and the time when they should be interrogated. This information is stored in the program memory. During the orbit the programmer maintains communication with the memory so that it can send addresses from

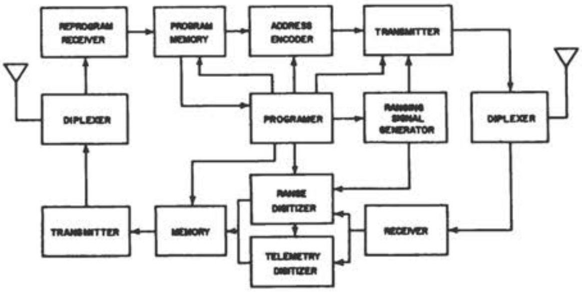

FIGURE A6. Block diagram—satellite electronics.

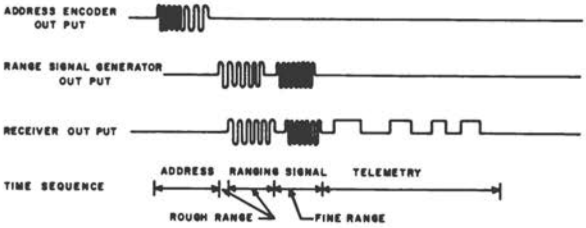

FIGURE A7. Satellite-electronics timing diagram.

the memory to the address encoder at the proper time. The encoded addresses are transmitted to the balloon by the transmitter shown in the upper right-hand portion of Figure A6.

After the address, the programmer switches on the ranging signal generator. The range digitizer measures the time delay between the leading edge of the transmitted ranging subcarrier and the leading edge of the returned signal. Next the digitizer makes a phase comparison between the transmitted and received signal. This improves on the accuracy of the range measurements. Additional range resolution is obtained by shifting the range signal generator to a higher frequency and making another reading. The output from the range digitizer is stored in the memory. The time is inserted into the memory by the programmer.

When the range measurement has been completed the programmer switches off the range digitizer and turns on the telemetry digitizer. In the telemetry digitizer the pulse width information from the balloon is converted into digital form and inserted in the memory. The sequence repeats for each balloon measurement. A phase diagram for a single balloon interrogation is shown in Figure A7.

At the completion of an orbit the contents of the memory are transmitted to the ground and the satellite is reprogrammed for a new orbit.

APPENDIX B

The Interrogation, Recording, and Location (IRL) System Experiment

INTRODUCTION

The periodic monitoring of geophysical, oceanographic, and meteorological data will provide an invaluable means for gaining a better understanding of the dynamic behavior of the earth's atmosphere and its oceans. The most serious limitation of existing programs has been the difficulty encountered in collecting the various data from the monitoring stations.[1-3] The extension of these systems to achieve global coverage would require a significant number of manned stations with their inherent high operating costs and acute logistic problems (especially in the areas of high interest, the poles and the equatorial regions).

Earth satellites are being used for making limited observations of the atmospheric conditions near the earth's surface[4,5] but do not have the means to provide sufficient and varied data to enable a complete and synoptic presentation of the state of the atmosphere to be made. Since data links between these satellite systems and the appropriate agencies now exist, it seems logical to use this means in extending the coverage to the earth's surface.

For these reasons a network of automatic unmanned stations that take data in some prescribed sequence and store and/or relay these data through a suitable communication system to a central point for processing is highly desirable.

An experimental system for the interrogation, location and recording of data from these automatic, unmanned stations is proposed for the Nimbus B Meteorological Satellite.

THE SYSTEM

The simplified block diagrams of the satellite and surface station in Figures B1 and B2, show how the basic functions of the IRL system are performed. As the title implies the first of these functions is *Interrogation.* This function allows the satellite to communicate with any specific surface station. The interrogation sequence of the surface stations is programmed for each orbit at the satellite Command and Data Acquisition (CDA) station. Each surface station is assigned a discrete address. In the IRL system design, the address consists of a digitally coded number containing 16 bits. The arrangement of the bits is specified in such a way that the address of any one surface station differs from all others by at least three bits. Using this rule to assign addresses in a code group of 16-bit positions allows up to 2,048

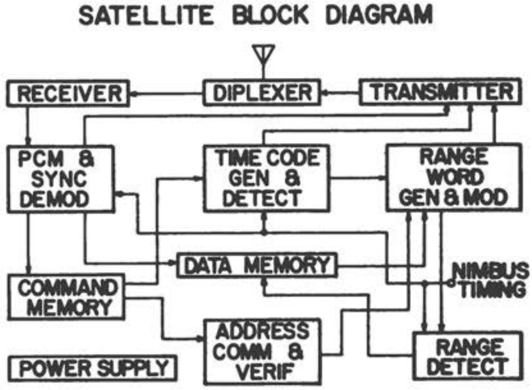

FIGURE B1. IRL system simplified satellite block diagram.

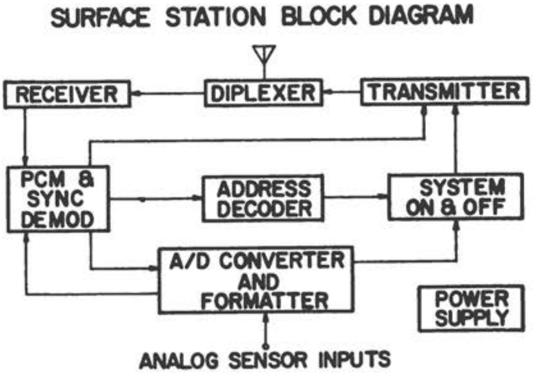

FIGURE B2. IRL system simplified surface station block diagram.

station addresses to be assigned. The reason for requiring a three-bit position difference in each coded address is to assure maximum security against having the wrong station respond to an interrogation. An interrogation command consists of two parts: (1) the address of the station to be interrogated and (2) the exact time, referenced to satellite-orbit time, that the station is to be interrogated. These two requirements are met by assigning a command of 32 bits, 16 of which specify the address and 16 specify time. On the Nimbus spacecraft, a very stable clock[6] is used to control the time of execution of critical operations throughout any one orbit. This same clock is used in the IRL system experiment to keep track of time in the orbit relative to a starting time. The starting time is reset to zero when the CDA station at Fairbanks, Alaska, communicates with the spacecraft. In the IRL system, a counter, synchronized by the Nimbus clock, is used to develop a 16-bit code word corresponding to the orbit time relative to zero and is updated each second of real time. The coding arrangement is simple binary coding and corresponds to the coding arrangement of each command word. Thus a means for developing a time code in the satellite which can be compared to any time code in an interrogation command word is achieved.

Once a surface station interrogation sequence is planned by the CDA station computer, a series of 32-bit command words is generated and punched onto paper tape. The total number of commands needed depends on the deployment of the surface stations relative to the next satellite pass over the earth. When the satellite is in communication view of the ground station at Alaska, a command is routed via the Nimbus spacecraft command system to the IRL system experiment. This command performs two functions: (1) the IRLS clock is reset to zero time in the counter, and (2) the IRLS communication system is turned on allowing the ground station to receive stored data from the previous orbit and load a new set of interrogation command words into the IRL system command memory.

On the spacecraft, the IRL system contains a memory that enables it to store all the command words sent by the CDA station for controlling the interrogation sequence. This memory is made up of magnetic cores and is large enough to accommodate 20 command words of 32 bits each. The memory size is dictated by the experiment capability and does not represent the maximum system capability. When it has been determined that all commands are received and stored correctly in the command memory, communication with the ground station is terminated and the IRL system begins its surface station interrogation sequence. The first command word in the memory is read into a 32-bit storage register. This register splits the command word into its two parts, address and time. The time-code portion is continuously compared to the satellite time. When a time-code match occurs, the IRL system is instructed to start interrogating the first surface station. This is done by transmitting the address code of that station serially at the rate of 1,041 bits per second, as a digital subcarrier of the fundamental system bit rate of 12.5 kilobits/sec. Transmission of the 16-bit coded address continues until the surface station responds. The total time of a complete interrogation sequence for any surface station is 3.2 sec or less.

Each surface station contains an address decoder that compares any incoming 16-bit word with the one wired in as its assigned address. When it determines that the code received matches the address code assigned, the surface station starts its UHF transmitter and replies on the IRL system frequency channel by transmitting its own address back to the satellite.

The satellite electronics receives the surface-station transmission and first determines, through an address verifier, if the correct station is replying. When it has been determined that it is correctly identified, the IRL system in the satellite switches its transmission to the complement of the address and sends this to the surface station confirming correct reply and prepares the storage system on the satellite to receive the surface-station data.

The surface station looks for the coded address complement before it starts the data transmission. When recognition is achieved the data are transmitted to the IRL system aboard the satellite for storage. In the event that a surface station does not reply to the IRLS address transmission, the system is shut off in 3.2 sec and the next command word is placed in the storage register.

Once interrogation of a surface station has been completed and confirmed by the IRL station, the second function of the system design, *recording*, must be carried out.

The scientific data measured and encoded at the surface station are transmitted to the satellite where they are stored for subsequent readout to the ground station at Fairbanks, Alaska. The amount of data which is stored during any single orbit is a function of the number of surface stations interrogated, the number of data points, and the resolution of the digitization at the surface station. The size of the data memory specified for the Nimbus B IRL system experiment is 20,000 bits, and is based on up to 20 interrogations per orbit averaging 1,000 bits of data per interrogation. A serial read/write magnetic core memory is used as best meeting the over-all system requirements.

The storage of data is carried out by assembling the data at the surface station in orderly frames of 272 bits each. (See Figure B3.)

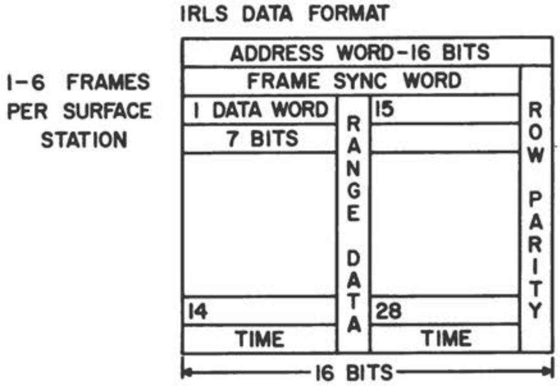

FIGURE B3. Single data frame as transmitted from a surface station. Range data inserted in center column.

A single frame consists of an address word, a frame synchronization word, and 28 data words of seven bits each. The surface-station design allows up to six frames, each having an appropriate number of sensors as its data to be transmitted. In addition to these data bits, each frame contains bit positions that are vacant (e.g., zero) when transmitted to the satellite. These vacant bit positions are used for inserting the range data and vernier time information required in computing the location of the surface station.

The data as they are transmitted to the satellite from the surface station at the rate of 1,041 bits/sec are loaded serially into the magnetic core memory. The loading is controlled from synchronizing signals developed in the digital circuits. When all frames from a station have been loaded, an end of message signal is transmitted from the surface station which automatically stops the memory loading process and terminates the interrogation. The satellite transmission terminates 3.2 sec after initiation of the interrogation and proceeds to the next command word cycle.

At the completion of the orbit, the CDA station sends a command for the readout of all data stored during the orbit. This is performed through the Nimbus command system as described earlier under INTERROGATION. When it has been established at the ground station that communication with the IRL system is satisfactory, a 16-bit word is transmitted to the satellite through the IRL system UHF channel signaling the commencement of data transfer. This is done at the rate of 1,041 bits/sec until the entire contents of the 20,000-bit memory has been read out. At this time, a signal is automatically sent by the satellite to the ground station to indicate that it has concluded the data transmission and is ready to accept a new set of command words.

With the data received on the ground and stored in a buffer memory, further processing is required to separate the message frames. This is done by a small computer whose function is to sort out frames by employing the rules of coding designed into the system and assemble the data into a suitable format for distribution to the appropriate agency. This output format will consist of each station's identification address, decoded data, the time of interrogation, and the additional data developed by the satellite, which enables surface-station location to be computed.

The function that separates the IRL system from a pure data-relay system is the provision for determining the LOCATION of each surface station in terms of its earth latitude and longitudinal coordinates. The location is determined by using the unique geometrical relationship that exists between the satellite and the surface station, which yields a unique mathematical solution when the distances between the satellite and surface station are known. The IRL system provides the distance information by a range-measurement technique.

The instrument surface station is located by making multiple measurements of the distance between the satellite and surface station and using these measurements in the geometrical equation. This geometry is shown in Figure B4. Computer analysis of this problem has shown that two measurements of the distance denoted as R_1 and R_2 are all that is required to establish the surface station location. The two range measurements (distance) and the chord distance that the satellite travels between measurements R_1 and R_2 defines a plane triangle in space, intercepting the earth at the surface station. Since the satellite ephemeris is known, all sides of the triangle can be determined. In the IRL system experiment, the exact time of each range measurement is recorded, which, together with the satellite orbital

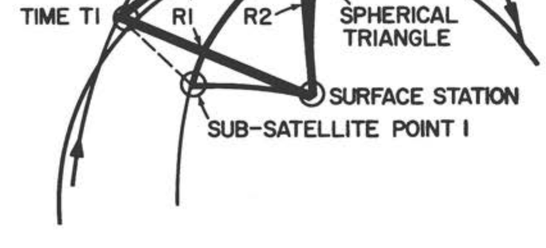

FIGURE B4. Position geometry to determine the location of an IRL system surface station.

parameters, allows the third side of the plane triangle to be calculated. The vertical projection of this triangle onto the earth's surface defines a spherical triangle having as its vertices, the subsatellite points SS_1 and SS_2 along the ground track (Figure B4) and the surface station.

Once this construction is complete and the subsatellite points coordinates have been computed from the ephemeris data, the surface-station coordinates can be computed.

In any experiment, there are sources of error that must be included in the analysis. In the IRL system experiment, the significant errors contributing to the surface station coordinate errors are run on full measure: (a) the error in the distance measurements R_1 and R_2, (b) the uncertainty in the orbit prediction, and (c) the accuracy of the specific time of each measured range.

A detailed error analysis has been carried out that accounts for these. The results are shown on Figure B5. These curves show how the accuracy of the coordinate calculations depends on the surface station distance from the ground track as a function of three range measurement accuracies. Since the range measurement is bounded by a tolerance, the plane triangle projection onto the earth's surface causes a spread of tolerances at the surface-station location. For measurements made at angles greater than 15° from the satellite vertical, the projected error bounds of R_1 and R_2 are linear as the error limits change. The data presented in Figure B5 were computed on an IBM 7090, which simultaneously solved for the optimum time separation of the two measurements. For a satellite whose altitude will lie in the region of 1,000 km to 3,000 km, this time is 150 sec.

In addition to the incremental error problem, there is a gross error or ambiguity owing to the fact that the geometry is symmetrical about

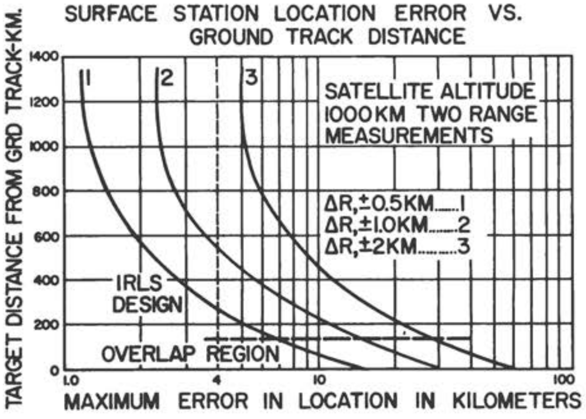

FIGURE B5. Calculated location uncertainty as a function of target distance for various range accuracies.

the satellite ground track. Therefore, two solutions to the coordinate sets are obtained. This error is easily resolved in either of two ways. First, the general location of any surface station is known well enough, through records kept, to enable the erroneous solution to be rejected most of the time. When the surface station lies close to the ground track and the incremental errors are of the same magnitude as the ambiguity error, it is possible to interrogate the same surface station on the next orbital pass when the surface station position is most favorable. The IRL system experiment has been designed to allow the range distance to be measured to an accuracy of ±0.5 km. The shaded portion of this curve on Figure B5 bounded by the orbital pass overlap line represents only 5 percent of the area in any orbit.

This assures that the location error will be within ±2 km with a 0.95 probability assuming a uniform distribution of surface stations on the earth's surface.

The error analysis, as computed, was based on a mean-time error of ±0.05 sec, a satellite altitude of 1,500 km, and a satellite-positional error of ±0.3 km, which is representative of current prediction capability.

The measurement of the distances R_1 and R_2 is done by measuring the round-trip propagation time of the radio signal between the satellite and surface station. A digital code word is transmitted between the two points; the effective wavelength is 4,608 km. This assures that the message fills the space between the stations or the region of distance uncertainty. The code sequence used is 192 bits long and is transmitted by the PCM-FM communication link at a bit rate of 12.5×10^3 bits/sec, controlled from a clock whose frequency stability is better than 1 ppm.[6] The repeating sequence is made up of 16 words, each containing 12 bits. The word structure is chosen to allow rapid synchronization of code sequence regenerators in the surface station receiver and in the satellite receiver. The synchronization code structure contains a fixed sequence of eight bits whose cross-correlation function provides maximum noise rejection and contains an equal number of ones and zeros. The code is 10101100 in the normal format. Following each 8-bit code is a 4-bit word used to count the 12-bit words from zero to fifteen thus providing a unique signature for each word as well as the entire sequence. The code sequence regenerators are also synchronized to the word count by simultaneously autocorrelating two successive 4-bit words. Since successive words differ by one count, the arithmetic adder is used to bring successive words to the same count value. The count of zero is decoded and indicates the zero position of the message sequence.

To measure the propagation time (Figure B6) a counter in the satellite system, driven from a 1.6-mc/sec clock signal, is started at the beginning of each received range code sequence and stopped at the beginning of each transmitted sequence. The counter contains fifteen stages and is capable of resolving time increments of 0.625 sec which is equivalent to a one-way range resolution of ±98 m. The time jitter and stability between the transmitted and received bit-time clocks is held to less than ±2.0-sec peak or ±300 m one-way range.

Over-all system delays in the round-trip path including receiver time-delay uncertainties are held below ±1.0-sec or ±150 m. The accumulative errors that contribute to the peak over-all range-distance error is then ±550 m. The combined resolution limits and noise-perturbed errors will guarantee a maximum error under ±500 m on the average.

The 15-bit word stored in the counter register is multiplexed into the incoming surface-station data aboard the satellite.

Since it is necessary to transmit data on the ITL system links (i.e., address data to the surface station and scientific data to the satellite), a frequency multiplexing technique is used. The fixed sequence of 8 bits (10101100) is transmitted normal for a data bit of one (1) and its complement (01010011) transmitted as a data bit zero (0). This has no effect on regenerator synchronization but does allow 16 bits of data to be transmitted and efficiently synchronized with the range code sequence. It is for this reason that the data format is generated as multiplier of 16 bits. A by-product of this technique allows any bit position in a group of 16 to be identified at either receiving end. Through the use of this flexible synchronization system, the measured

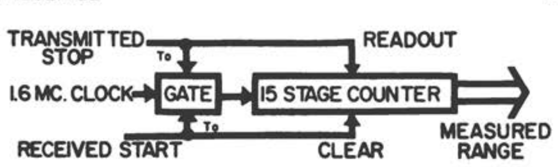

FIGURE B6. Range measurement timing diagram and simplified range detector.

range data and 7-bit time-code vernier is inserted into specific bit positions (see Figure B3) on the incoming data at the satellite. Figure B7 shows the performance of the system in terms of specific error rate curves for each digital subsystem. These curves are measured values made on the laboratory breadboard. Since the PCM system performance is directly related to the quality of the 12.5×10^3 bit/sec input bit stream, the effects on ranging and data errors can be interpreted in terms of the single-bit-error rate of this digital signal. At a single-bit-error rate of 5×10^{-2} in this stream, the range-sequence regenerator is in synchronization 99 percent of the time.

The data (1.041×10^3 bits/sec) error rate is 10^{-4}, which is a perfectly acceptable error rate since only an average of 1,000 bits of data are transmitted during each interrogation period. The actual system is not designed to operate nominally at this low signal-to-noise ratio but insures that a communication link fade as high as —10 dB from the nominal signal level can occur without resulting in a loss of synchronization.

COMMUNICATION SYSTEM

The design of the communication system is the result of a parametric study on certain critical parameters which would affect the performance. The factors most important are the operating frequency, modulation technique, and required RF bandwidth. Since state-of-the art advances limit the receiver noise factor, practical carrier frequency stabilities, and frequency allocations, leads to the choice of the 400/465 mc/sec UHF band for the Nimbus B IRL system experiment. Certain considerations relating to the spacecraft dictated limitations as to the antenna size and interference susceptibility. Comparisons made between different modulation methods showed that a pure FM system was most practical when the simplicity and lowest power required for such a receiver was of major importance in the surface-station system. The 400/465-mc bands allow a 15 percent frequency separation which is about minimum for the diplexer needed by the IRL system experiment.

The communication system gain parameters are affected by the satellite orbital geometry, data handling requirements, and the ranging accuracy. The parameters related to the orbit are: (a) communication pathlength, (b) antenna off-axis polarization, and (c) antenna pattern.

The maximum pathlength for a 1,000-km satellite altitude is 2,000 km to assure greater than tangential coverage at the equator. Circular polarization is used and the attendant loss of only —2.0 dB over the range of antenna angles is not as great as a linear polarization of random orientation, primarily at the surface station. A study has been made of the effect of altitude on the communication system gain and, when all parameters are considered, indicates that for an altitude range of 1,000 km to 3,000 km, the over-all communication gain varies less than 2.0 dB.

The antenna pattern chosen for establishing the communication system design constraints is that produced by a circularly polarized turnstile placed 0.37λ over a ground plane. The measured 3.0-dB beamwidth of this antenna is 110° with an on-axis gain of 7.0 dB over a circularly polarized isotropic source. Other antenna configurations are being investigated at the present time to determine what the trade-offs are for the experiment when the coverage and/or communication system performance is of prime importance.

The receiver that has been designed for the IRL system is presently yielding a noise figure of 3.5 dB at 465.0 mc/sec. The predetection bandwidth is 125.0 kc which is fixed by a specially designed phase linear crystal filter. The need for the wide bandwidth arises due to the center frequency tolerance of 0.0015 percent in both the transmitter and receiver, the Doppler effect at the worst communication angle, and the modulated spectrum of the PCM signal. The time delay of the demodulated PCM signal is known to an accuracy of ± 0.5 μsec in each receiver under all operating conditions of both the up and down communication links.

From these parameters, a complete communication system power budget is compiled and shown in Table B1. The sum of the negative tolerances, when weighted against the nominal carrier-to-noise (C/N) ratio shows that with 25 W transmitted power the system margin is adequate.

From the PCM performance curves of Figure B7, a worst case design limit +6.0B carrier-to-noise ratio in the receivers show the single bit error probability of the data to be less than 10^{-1} and ranging synchronization to occur 99.98 percent of the time. This is chiefly dependent on the pattern (code sequence) synchronization error rate.

The laboratory tests made on the breadboard IRL system confirm these design goals as being adequate and well within expected performance.

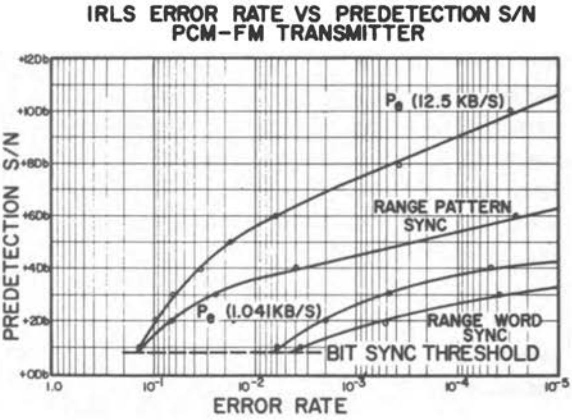

Figure B7. Measured predetection carrier-to-noise ratio versus error rates.

TABLE B1. *IRL System Communication Power Budget*

Minimum range		2,000 km
Maximum frequency		465 mc/sec
Parameter		Negative Tolerance
Path loss	—152.3 dB	—0.5 dB
Antenna gain		
G_{81} surface station	+ 3.0 dB	—1.0 dB
G_{82} satellite	+ 3.0 dB	—1.0 dB
Circularity loss	— 2.0 dB	—1.0 dB
Satellite cable losses	— 0.5 dB	—0.5 dB
Surface station cable losses	— 0.7 dB	—0.5 dB
Receiver diplexer loss	— 0.8 dB	—0.2 dB
Receiver noise figure	+ 3.5 dB	—0.5 dB
Sky temperature	300°K	
Transmitted power (25 W)	+ 44.0 dBm	—1.0 dB
Noise bandwidth (125 kc)	+ 51.0 dB	
		—6.2 dB
Power received	—106.3 dBm	
Noise power	—119.4 dBm	
Nominal C/N	+13.1 dB	
Worst case	+6.9 dB	

NIMBUS INTERFACE

The IRL system will integrate with the Nimbus B spacecraft and present unique interfaces with the spacecraft mechanical, thermal, and electrical systems. The mechanical design conforms with the Nimbus concept of modular design. The total volume occupied by the system is 390 in.^{3}. This is contained within five separate modules specified below with the weight and Nimbus nomenclature breakdown. The thermal interface is represented by the power dissipation within each module and is given in the breakdown, Table B2.

TABLE B2. *Spacecraft—Volume and Power Budget*

Module	Size	Weight (lb)	Power (W)
1. UHF transmitter	2/0	7.0	9.8 (continuous) 117.8 (peak)
2. UHF receiver	1/0	2.5	1.5 (continuous)
3. Digital logic	1/0	2.0	1.5 (continuous)
4. Memory system	1/0	2.5	0.25 (continuous) 0.35 (peak)
5. Power control	1/0	2.0	0.40 (continuous)
Total		16.0	13.45 (continuous) 121.55 (peak)

The duty cycle of the peak power demand is given by $(T_{RO} + N \times T_I)/T_{ORBIT}$, where N is the number of stored interrogation commands, T_I is the interrogation time interval, T_{ORBIT} is the period of the orbit and T_{RO} is the data readout period. The experiment then yields a duty cycle of $(32 + 20 \times 3.2)/6600 = 0.014$. It should be noted that the time of each interrogation will be randomly distributed during any orbit period. The average dissipation is given as $(13.45) + 0.014\ (108.1 - 25)$ W or 14.61 W. This together with the knowledge of the peak dissipation $\times\ T_I$ specifies the thermal load to the Nimbus B spacecraft.

The electrical load presented to the spacecraft power system will occur on the regulated —24.5-V buss and is: 0.55 A continuous and 5.10 A peak at the same duty cycle discussed above. The load conforms to the Nimbus B power load noise specification as relates to noise fed back from the IRL system to the spacecraft power system.

The electrical interface requires, in addition to the primary DC power, three frequency sources from the Nimbus B clock system, three unstored commands from the spacecraft command system, and twenty-five telemetry points to be telemetered through the spacecraft PCM system; the three frequencies required are:

CLOCK SOURCE INTERFACE

Frequency (cps)	*Stability*	*Load Z* (ohm)	*Level*	*Waveform*
1.6×10^6	Nimbus clock	50	0.1 Vrms	Sine
5×10^4	Nimbus clock	600	1.0 Vpp	Square
10	Nimbus clock	600	1.0 Vpp	Square

Square-wave symmetry must be within 5 percent. The no-load Thevenin equivalent of all frequencies except the 1.6×10^6 cps must be nominally —5.5 V from a 3,000-ohm source impedance. All frequency sources should be unbalanced to ground.

COMMAND INTERFACE

Three nonstored commands are used to:

(1) Turn "on" primary DC power to the IRL system.
(2) Turn "off" primary DC power to the IRL system.
(3) Start the data readout and command reading from the ground station at Fairbanks, Alaska.

The third command function must be initiated from the CDA station at a predetermined time. This is necessary since the computed commands prepared on paper tape during the previous orbit must be referenced to a zero time reset to within ±50 msec in the IRL system interval clock. The data readout command (3) resets this clock to zero time reference.

The IRL system is designed to allow each command interface connection to be electrically isolated from all other circuits and ground.

ANTENNA

An antenna system must be provided to operate in the 401.5 mc/sec to 466.0-mc/sec band and yield a minimum gain of +3.0 dB over an angle of ±55° at all orientations from the spacecraft vertical with right-hand circular polarization.

TELEMETRY INTERFACE

The IRL system will have twenty-five telemetry channel outputs, each compatible with the planned Nimbus B PCM system (i.e., zero to —6.4 V for full-scale output). There will be up to ten analog telemetry signals where an appropriate calibration curve for each sensed parameter (for example, temperature, pressure) is provided. Fifteen telemetry points will be digital in nature and will only be used to monitor the state (yes or no) of critical mode control circuits of the IRL system in the spacecraft.

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APPENDIX C

The EOLE Experiment

Several systems for keeping the earth's atmosphere under permanent surveillance can be imagined. In the present proposal the tropospheric parameters are measured by a suitably instrumented automatic station carried by a balloon drifting freely in the atmosphere. The satellite serves only as a buffer memory as it interrogates and records the informations telemetered by the automatic stations.

Three such systems have been studied in considerable detail:

(1) The "Interrogation, Recording, Locating System" (IRLS) under consideration by NASA for installation on the Nimbus B satellite scheduled for 1966;

(2) The "Global Horizontal Sounding Technique" (GHOST) presently in the design study stage;

(3) The "EOLE" experiment scheduled by the Centre National d'Etudes Spatiales of France for flight on a small special purpose satellite early in 1968.

The present report reviews the main results of the EOLE design study program.

DESCRIPTION OF THE SYSTEM

The balloon locations and interrogation system must interrogate one particular balloon among all the balloons present in the observation range of the satellite, measure the distance from the satellite to this balloon with sufficient accuracy (of the order of ~ 1 km), transfer meteorological data measured by the balloon instrumentation into the satellite memory, and allow for multiple readout of the content of this memory by suitable ground data acquisition stations without destroying the data stored.

In addition, the system must satisfy several design criteria of paramount importance: the balloon transponder must be vanishingly light and consume no significant amount of power, and the interrogation-location-telemetry operation must be as short as possible to allow the interrogation of the many balloons possibly present in the same observation range.

Design studies and actual experimentation with models of the transponder equipment have shown that these design goals can be reasonably well met.

Range measurement. The problem is to determine the propagation time of a radio-frequency signal sent out by the satellite and transmitted back by the balloon transponder (i.e., the phase lag between the satellite master clock and the signal received from the answering balloon). This time-lag measurement is performed in two successive steps over the same VHF channel (400 Mc).

First, an adjustable oscillator or "clock" carried by the balloon is synchronized on the digital (video) frequency of the interrogation signals broadcast by the satellite. These interrogation signals consist of short C4 bits words (lasting 12.8 msec) transmitted every 256 msec or about four times per second. The balloon "clock" has a sufficient memory to capitalize on several interrogations filling the gap between two successive interrogation-synchronization words (i.e., 243 msec out of 256) by "flywheel" action. After receiving some 20 interrogations (within a 5-sec "synchronization" period), the balloon clock is perfectly synchronized with the coherent signals arriving from the satellite.

The second step is taken only when one interrogation word includes the proper code number characteristic of the balloon being interrogated. Immediately after receiving this proper code number, the balloon transponder sends out its reply in the form of a coherent 240-bit sequence (lasting 192 msec) perfectly synchronized on the balloon "clock," i.e., on the phase of the incoming interrogation signal. The reply of the balloon is received by the satellite and decoded. The time of arrival of the final code number identifying the 240 bits sequence provides a coarse measurement of the satellite-to-balloon distance. A fine comparison of the phase of this digital sequence with respect to the master clock of the satellite provides a more accurate measurement of the distance.

Since the time lag for maximum range (3,000 km) does not exceed 20 msec, the total interrogation and ranging sequence lasts 225 msec at most. A new interrogation signal is, therefore, broadcast by the satellite after 256 msec. The full interrogation cycle for 512 addresses, therefore, lasts about 130 sec, allowing three successive interrogations of the same balloon within the minimum "visibility" period of 6.5 min.

Scientific data telemetry. In order to obtain a sufficiently accurate phase lag measurement on the satellite, the balloon reply sequence must be fairly extended in time (192 msec). This long sequence provides, therefore, ample space for telemetering scientific data (up to 200 bits per interrogation). This ample data handling capability is not completely used in the EOLE project, since it is satisfactory for present purposes to transmit only a 13-bit word.

On-board data processing and recording. It would, of course, be quite unreasonable to record the result of each interrogation performed cyclically by the satellite: one wishes only to record the useful information, i.e., the data obtained when one balloon is within good range and sends back a reply. These data are:

Time of the interrogation (characterized by the interrogation cycle number)	5 bits
Balloon address number	9 bits
Distance	11 bits
Scientific data	13 bits
Total	38 bits

At least three successive interrogations are needed to obtain a good fix of the drifting balloon, so that a successful contact with one station involves the recording of 3 × 38 or 114 bits. If the 512 balloons are all overflown during one orbit, a memory capacity of approximately 60 k bits is needed. This is well within the capability of present spaceborne random-access memories (c.f., 200 k bits for the Orbiting Astronomical Observatory).

The memory is handled as a sequential storage bank which can be read out much in the same fashion as a closed-loop magnetic tape, without erasing the stored data.

THE SPACECRAFT

The satellite and balloon electronic packages at present limit the maximum useful interrogation range to 2,700–3,000 km. This range is not quite large enough to allow a complete global coverage with a unit probability of finding all stations twice on two successive passes 100 min apart. Under present conditions, this coverage can be obtained only in a zone extending from lat. 75°N to 75°S, with an orbital inclination of 55°. It is quite possible that this maximum useful coverage will be traded for more frequent interrogations in a somewhat more limited area. For example, the choice of a strictly equatorial orbit would allow a fix of all balloons in a zone extending from 20°N to 20°S once every 100 min. The preferred orbit could, therefore, in this case be a 500-nautical-mile quasi-circular orbit slightly inclined to the Equator.

The spacecraft can be placed on this orbit by a Diamant rocket or equally well by a SCOUT rocket. Its altitude in flight will be passively controlled by gravity gradient in order to optimize the radiofrequency gain with the help of directional antennae.

The total weight of the spacecraft itself amounts to 55 kg and its average power consumption is approximately 5 W. The interrogation subsystem itself (transmitter–receiver–clock memory and logics) weighs about 9 kg. Most of the power is used for broadcasting the interrogation signals at 400 Mc/sec.

THE BALLOONS

Balloon fabrics are now under study for low coefficient of diffusion, good mechanical strength, and good sealing characteristics. Multilayer plastic laminates have proved quite satisfactory for sealing and low coefficient of diffusion. Investigations of textile nets incorporated in the plastic laminates have been undertaken. It appears now that suitably permanent superpressure balloons will require a rather heavy envelope (50 μ or more) at least at the altitudes contemplated (500 and 250 mb).

The balloon equipment design has been based exclusively upon existing electronic components and would, therefore, not include any advanced two-dimensional device of the type contemplated in the GHOST study. It must be pointed out that this appeared to be a reasonable approach for an experiment limited both in area (Southern Hemisphere) and in time (a few weeks). This design philosophy does indeed provide great savings of both money and time for the development of the balloon payloads.

As it is, the balloon equipment is divided into two parts: the electronic package including the transponder, coder, and antenna, and a power supply package. The two packages are suspended at about 10 m and 20 m below the balloon.

Balloon electronic package. The electronic package weighs about 1 kg (including an expanded foam container and the antenna). Its power consumption amounts to 50 mW, mostly for operating the receiver (pulsed stand-by operation).

Balloon power supply. Several balloon power supplies have been investigated. A possible power system includes solar cell generator (90 solar cells), a nickel–cadmium storage battery and a dc-to-dc voltage converter for operation of the high-power radio-frequency emission transistors. Two hours of good lighting conditions provide enough power for 1-day operations. Such a power supply would weigh less than 1 kg including the insulation of the Ni–Cd battery.

Fuel-cell power supply operating on pure hydrogen and oxygen is also under investigation. Such a cell could easily provide up to 3 months of power for a negligible solid weight (discounting, of course, the weight of the gas supply stored at atmospheric pressure in small auxiliary balloons).

Instrumentation. At the rather low altitude considered presently (500 and 250 md), radiative effects on temperature sensors present no problem. Small head thermistors, 0.4 mm in diameter, have been studied at atmospheric pressure under conditions of extremely small ventilation rate. The temperature error due to radiation heating does not exceed 0.5°C without ventilation.

Suitable miniaturized pressure transducers are not currently available. Special pressure gauges will, therefore, be designed and manufactured for the limited pressure range encountered in actual flight (i.e., for example, 400 to 600 mb at the nominal 500-mb level). These transducers will be based upon the BOURDON manometric capsule and fitted with strain gauges to measure their deformation.

A reasonably light balloon payload (less than 2 kg separated in two packages) can be built soon enough to ensure reliable operation during the experimental program. More development work would be needed to make the present design suitable for large scale operation.

OPERATIONS

Balloons will be launched from 20 to 40 stations suitably located in the Southern Hemisphere.

Normal delayed operation. Tracking and data acquisition of the satellite will normally be done from the tracking and telemetry stations of CNES located approximately along a meridian segment extending from 30°N to 30°S in Africa. Those stations will read out the data stored in the satellite memory without erasing it.

Real-time operation. A different operational mode can be thought of since the satellite memory can be read out without destroying any data. A suitably located special-purpose telemetry station could then interrogate the satellite as it flies by and thereby obtain in real time two successive (paired) locations of all balloons within a range equal to twice the maximum visibility range of the satellite (i.e., 5,000 km). This type of operation will be ideally suitable for local studies or short-term warning about the incoming weather.

ANALYSIS OF THE PERFORMANCES

Analysis of radio communication over the satellite-to-balloon distance shows that the range measurement accuracy will be of the order of 0.8 km. The location of a balloon with respect to the satellite track is determined by three range measurements and the over-all accuracy of the fix will be of the order of 3 km. This uncertainty is to be compounded with those due to the satellite position error and to the effect of random wind. Present-day satellite tracking techniques are such that the position of the spacecraft can be known at all times with a probable error of less than 100 m. For the present purpose, the satellite trajectory can, therefore, be assumed to be perfectly determined. On the other hand, random winds (gusts) do introduce a sizeable and quite irreducible location error of the order of 1 km per 10 km/hr of random wind speed. The final location error can, therefore, be estimated to be of the order of 5 km or less on each individual fix.

The interrogation-ranging sequence lasts approximately 256 msec. This interrogation and ranging time, therefore, places a limit on the number of balloons which can be successfully interrogated within a given visibility range. Assuming a minimum mutual visibility time of seven minutes on the edges of the area overflown by the satellite, about 500 balloons at most can be interrogated three times during the pass.

A further limitation is imposed by the very simple interrogation logics contemplated for the EOLE experiment. Since the 512 addresses are called cyclically, one cannot operate more than 1,000 or 1,500 stations altogether at a given instant (two or three stations answering to the same address number would not bring any difficulty provided these stations are sufficiently far apart).

The telemetry channel performance is quite low in the EOLE experiment project since one has deliberately chosen to transmit only three words of 13 bits to measure only the local temperature and pressure. The data handling capability of the balloon-to-satellite communication link, is however, much larger. Up to 600 bits of information could easily be accommodated on this link with optimum digital coding (at the price, however, of providing a more sophisticated data encoder on the balloon and a large storage memory on the satellite).

APPENDIX D

Comments on the Statistics of the Distribution of a Large Number of Constant-Volume Trajectories

Let us consider a very large number of marked points distributed at random over a very large area. To describe the spatial distribution of these points, we may make use of the distances from some independently chosen points in space—or from the marked points themselves—to the nearest marked point. Since the number of points is very large, and they are distributed at random, the two types of distances will have the same frequency function. It has been shown earlier[1] that this frequency function has the form

$$f(r) = 2\pi r\chi e - \pi r^{2}\chi, \tag{1}$$

where r stands for the distances from our reference points, and χ is the concentration of marked points or number of marked points per unit area. The mean value of these distances,

$$d = \int_{0}^{\infty} r f(r)\, dr,$$

is, by Eq. 1, equal to

$$d = 1/2\,(\chi^{-1/2}). \tag{2}$$

It is convenient to choose the unit of length so as to make $\chi = 1$; in this case we have

$$d = 0.5 \tag{3}$$

when the marked points are distributed at random.

It seems reasonable to expect the nondivergent part of the quasi-horizontal air motions to produce a random distribution from initially organized particles floating with the wind, and to maintain the randomness of the distribution once it is reached. Thirty-day nondivergent diagnostic trajectories of particles, starting at the grid points of the NMC 1977-point grid, and defined to stay on the $\rho = 0.908$ kg m^{-3} isopycnic surface, have been used to check this expectation. Frequency functions of distances from these marked particles to their nearest neighbors have been computed as well as mean values of these distances. Except for irregularities due to the finite number of particles, the frequency functions approached the random distribution of Eq. 1, reaching it in about 10 days, and remaining later in a very good agreement with it. The mean values of these distances, shown in Figure D1, illustrate the time rate of this process. In the next 18-day period $\bar{d}$ oscillated about the random distribution value, having an average of 0.499. It seems, therefore, fairly safe to conclude that the nondivergent part of the air motions does have the property of producing and maintaining the random distribution of floating particles.

In this experiment the concentration of marked particles was initially a function of latitude, being about twice as great near the boundary as in the vicinity of the pole. In addition, particles were spatially organized relative to one another. To realize the random distribution, nondivergent air motions had to (a) attain spatially constant concentration through the meridional eddy transport of marked particles, and (b) completely destroy the organized spacing of the particles relative to one another. The two processes obviously need not have the same time rate, depending as they do on the

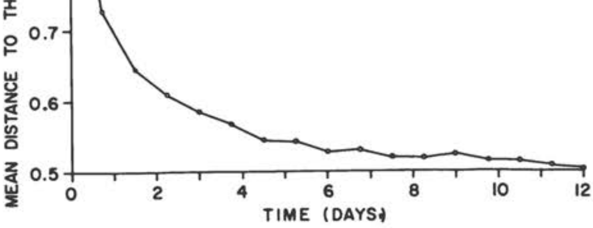

FIGURE D1. Mean distances from constant-volume particles to their nearest neighbor, as a function of time, for the nondivergent trajectories. Initial positions of particles coincide with the 1,977 points of the NMC grid.

meridional gradients of the concentration and on the concentration itself. If both of these processes are completed, the distribution of marked particles will be random and the frequency function of the distances to the nearest of them will conform with Eq. 1.

In a similar experiment using both nondivergent and divergent parts of the horizontal air velocity, the randomization will no doubt occur; however, the divergence of the air motions will now make it impossible for the concentration to become, or remain, if it were initially, spatially constant. In this case we shall have to deal with the concentration as a function of the space cordinates, $\chi = \chi\ (\phi, \lambda)$, where ϕ is the latitude and λ is the longitude. Otherwise, however, the particles will be organized at random relative to one another, at least after some time.

We may describe the distribution of marked particles in such a case simply by the concentration as a function of space, and also, in a more compact way, by the frequency function of one of the two types of distances to the nearest particle. The two frequency functions are determined by the concentration χ, and they are not identical, as was the case when the concentration was constant.

To write the expressions describing the dependence of those frequency functions on χ, let us observe that in the definition of the concentration

$$\chi = \delta n/\delta A. \tag{4}$$

δA has to be a "small" area, but still large enough to contain many marked particles δn, and so give χ as a smooth function of space. Hence the scale of space changes in χ must be necessarily greater than $(\delta A)^{1/2}$. At the same time the scale of distances to the nearest marked particle must be less than $(\delta A)^{1/2}$. Concentration therefore can be considered constant on the scale of *d*, and the relation in Eq. 1 will describe the probabilities of finding different values of *d* as a function of χ.

Hence, when we consider an area

$$A = \int_A a^2 \cos \phi d\phi\, d\lambda, \tag{5}$$

where *a* is the radius of the earth, and denote by $f_1(r)$ the frequency function of the distances from every point in space to the nearest marked particle, we have

$$f_1(r) = \frac{1}{A}\int_A 2\pi r\chi(\phi, \lambda) e^{-\pi e^2\chi(\phi, \lambda)} a^2 \cos \lambda d\phi\, d\lambda. \tag{6}$$

On the other hand, when we denote by $f_2(r)$ the frequency function of the distances from every marked particle to its nearest neighbor, we have

$$f_2(r) = \frac{1}{N}\int_A 2\pi r\chi^2(\phi,\lambda)e^{-\pi r^2\chi(\phi,\lambda)}a^2\cos\phi\, d\phi\, d\lambda, \tag{7}$$

where

$$N = \int_A \chi(\phi,\lambda)\, a^2\cos\phi\, d\phi\, d\lambda, \tag{8}$$

is the total number of marked particles found in the area A. Both of the frequency functions, $f_1(r)$ and $f_2(r)$, reduce of course to $f(r)$ when χ is constant.

The mean value of the distances from every point in space to the nearest marked particle

$$\bar{d}_1 = \int_A^\infty r f_1(r)\, dr$$

and the mean value of the distances from every marked particle to its nearest neighbor

$$\bar{d}_2 = \int_A^\infty r f_2(r)\, dr$$

are, by Eqs. 6 and 7, equal to

$$\bar{d}_1 = \frac{1}{2A}\int_A [\chi(\phi,\lambda)]^{-1/2}a^2\cos\phi\, d\phi\, d\lambda \tag{9}$$

and

$$\bar{d}_2 = \frac{1}{2N}\int_A [\chi(\phi,\lambda)]^{1/2}a^2\cos\phi\, d\phi\, d\lambda. \tag{10}$$

Both of the mean distances, $\bar{d}_1$ and $\bar{d}_2$, again reduce to $\bar{d}$ when χ is constant.

Let us see how the distances $\bar{d}_1$ and $\bar{d}_2$ change when the initially constant concentration N/A is changed into

$$N/A + \epsilon g(\phi,\lambda),$$

where ϵ is a constant, and $g(\phi,\lambda)$ is a function subject to the constraint,

$$\int_A g(\phi,\lambda)a^2\cos\phi\, d\phi\, d\lambda = 0, \tag{11}$$

but otherwise arbitrary. The variation $\delta\chi = \epsilon g(\phi,\lambda)$ therefore is constrained not to change the average concentration of marked particles in the area A. The corresponding change in $\bar{d}_1$,

$$\Delta\bar{d}_1 = \frac{1}{2A}\int_A \left\{\left[\frac{N}{A} + \varepsilon g(\phi, \lambda)\right]^{-1/2} - \left(\frac{N}{A}\right)^{-1/2}\right\} a^2 \cos \phi d\phi \, d\lambda$$

is, by Eq. 1, always positive for small values of ϵ. The distance $\bar{d}_1$, therefore, for a particular value of the average concentration, has a minimum when the concentration is spatially constant and everywhere equal to N/A. Using the technique of the calculus of variations it can be seen that this is the only stationary value of $\bar{d}_1$. Hence, when choosing the unit of length so as to make the average concentration equal to 1, 0.5 is the lower limit of the nearest-marked-particle distance $\bar{d}_1$. Using the same procedure, we can see that 0.5 is the upper limit to the mean nearest-neighbor distance $\bar{d}_2$, and is equalled when the concentration is spatially constant, i.e., everywhere equal to N/A.

The frequency function $f_1(r)$ seems to be the most suitable for the description of the distribution of a large number of constant-volume divergent trajectories, so far as the practical interest in this problem is concerned. If the marked constant-volume particles simulate the constant-volume balloons, performing upper-air observations, we are interested in distances from some uniformly spaced fixed points, i.e., grid points for numerical analysis, to the nearest balloon. The unfavorable effect of divergence in air motions and consequent clustering of balloons will show in the change of shape of $f_1(r)$, compared with $f(r)$, so as to increase the average distance to the nearest balloon.

The frequency functions $f_1(r)$ have been computed for the divergent trajectories in two isopycnic surfaces, $\rho = 1.012$ and 0.458 kg m^{-3}, which are the densities corresponding to pressures of 800 and 250 mb in U.S. Standard Atmosphere. The divergent part of the air motions has been computed by solving the quasi-geostrophic equation for the vertical velocities and then for the velocity potential. The scheme for solving the quasi-geostrophic vertical velocity equation was designed by John A. Brown, Jr., using five vertical levels. Frictionally and topographically induced vertical velocities were taken into account. Diabatic heating was, however, neglected. Trajectories were computed for the 30-day period, 00 GCT 5 December 1962 to 00 GCT 4 January 1963, using NMC numerical analysis data. Since we are interested in the spatial variation of χ produced by the divergent part of the air motion, computations were started with a spatially constant concentration of marked particles, i.e., with 1,908 particles put at random inside the boundary of the NMC 1,977-point grid. This number makes the initial concentration equal to the average concentration of the grid points in the NMC 1,977-point grid. Flow through the boundary in and out of the computation region was allowed, assuming a constant concentration of marked particles outside of the boundary, and equal to the initial concentration inside of the boundary. The frequency functions $f_1(r)$ were obtained by computing distances from a set of 1,750 points, placed at random inside the boundary, to the nearest marked particle. The unit of length was always chosen so as to make the average concentration of marked particles equal to one.

Histograms representing the frequency functions $f_1(r)$ are shown in Figures D2 and D3. The dashed curves in the same figures represent the frequency function $f(r)$ describing the random distribution of the marked particles. The histograms are averages of the histograms 15, 20, 25, and 30 days after the initial situation.

The increase in distances to the nearest marked particle is small. The average distance is increased only 4.0 percent and only 11.6 percent at the lower level. This difference was not the consequence of greater intensity in the divergence patterns; these were only slightly more intense at the lower level (the areal and time averages of the absolute values of div $\mathbb{V}$ were 2.39 and 2.32×10^{-6} sec^{-1} at the 1.012 and 0.458 kg m^{-3} levels, respectively). Instead, differences in the effects of divergence at the two levels must have been produced by the different intensity of the nondivergent motions; these tend to destroy the spatial variation in the concentration of the marked particles. In both histograms one observes a deficiency in the medium distances and a corresponding surplus in the large distances, relative

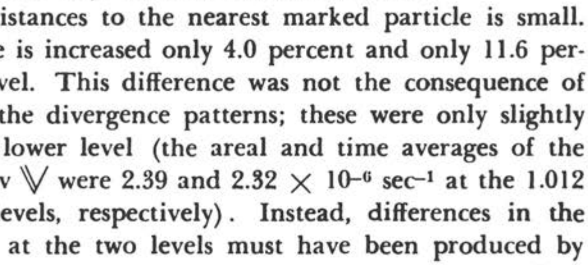

FIGURE D2. Average histogram of distances from 1,750 random points to the nearest constant-volume particle, for isopycnic surface corresponding to Standard Atmosphere pressure of 300 mb. Dashed curve represents the frequency function of those distances for the case of the random distribution of constant-volume particles. $\rho = 0.458$ kg m^{-3}; $\bar{d} = 0.520$.

to the random-distribution curve, and no apparent change in the small distances. We should not expect the clustering of particles necessarily to produce an increase in small distances; for instance, in the extreme case where we imagine all the marked particles to be clustered in one or several clusters, there would be almost no small distances.

At the higher level especially the marked feature of the spatial particle distribution was not the formation of distinct clusters of particles, but rather the formation of a definite meriodional profile of the particle concentration as a consequence of the meridional profile of div $\mathbb{V}$. This is illustrated in Table D1, where the concentrations in 10° latitude belts at the end of the computation period are shown. Initially, at both levels, the concentration was equal to 0.975 particles/10^{11} m^2, and this value was assumed to hold outside of the boundary during the trajectory computations. The three-cell structure was observed in the 30-day mean meridional velocity profile, and this undoubtedly produced the given meridional profiles of marked particle concentration.

TABLE D1. *Concentration of Marked Particles 30 Days After the Initial Situation, in Units Particles/10^{11} m^2*

	Latitude belt						
	90–80°	80–70°	70–60°	60–50°	50–40°	40–30°	30–20°
0.458 kg m^{-3}	1.26	1.07	1.01	1.16	1.00	1.21	1.02
1.012 kg m^{-3}	1.55	1.77	1.38	1.40	1.36	0.91	0.71

Instead of computing trajectories and distances to the actual marked particles, it would have been possible to obtain the same results by use of the equation.

$$\frac{\partial \chi}{\partial r} = -\mathbb{V} \cdot \nabla \chi - \chi \nabla \cdot \mathbb{V} + K \nabla^2 \chi \tag{12}$$

and then computing the function $f_1(r)$ from the resultant function $\chi(\phi, \lambda)$ and Eq. 6. Here the diffusion coefficient K describes the assumed Fickian diffusion on the scale smaller than $(\delta A)^{1/2}$.

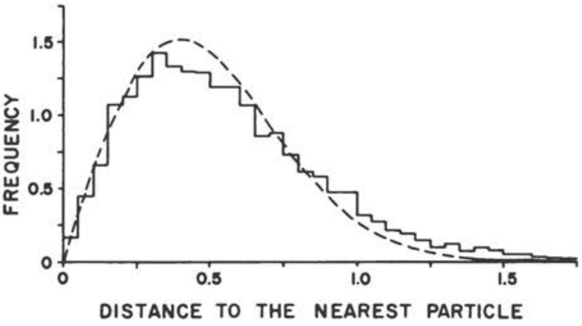

FIGURE D3. Average histogram of distances from 1,750 random points to the nearest constant-volume particle, for isopycnic surface corresponding to Standard Atmosphere pressure of 800 mb. Dashed curve represents the frequency function of those distances for the random distribution of constant-volume particles. $\rho = 1.012$ kg m^{-3}; $\bar{d} = 0.558$.

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APPENDIX E

Preliminary Cost Estimates

In the following we append cost estimates for the development of a satellite–balloon–buoy–radiometric system and its employment in a global observation experiment, which, for definiteness, we assume to be of 3 months' duration. The estimates made by the working groups of the Panel were checked in consultation with a number of independent authorities. Differences of opinion concerning individual components of the system were found to be reconcilable, or at least not so great as to destroy confidence in the approximate validity of the over-all figures. Nevertheless, it should be emphasized that the estimates are for a particular configuration of the system, which might well be altered after careful engineering design studies have been performed, and that pending such studies the estimates can be regarded only as provisional. They are intended merely to show that the probable cost lies within economically allowable limits in consideration of (a) the scientific and economic benefits to be derived from the acquisition of global data and the development of a new and powerful observational technology, and (b) the far greater cost of a global extension of the present network by conventional means. All estimates place the latter cost at several times that of the proposed system, and without shrinkage potential.

BALLOON–SATELLITE SYSTEM

Costs are broken down for both the development of the balloon–satellite system and the conduct of a global experiment.

DEVELOPMENT COSTS

First Year	(1,000's of dollars)	
System Design Study	400	
Determination of Hazard Problem	100	
Southern Hemisphere Flight Tests (funds already budgeted)	100	
Thin-Film Battery Development	50	
Balloon Research and Development	200	
SUBTOTAL		850
Second Year		
Satellite Development	2,500	
Ground Environment	2,000	
Determination of Hazard Problem	1,000	
Balloon Platform Electronics	1,000	
Battery Development	200	
Balloon Development	200	
Southern Hemisphere Flight Tests	150	
SUBTOTAL		7,050
Third Year		
Satellite Development	2,000	
Ground Environment	3,000	
Balloon Platform Electronics	1,000	
Balloon Development	200	
Southern Hemisphere Flights	150	
SUBTOTAL		6,350
Fourth Year		
Satellite Development	1,000	
Ground Environment	1,000	
System Test	2,000	
SUBTOTAL		4,000
TOTAL DEVELOPMENT COSTS		18,250

GLOBAL OBSERVATION EXPERIMENTS
(3-month program)

Check-Out and Launch Stations (30)	300
Ground Station Operation	3,000
Satellite System	3,000

Balloons

Level	Number		Replacements		Unit Cost	Combined Cost
30 mb	1000	×	1	×	$400	$ 400
100 mb	2000	×	1	×	300	600
200 mb	2000	×	1	×	250	500
300 mb	2000	×	1	×	200	400
500 mb	2000	×	1	×	200	400
700 mb	2000	×	3	×	50	300
850 mb	2000	×	6	×	50	600
	TOTAL					$ 3,200

Balloon Electronics (27,000 systems at $800)	$21,600	
TOTAL EXPERIMENT COSTS		$31,100
TOTAL FOR BALLOON–SATELLITE DEVELOPMENT AND GLOBAL EXPERIMENT		$49,350

RADIOMETRIC SYSTEMS

INFRARED SPECTROMETER

First Year

	(1,000's of dollars)	
Computer Facilities	15	
Experimental Satellite Instruments	400	
SUBTOTAL		415

Second Year

Development	200	
Experimental Satellite Instrument	200	
Computer	15	
SUBTOTAL		415

Third and Fourth Years

Development	250	
Operational Satellite Instrument	750	
Computer Facilities	300	
SUBTOTAL		1,300
TOTAL for Infrared Spectrometer		2,130

INFRARED INTERFEROMETER

First Year

Development	250	
Computer	50	
SUBTOTAL		300

Second Year

Development	200	
Experimental Satellite Instruments	300	
Computer	50	
SUBTOTAL		550

Third and Fourth Years

Development	150	
Operational Satellite Instruments	300	
Computer	900	
SUBTOTAL		1,350
TOTAL for Infrared Interferometer		2,200

MICROWAVE RADIOMETER

First Year

Development (except local oscillator)	500	
Computer	15	
SUBTOTAL		515

Second Year

Development (except local oscillator[*])	1,000	
Computer	35	
SUBTOTAL		1,035

Third-Fifth Years

Experimental and Operational Instruments	800	
Computer	275	
SUBTOTAL		1,075
TOTAL for Microwave Radiometer		2,625

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[*] The cost of development of a microwave radiometer for temperature determination from O_2 emission is not included in the estimates because of present uncertainties in the possibility of developing a solid state oscillator in the 5-mm region. In view of these uncertainties, we do not propose to include such an instrument in the observation system. Yet, because of its potentially great value, we repeat our recommendation that serious consideration be given to its future development.

SYSTEM FOR OCEAN-SURFACE OBSERVATIONS

Station Type	*Number*	*Develop-ment*	*Cost Per Unit*	*Initial Pro-curement*	*Operating Cost Per Year*	
Unmanned island	120	$1,000	$2	$ 300	$ 200	
Unmanned anchored	100	1,500	50	5,000	3,000	
Unmanned drifting	730	1,000	5	3,700	8,400	
Ships of opportunity (general set)	40	1,000	50	4,000	3,000	Upper Air
Ships of opportunity (minimum set)	160		2	400	400	
Manned stations	50		50	2,500	1,000	Upper Air
TOTAL	1,200	$4,500		$15,900	$16,000	

To derive the cost of a single experimental observation period extending for 3 months we may omit the additional upper-air stations as unjustified for a short period; we may reduce the number of required unmanned drifting stations to one fourth of the annual requirement, and we may omit additional research provisions. Initial procurement costs would then be about $7 million and operating costs about $10 million. The savings over annual costs would be partially offset by the additional manpower and facilities needed for a short-period experimental program.

COST SUMMARY OF GLOBAL OBSERVATION EXPERIMENT

(1,000's of dollars)

System Component			
Balloon–Satellite	18,000	31,000	49,000
Radiometric			
IR spectrometer	1,000	1,000	2,000
IR interferometer	1,000	1,000	2,000
Booster Rocket			3,000
Ocean-Surface Observations	4,500	17,000	21,500
		GRAND TOTAL	77,500