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Edited by HERBERT FRIEDMAN, U.S. Naval Research Laboratory

Global Atmospheric Research Program

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New space and computer technology and improved theory will lead a renaissance of meteorology in the next decade

Until very recently, meteorologists pursuing science or involved in operational weather prediction had every right to be discouraged. Their domain—the Earth's atmosphere—is so massive it contains nearly two-million tons of fluid for each person on Earth. It is so complex that only in rare instances can controlled laboratory experiments elucidate any of its workings. Meteorologists have had to use the atmosphere itself as the laboratory. In many instances they could not introduce satisfactory experimental controls, or could not make the observations needed because of extraordinarily high cost or the lack of suitable technology.

Although physical equations had been developed, the millions of computations required even for a relatively simple problem prevented their solution in any realistic form by hand. Development of modern digital computers shortly after WW II aroused new hope. Meteorologists were among the first to grasp the potential significance of this important development. A group at Princeton Univ. under the late John von Neumann developed numerical atmospheric models suitable for use on one of the earliest computers, and used these models to study atmospheric processes.

Progress in this new approach to meteorology has been very rapid, with the development of more realistic mathematical models of the atmosphere going hand in hand with the rapid development in computer technology. The meteorologist looked forward to using the computer as his laboratory. A few milestone dates show the swift gains. The Princeton group began forming in 1946. Their first, very crude model to show some predictive capability successfully went through a run in 1950. The Joint Numerical Weather Prediction Unit was established in Washington, D.C., in 1954 to apply numerical prediction techniques to operational use. They began running their first numerical prediction model on a daily, operational basis in 1955.

Today's operational models require more than 100 times the calculations of the first models per unit forecast time interval. Operational numerical predictions now extend up to 72 hr into the future and often cover the entire globe, compared to 24-hr predictions for a portion of the Northern Hemisphere in 1955.

DAVID S. JOHNSON (AF) has taken part in the U.S. meteorological satellite program since its inception in 1958. Since 1965 he has directed the National Environmental Satellite Center of the U.S. Department of Commerce Environmental Science Services Administration. The Center runs the U.S. operational meteorological satellite system, conducts research on environmental problems using satellite data, and works with NASA in developing new environmental sensors and space systems. Johnson has helped plan the Global Atmospheric Research Program and the World Weather Watch through COSPAR, the World Meteorological Organization, and as consultant to the International Joint Organizing Committee for GARP.

Computers still limit mathematical modeling of the atmosphere and operational numerical weather prediction. It takes many simplifying assumptions to accommodate numerical prediction models to even the fastest of today's computers. One of the most advanced models used in research requires 18 hr of computing time to make a 24-hr prediction. Of course, this is not practical for operational use. The present Weather Bureau operational prediction model requires about two hours of computation time for a 72-hr forecast. However, computer capacity should grow enough to cease limiting numerical prediction in 5-10 years.

Lack of observations already has become the main stumbling block. The numerical prediction model must be given the initial state of the atmosphere in order to predict its future state. The development and verification of new improved theories and mathematical models can only be achieved by comparison with the real atmosphere. The basic (but not only) observations establishing the starting point for the prediction calculations are temperature, humidity, and wind as a function of pressure, from the Earth's surface to approximately 30 km in the stratosphere. These observations are required over the entire globe at least once and preferably twice per day.

Rawinsonde readings now cover a portion of the Earth. A balloon-borne instrument transmits pressure, temperature, and humidity data to a ground receiver, and a radio direction finder or radar tracks the movement of the balloon as a function of height for wind calculations. This observing technique came into widespread use during WW II and served adequately in the early years of numerical prediction.

But the approximately 600 rawinsonde observations received at the

Weather Bureau's National Meteorological Center (NMC) during the 12-hr data collection cycle are too few for either hemispheric or global macroscale prediction. During the same time cycle, about 1000 aircraft reports and 2000 surface observations come in. The aircraft reports come mostly from transoceanic planes flying on major air routes. The surface and aircraft observations provide information on only two levels of the atmosphere compared to the six or more considered minimum.

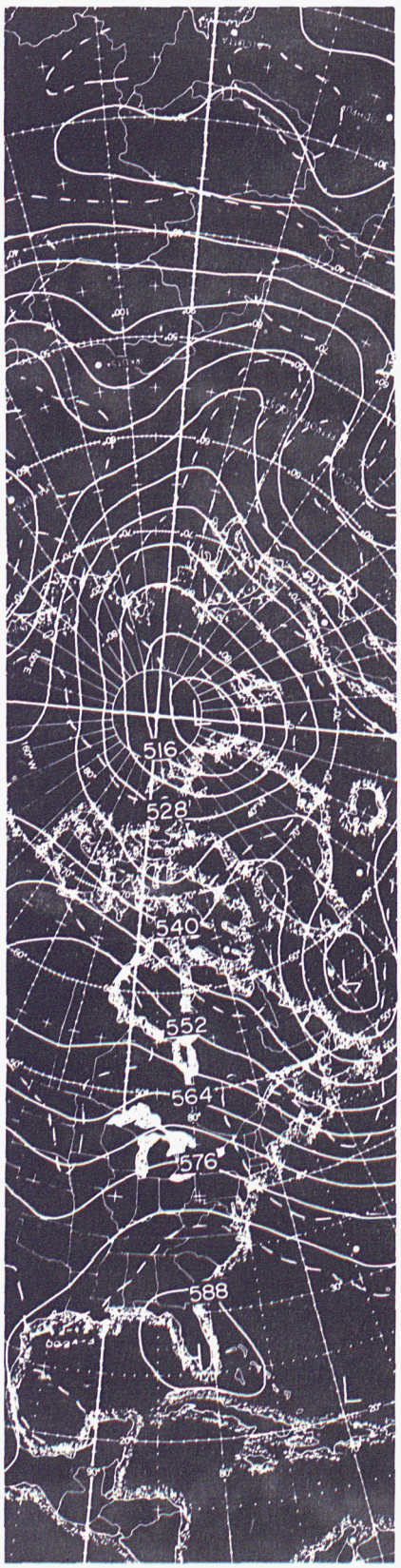
Most of these observations come from one-fourth of the globe, namely the Northern Hemisphere poleward of 30 deg latitude. Indeed, fewer than 100 upper air observations arrive each day from the entire Southern Hemisphere. Even in the Northern Hemisphere, the populated continental areas account for almost all rawinsonde observations.

To meet present estimated observational needs would take a global network of stations reasonably uniformly spaced 400-500 km apart. This means establishing some 2000 more stations than exist today! Ships or remote stations needing expensive logistics support would make up the majority. The total estimated cost to get all the observations for one year exceeds $2 billion.

Clearly, meteorology needed another technological innovation to bring observational costs within reason. Satellites with remote sensing promise to do so. In the late 1940s, a few farsighted meteorologists began to contemplate the kinds of meteorological observations which might some day be possible from satellites. However, lack of support for space technology stifled these early initiatives. Some hope revived when two meteorological experiments were included in the Vanguard satellite program for the International Geophysical Year. But the launch of Sputnik I in October 1957 provided the needed catalyst. The dust was blown off of the earlier studies, which formed a sound beginning to a meteorological satellite development program.

The first satellite devoted exclusively to meteorology was launched successfully on April 1, 1960. This early success, along with promising feasibility studies of remote sensors for measuring such parameters as temperature and water vapor, stimulated thinking about a major international effort.

In a speech in 1961 before the UN, the President of the United States proposed an international program for the peaceful uses of outer space, a major portion of which called for an international cooperative effort in meteorology. The UN General Assembly then adopted resolutions 1721 (1961) and 1802 (1962) calling for all member states, the World Meteorological Organization, and the International Council of Scientific Unions to undertake early and comprehensive studies, "in the light of developments in outer space," of measures to advance the state of the science and to develop forecasting capabilities. As a result, the concepts of the World Weather Watch and the Global Atmospheric Research Program have developed.



Operational numerical weather prediction for 500-mb level (about 20,000 ft) extends 24 hr into the future. Based upon equations of atmospheric dynamics rather than simple projections of past experience, numerical predictions are issued for up to 72 hr from starting conditions. GARP aims, among other things, at improving the predictions.

In his review, "Threshold to the World Weather Watch," in the January 1967 *A/A*, Morris Tepper outlined the early planning and discussed possible applicable satellite technology. I shall only touch briefly on a few milestones reached since then in the evolution of the international program and in the development of some key meteorological satellite sensors.

In response to the UN resolutions, plans for a World Weather Watch (WWW) were developed under the aegis of the World Meteorological Organization (WMO), a specialized UN agency. The Watch would have three major components: the Global Observing System, the Global Telecommunication System, and the Global Data Processing System including analysis and prediction. The WMO Congress approved plans for implementing the first phase (1968-71) in 1967. The major thrust in this first phase was toward extending the existing conventional observation network, beginning to integrate meteorological satellites into international operations, taking major steps in improving international telecommunications for collecting and exchanging weather observations and products, and detailed planning of the second phase (1972-75). The WMO Congress meets again in 1971 to decide on the second-phase program.

Following the UN resolutions, planning of R&D to improve operational weather prediction and services proceeded in a loosely coordinated fashion in various nations, the WMO, the International Council of Scientific Union's (ICSU) International Union of Geodesy and Geophysics, and the Committee on Space Research (COSPAR). These activities culminated in a 1967 international Study Conference on the Global Atmospheric Research Program (GARP) in Sweden, and a

formal agreement between WMO and ICSU in October 1967 on the joint planning and development of GARP, in consort with member nations. A Joint Organizing Committee (JOC) and a Joint Planning Staff for GARP served as the focal point for the international planning activities.

The JOC has developed plans for key GARP tropical experiments. An intergovernmental conference in March 1970 recommended proceeding with a major portion of these experiments in the tropical Atlantic in 1973 or 1974. Preliminary plans have been completed for the First GARP Global Experiment (FGGE) over a one-year period about 1976. Because of the crucial role of satellites in the global experiment, COSPAR Working Group VI, chaired by Morris Tepper, has worked closely with JOC.

The broad outlines of my discussion of the FGGE observing system mostly agree with the international planning reports. Some of the details reflect my own views.

The observing system will have low-altitude spacecraft in polar orbit, and geostationary spacecraft. One, and preferably two, spacecraft would operate in polar, or sun-synchronous, orbits at an altitude of about 1500 km. Orbits for two satellites should intersect at right angles to provide coverage of each point on the Earth once every six hours. Four geostationary spacecraft, equally spaced along the equator, would provide nearly continuous imaging of the Earth's surface and atmosphere between about 50 deg north and south latitude, and would collect data from automatic, *in-situ* sensors located throughout the world except at very high latitudes.

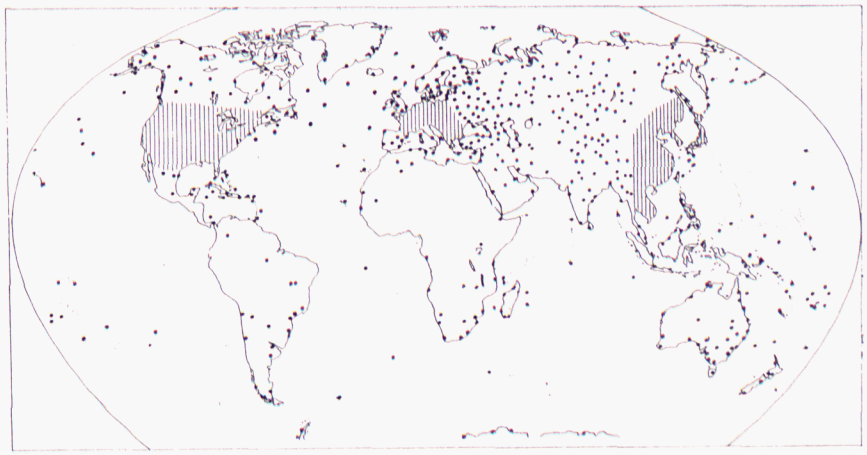
The spacecraft in polar orbit will carry an infrared spectro-radiometer sounding instrument for determining surface temperature and vertical profiles of air temperature and water vapor. The instrument takes measurements at a number of frequencies, with high spectral resolution (on the order of five wave numbers), and relatively high spatial resolution (10-50 km) to minimize the effect of clouds on the observations. A series of measurements at different frequencies in the CO_2 absorption bands of the atmosphere establishes the vertical temperature profile. The temperature profile and a set of measurements in the atmospheric water-vapor absorption bands determine the vertical distribution of water vapor. A measurement in an atmospheric absorption "window" at 11μ is used to infer surface temperatures in clear areas and to correct for the presence of clouds. To improve the accuracy of the corrections for partial cloud cover may require a few additional channels.

The successful test of a number of such instruments on the Nimbus III and IV experimental satellites in 1969 and 1970 reached a major milestone be verifying the basic techniques of remote sounding. Indeed, the output of one of the experiments, the Satellite Infrared Spectrometer (SIRS), has been used almost daily for over a year in the Weather Bureau's operational numerical weather prediction model. The experiments clearly showed the need for a number of improvements, mainly in higher spatial resolution of the sensors, and continuous horizontal coverage across the satellite track to reduce the effect of clouds on the soundings and improve their geographical distribution. But the future course now seems clear, and the necessary developments well advanced.

From the satellite soundings come temperature and water vapor as a function of pressure. The hydrostatic equation then gives the vertical thickness of the atmosphere between different constant pressure surfaces. However, to tie these data to sea level, the height of some pressure surface must be known. Traditionally, meteorologists have observed the surface pressure at many stations over the Earth, corrected for the altitude of each station above mean sea level, and produced a map of atmospheric pressure at zero elevation. Outside of the tropics the number of surface observations in the Northern Hemisphere nearly suffices for providing a pressure-height reference surface for the satellite soundings. However, it is totally inadequate in most of the Southern Hemisphere.

The most promising alternative entails setting constant volume balloons equipped with simple radio-altimeters drifting with the wind around the hemisphere on a constant density surface at an altitude of about 12 km. The satellites in polar orbit would determine the horizontal position of the balloons on each over-flight by doppler techniques, and receive the balloons' temperature, pressure, and altitude data in order to establish the reference level for the satellite soundings. The sounding then can be integrated down to sea level to obtain the surface pressure. As a byproduct, a series of balloon positions can provide wind measurements at balloon altitude. Some 1000 balloons would be in flight at all times in the Southern Hemisphere extra-tropics.

Suitable balloons and launching techniques give an average balloon lifetime of several months. Limited



Rawinsonde provides basic data with which a numerical prediction starts. A balloon carries the instrument to 30 km altitude while it radios temperature, humidity, and indirectly, wind, as a function of pressure. Map of rawinsonde reports received in a 10-hr period on August 21 shows most such observations come from north of 30 deg N. In shaded areas, stations are closer than 500 km apart. To meet present needs would require establishing 2000 more stations, and spending $2-billion a year for all the observations. Thus satellites.

balloon and aircraft tests have demonstrated the principle of a small, inexpensive radioaltimeter. Preprototype units now are being assembled for balloon-system tests in the Southern Hemisphere beginning late this year. The Interrogation, Recording, and Location System (IRLS) performed successfully on Nimbus III and IV. France has scheduled a similar experiment of its own, Eole, for launch in 1971. In this experiment, about 500 balloons afloat in the Southern Hemisphere will provide both a full-system test and valuable research data on circulations there.

Both the IRLS and Eole require a relatively complex and costly electronics package on the balloon. Designs are now being developed based on differential doppler measurements and non-addressable balloons. This approach should significantly reduce the cost of the balloon package without a serious sacrifice in location accuracy. A flight test of this approach may take place about 1973.

Originally planners had hoped for constant volume balloons with lifetimes of several weeks or months in the troposphere, at least at altitudes above major mountain ranges. However, no balloon system yet devised will survive in cloudy regions. Thus, for the FGGE, we cannot plan on the use of balloons as tracers to obtain the winds required at several levels in the troposphere. Outside of the tropics, this does not present a major problem. There, the potential accuracy of the satellite soundings appears good enough for calculating the wind field from the horizontal pressure field derived from satellite data at a number of levels in the atmosphere. But in the tropics, the wind relates much less strongly to the horizontal pressure gradient and must be measured directly.

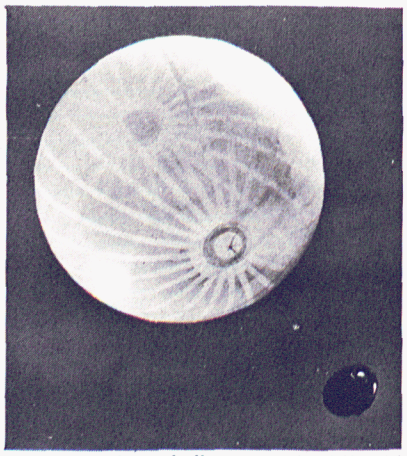
The four geostationary satellites will play a key role in obtaining wind observations in the tropics. The ATS I and III geostationary satellites both carried the spin-scan camera experiment devised by Professor Suomi and his colleagues at the Univ. of Wisconsin. The camera takes pictures of the full Earth's disk in solar illumination beneath the satellite every 20 or 30 min with a resolution at the subpoint of about 3 km and high geometric stability. A sequence of pictures reveals cloud motions and other atmospheric dynamics. By selecting individual clouds which experience shows move with the wind, an analyst can infer wind speed and direction at cloud level by carefully measuring cloud displacements. Observations made over a two-hour period within 55 deg of great circle arc from the satellite subpoint have yielded an average vector error in cloud velocity of less than five knots. In general, this technique gives winds at only two levels in the atmosphere. Small cumulus clouds provide information at an altitude of about 1-2 km, and cirrus clouds, 8-12 km.

Poor estimates of the altitude of high clouds in pictures taken by visible light often significantly reduce the accuracy of upper wind velocities. Judging cloud altitude by the temperatures of their tops could improve the estimates. Reasonable temperatures for the tops of opaque clouds result from measuring infrared radiance through an atmospheric "window." For dense cirrus or cirrus blown off cumulo-nimbus, temperature vs. height observations from the sounder on the polar orbiter then convert cloud-top temperature to altitude.

NASA is now developing the Synchronous Meteorological Satellite (SMS) for launch in 1972. This new spacecraft will have a telescope with an aperture of 40 cm operating in the same manner as the spin-scan camera on ATS. The large aperture and detector cooled by radiation to space will provide infrared images obtained in the 11μ "window" with a resolution of about 8 km at the satellite subpoint. A channel in the visible will have a resolution of about 1 km. In addition to enabling 24-hr-a-day observing, the infrared camera should greatly improve the estimates of cloud height, as described above.

Unfortunately, winds are required at a minimum of two more levels in the middle troposphere in the tropics. No reasonably certain technique has yet emerged to fill this void at reasonable cost. Surface-based rawinsondes appear too expensive, even if restricted to the tropics. Vincent Lally of the National Center for Atmospheric Research has suggested dropping "navaidsondes" through the atmosphere from constant volume "mother-bal-

Satellite data gathered by infrared spectrometer, solid line, compares well with that from ground-launched rawinsonde. Experiments on Nimbus III and IV verified the techniques of remote sounding. In GARP set-up, one, or maybe two satellites in polar orbit would carry this instrument.



Constant volume balloons would drift with the wind at about 12 km altitude in the Southern Hemisphere to provide a pressure-height reference surface for GARP by radioing data to satellites. Experiments now underway use the GHOST constant volume balloon shown here.

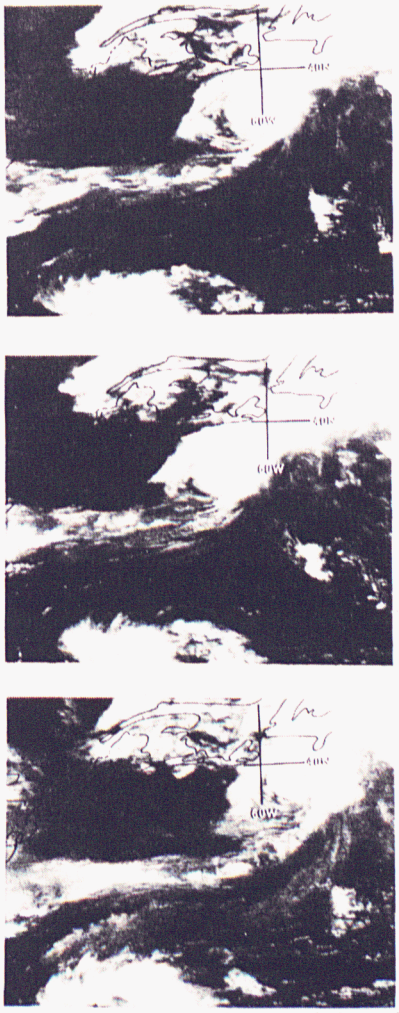
loons" drifting horizontally in the upper stratosphere. Each mother-balloon would carry about 100 sondes which it would drop on command from the appropriate geostationary satellite. The mother-balloon and geostationary satellite would relay signals from the sondes to a processing and analysis center.

The change in horizontal position of the sonde during its fall through the atmosphere on a special parachute reveals the winds. The sonde would receive and relay a single channel of signals emitted by the global Omega navigation system for tracking. To achieve the required wind accuracy, the Omega signals must be integrated over several minutes for each atmospheric layer. A total fall-time of nearly an hour results, ruling out high-altitude jet aircraft as an economical launch platform. Preliminary estimates indicate the balloon portion of the system would cost on the order of $20 million for the FGGE.

In addition to the observations described above, FGGE will need data from isolated weather stations and automatic stations on unpopulated land masses and ocean buoys, particularly in the tropics. Both geostationary and polar-orbit satellites will collect and relay this data. The latter may also track small, drifting buoys.

One might ask if such a complex observing system will really come to pass in just six years, even for the limited period of time of the FGGE. I think the answer is yes. Except for some of the wind observations required in the tropics, the technology required is at hand and at reasonable cost. Also, operational satellite systems will play a major role. This is not surprising, since operational weather predictions are based on mathematical models similar to those used in research and having similar data requirements.

In the United States, the second-generation operational weather satellite in Sun-synchronous orbit, the Improved TIROS Operational Satellite (ITOS), went into service this year. Operational sounding capability will be added to the system in 1972. The third-generation operational satellite is planned for launch in 1975. Design studies now underway reflect the GARP and WWW data requirements. The Synchronous Meteorological Satellite scheduled for launch in 1972 will serve as the operational prototype of the Geostationary Operational Environmental Satellite, which will complement ITOS. At first, the U.S. will keep one geostationary spacecraft in



Cloud movements reveal upper winds, and show rapid progress of a North Atlantic storm in this six-hour sequence of pictures taken by ATS-III. Similar sequences taken by ATS-1 have furnished data for charts of velocities of winds at 1-2 km over the Pacific. Estimates of height, however, are often poor. Cloud-top temperatures from infrared pictures may yield more accurate indications of altitude.

operation at all times, but it is hoped a second will join it before the FGGE. Although NASA has not yet made known firm plans for experimental meteorological satellites at the time of the FGGE, it is reasonable to assume the agency will play an important role.

Both France and Japan have the development of synchronous satellites for the FGGE under consideration. ESRO and the United Kingdom may each build polar-orbit meteorological satellites for launch about the time of the FGGE. In addition, the USSR now operates meteorological satellites in quasi-polar orbit and is developing sounding instruments.

Thus it appears that a space-based observing system will furnish a major portion of the data for the FGGE. By the time of the experiment, the U.S. operational meteorological satellite system will approach the coverage needed, except for the four synchronous satellites. Promising signs of significant contributions toward these come from other countries.

I have had to omit many important aspects of GARP from this brief review, such as the study of the boundary layer at the Earth's surface and the energetics of the tropics. The mathematical models must account for these processes, so we must learn about them to properly formulate them in the models and determine the needed observations. Nevertheless, this simplified account of GARP illustrates the convergence of technology and improved theories which has lifted the meteorologists' discouragement, and given them new hope they can solve scientific problems and significantly improve weather services. The Global Atmospheric Research Program and the World Weather Watch will play central roles in the renaissance of meteorology in the next decade.

Additional Reading

1. "GARP Topics," a continuing occasional series in the *Bulletin of the American Meteorological Society*. Issues to date: pp. 136, 345, 539, 587, 702, and 792, Vol. 50, 1969; pp. 26, 144, 222, 327, 414, and 490, Vol. 51, 1970.

2. International Council of Scientific Unions and World Meteorological Organization, GARP Publication Series: (1) "An Introduction to GARP," Joint Organizing Committee (JOC), 22 pp., 1969; (2) "System Possibilities for an Early GARP Experiment," COSPAR Working Group VI Report to JOC, 55 pp., 1969; (3) "The Planning of the First GARP Global Experiment," JOC, 36 pp., 1969; (4) "The Planning of GARP Tropical Experiments," JOC, 78 pp., 1970; and (5) "Problems of Atmospheric Radiation in GARP," F. Moller and C. D. Rogers for JOC, 18 pp., 1970.

3. ICSU-WMO GARP Special Report No. 1, "Report of Planning Conference on GARP, Brussels, March 1970," 42 pp., 1970.

4. "The Feasibility of a Global Observation and Analysis Experiment," report of Panel on International Meteorological Cooperation to the National Academy of Sciences Committee on Atmospheric Sciences, NAS Publication 1290, 172 pp., Washington, D.C., 1966.

5. "Scope of the 1972-75 Plan with particular reference to the Meteorological Satellite Sub-System," World Weather Watch Planning Report No. 30, 23 pp. and 10 appendices, 1969, World Meteorological Organization.

Note: Those publications listed under item No. 2, 3, and 5 are available on sale from the Secretariat, World Meteorological Organization, Case Postale No. 1, CH-1211, Geneva 20, Switzerland.

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