D. S. Johnson
(corrections: Biography + p. 6)

The Voice of America

FORUM LECTURES

Meteorological Satellites and Weather Forecasting

By David S. Johnson

Space Science Series **2**

DAVID S. JOHNSON, *Chief of the U.S. Weather Bureau Meteorological Satellite Laboratory, was born in Porterville, California, in 1924. Educated at the University of California in Berkeley, Reed College and Harvard University, Mr. Johnson pursued research in cloud physics at the University of California in Los Angeles. From 1952 to 1956 he worked on weather instrumentation at the Hawaii Pineapple Research Institute, after which he became chief of the Observation, Testing and Development Center of the U.S. Weather Bureau. Mr. Johnson joined the staff of the Meteorological Satellite Laboratory in 1958, when it was first established, and became its director in 1959. A member of the Meteorological Society and the American Geophysical Union, Mr. Johnson ~~directed~~ was involved in the planning and instrumentation of the TIROS weather research satellites.*

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Meteorological Satellites and Weather Forecasting

David S. Johnson

The successful launching in 1960 of the first TIROS satellite gave the meteorologist powerful new eyes with which to view his atmospheric domain. Within 60 hours of the launching of TIROS I, forecasters were using the satellite observations of clouds to improve their analyses of weather systems.

The importance of meteorological satellites in weather analysis and forecasting can be appreciated by considering the global nature of weather. The Earth's atmosphere, upon which man's existence and activities are so dependent, is a giant and complex heat engine. Heated by the Sun and cooled by radiation into space, the atmosphere is set into motion in a constant effort to equalize the resulting energy unbalances. The wind systems and associated weather so created vary widely in size from small turbulent eddies to planetary waves. These waves are large undulations in the upper level westerly winds surrounding the Earth, and their wavelength is of the order of 5000 kilometers. To forecast these winds and associated weather, the meteorologist requires measurements over an area comparable with the scale of motion and with a frequency in space and time compatible with the physics which dictate the forecasting techniques.

Meteorologists have long been handicapped by inadequate measurements of the Earth's atmosphere at any one time. The last century saw the start of the establishment of national weather services to provide forecasts to the public. At that time, the value and scope of the forecasts were limited by lack of adequate communications, observing stations, and understanding of atmospheric processes. Improvements have resulted in weather forecasting as observing networks expanded geographically and in altitude, and as associated communication systems were developed. Nevertheless, even today, exclusive of satellite observations, less than 20 per cent of the Earth's atmosphere is adequately observed. Weather observations are particularly sparse over the vast oceanic and polar regions of the Earth. Unknown weather disturbances in these regions can have a significant influence on the future weather in distant, populated areas. Thus the accuracy of forecasts of the weather for more than a day or two in advance is limited unless these disturbances are observed.

Earth-orbiting satellites provide meteorologists with a global observation platform from which measurements can be obtained to fill in these large voids between land-based observing stations. Although most significant improvements in meteorological analysis and forecasting will

come from an increased understanding of the atmosphere as a result of a broad research program to which meteorological satellite data are contributing, it has already been possible to utilize cloud data from the TIROS satellites in operational weather analysis and forecasting.

Weather data from TIROS satellites are gathered at two receiving stations. Here meteorologists rapidly process the cloud pictures received from the satellite and prepare cloud analyses in which the distribution, structure, and form of the clouds viewed by the satellite are depicted schematically on a map. These maps, called nephanalyses, are transmitted by facsimile circuits to the U.S. Weather Bureau's National Meteorological Center in Washington, D.C., where they are utilized in the preparation of Northern Hemisphere current weather maps and prognostic charts. Equipment recently has been installed which permits the transmission of selected TIROS pictures by wire from the receiving stations to the National Meteorological Center. The actual satellite pictures convey much more detail than it is possible to include in the cloud analyses. This is particularly important in determining the extent and severity of storms and depicting the wind direction over the large oceanic areas of the Earth.

Meteorological data for operational use are highly perishable. Their value decreases rapidly with age beyond a few hours from observation time. The average time between the actual observation of clouds by the TIROS III satellite and the receipt of the resulting cloud analyses in the National Meteorological Center is less than four hours. This is comparable to the time presently required to process and transmit conventional upper air soundings.

In addition to their use in the National Meteorological Center, the cloud analyses are relayed by weather facsimile circuits to many weather stations in North America. The U.S. Navy also broadcasts these analyses by radio from Guam, Hawaii, California, Virginia, and Port Lyautey in Morocco. Information on these broadcasts has been disseminated to all the member countries of the World Meteorological Organization, a specialized agency of the United Nations. Thus, it is possible for any country having proper receiving equipment and within radio range of one of the transmitting stations to obtain the cloud analyses broadcast by the Navy.

Although most of the weather services of the world are unable to receive the satellite cloud analyses by facsimile, many of these services, particularly those in the Northern Hemisphere, can receive weather data from the United States through a cooperative international meteorological teletypewriter network. A special teletypewriter code for the satellite cloud analyses has been devised for this means of communication. The meteorologists at the data acquisition stations convert the cloud maps to coded form for transmission to the countries served by the international teletypewriter net. Although the information content is reduced in the coding process, this does provide a means whereby many additional countries can obtain the observations in time to be of operational value.

On numerous occasions the TIROS cloud observations resulted in significant improvements in weather analyses and subsequent forecasts. For example, the Australian weather service used observations from TIROS II to forecast accurately a break in an extended heat wave. More recently, TIROS III pictures of the tropical storm Liza, located off the west coast of Mexico, showed that the analyzed position of the storm center as determined from the few conventional observations available, was in error by about 500 kilometers. The subsequent movement of the storm was determined from satellite observations. Hurricane Esther was discovered by means of TIROS III pictures.

Preliminary study of the radiation data from the TIROS satellites indicates they would be operationally useful in depicting the gross cloud distribution at night, when it is not possible to obtain television pictures, and in obtaining a measure of cloud top height. One of the sensors responds to terrestrial radiation in the 8 to 12 micron wavelength region. The atmosphere is essentially transparent to radiation in this portion of the spectrum so that the measurements obtained are proportional to the temperature of either the Earth's surface or the tops of clouds. Clouds are recognizable as they are generally colder than the Earth's surface. The variation of air temperature with altitude can be approximated from a knowledge of the existing weather situation. Knowing this relationship, the radiation temperatures of the cloud tops as measured by the satellite can provide an estimate of their height. Such observations contribute to weather analysis and forecasting in the determination of cloud type and the vertical structure and severity of weather systems. These data are not now being used in operational analysis and forecasting because it is not yet possible to process the radiation data within a few hours of observation. These data should be available on an operational basis within a year or two.

The United States plans to launch four more TIROS satellites at approximately four-month intervals, in addition to the three previously launched. This series of satellites should permit a nearly continuous operational program, within the limitations of the TIROS system, and provide much data of value in meteorological research.

The nature of the orbit and type of stabilization of the TIROS satellites do not permit the observation of the entire Earth on a daily basis. The plane of the satellite's orbit is inclined at about 48 degrees with respect to the Earth's equatorial plane so that the satellite does not traverse the polar areas. The spin stabilization of the satellite results in a constant change in the viewing angle of the sensors with respect to the Earth's surface. Indeed, during a large part of each orbit the television cameras are pointed toward space. This spin stabilization and the precession of both the orbit and the axis about which the satellite spins result in a continual change in the solar illuminated portion of the Earth's surface which can be photographed by the television cameras. Observational coverage is further limited by the number and location of

data receiving stations. As a result of these limitations, a little less than one-fifth of the Earth's surface and cloud cover is photographed by the TIROS satellite each day, and the area photographed gradually shifts from one hemisphere to the other with a periodicity of about eight weeks.

The Nimbus meteorological satellite now being developed by the NASA is designed to overcome the limitations in observational coverage of the TIROS satellite. It is expected that the first Nimbus satellite will be launched in late 1962 or early 1963. The quasi-polar orbit planned for Nimbus will result in the entire Earth's surface coming into the view of its sensors at least twice each day. An active stabilization system will be used with one axis of the satellite always directed perpendicular to the Earth's surface. The resulting complete global coverage on a regular basis will be a great impetus to the operational use of meteorological satellite data.

The oblateness of the Earth and its influence on the satellite's orbit results in a precession of the plane of the satellite's orbit. The amount of precession is determined primarily by the altitude of the satellite and the inclination of its orbit. By launching the Nimbus satellite in a retrograde orbit of approximately 80 degrees inclination with respect to the Earth's equator, and at an altitude of 1100 kilometers, the orbit will move in celestial space at a rate of one degree per day. By launching the satellite so that its northbound crossing of the equator is at local noon, optimum illumination for television pictures will be obtained. Because of the one degree per day regression (west to east motion), the satellite's orbital plane will contain the Earth-Sun line for an extended period of time, thus maintaining the same local times of observation.

Presently available television cameras will produce cloud pictures over the entire solar illuminated portion of the Earth once each day with a resolution of about 1 to 2.5 kilometers. The cloud distribution over the portion of the Earth in darkness will be determined by a scanning infrared radiometer similar to that now used on TIROS . It is now believed possible to develop a radiometer having a resolution of about five kilometers when used on the Nimbus satellite at an altitude of about 1100 kilometers.

The early Nimbus satellites also will obtain global measurements of solar and terrestrial radiation in varying spectral intervals similar to those of the TIROS satellites. While these data will be used initially only in meteorological research, techniques are under development for their eventual application to operational weather analysis and forecasting.

The success of the TIROS satellites and the use of the data from them in weather analysis and forecasting have resulted in the formulation of a plan for an Operational Meteorological Satellite System. This system initially will make use of Nimbus type satellites to meet operational requirements. The initial goal of the Operational Meteorological Satellite System is to assure that one Nimbus satellite is operating in orbit all the time, thus providing at least two observations a day of every point on the Earth's surface.

As the reliability and operating lifetime of the Nimbus satellite is increased, it is envisioned that the operational system may be expanded to provide two satellites in orbit simultaneously at all times. They could be launched so that one satellite crosses the equator northbound at 9:00 A.M. local solar time, the second at 3:00 P.M. Thus each point on the Earth's surface would be viewed at least once every six hours, twice in daylight (except for the winter polar regions) and twice in darkness (except for the summer polar regions). Television camera systems with increased sensitivity over those now in use would be required to obtain cloud images from sunrise to sunset over the solar illuminated portion of the Earth. Current development work indicates that such a camera system is feasible.

The complexity and tremendous volume of data expected from even the early Nimbus satellites will require the use of a complex and costly ground station for the control of the satellite and reception of data from it. While one such station located at a point poleward of about 80 degrees latitude would be able to contact the satellite on every orbit, it appears more practical to use two or three stations at lower latitudes.

It is presently envisioned that only limited processing and monitoring of the satellite data will be performed at the Nimbus receiving stations. Wide-bandwidth communications will be used to transmit rapidly all of the data from these receiving stations to the National Meteorological Center located in Washington, D.C., where meteorologists, assisted by high-speed data-processing equipment, will process the observations and prepare analyses and prognostic charts for both national and international use. The analyzed satellite observations will be distributed by teletypewriter and, where available, by high-quality facsimile equipment.

Improvement of the Operational Meteorological Satellite System is contingent on the development of new types of satellite measuring techniques as well as the results of meteorological research from which will evolve new techniques of weather analysis and forecasting. Instruments for eventual use on Nimbus, now under consideration or development, would provide measurements of the vertical distribution of temperature, water vapor and ozone in cloud-free areas, the vertical distribution beneath the satellite of cloud and precipitation by means of radar, and the location of thunderstorms by detection of electro-magnetic radiation.

An operational satellite system utilizing only polar orbiting satellites of the Nimbus type does not meet the meteorologist's objective of continuously monitoring the world's weather. A satellite in an equatorial orbit and synchronous rotation with the Earth, at 35,700 kilometers above the Earth's surface, will appear to be stationary with respect to the Earth. Four such satellites, equally spaced about the Earth's equator, would provide a system of observing platforms capable of continuously viewing all of the Earth in the zone between 60 degrees north and south latitude. The observational coverage of these "stationary" satellites

would be complemented in polar areas by frequent observations with the Nimbus type of satellite. These satellites might be equipped with low resolution cameras which would provide a new global cloud map (except for the polar areas) every few minutes to any weather station having the proper receiving equipment and located within view of one of the four stationary satellites. Other cameras capable of viewing smaller areas in greater detail also might be included in the satellites. The orientation of these cameras could be controlled by regional forecast centers to study critical areas such as developing storms.

It is quite clear from the foregoing that the advent of meteorological satellites will have a strong impact on operational meteorology throughout the world. In promoting international cooperation in this area, it is anticipated that the World Meteorological Organization will play an increasingly important role.

The World Meteorological Organization, affiliated with the UN~~ESCO~~ and in existence since 1950, is the lineal descendant of the International Meteorological Organization, established in 1878. The WMO, composed of 108 members, has these purposes: the facilitation of world-wide cooperation in the establishment of observing networks, the promotion of rapid exchanges of weather information, the encouragement of standardization of meteorological observations, the application of meteorology to transportation, agriculture, etc., and the encouragement of research and training in meteorology.

Within this framework of international cooperation in meteorology, spanning a period of 83 years, the appearance of meteorological satellites presents some novel aspects and opportunities. In contrast to most conventional observing stations, the satellite observatory is not at a fixed location in the home territory or on the high seas. Earth-orbiting satellites, truly global in their range, enable meteorologists to observe atmospheric phenomena over extensive areas rapidly and completely. Satellites also make possible some measurements which cannot be made at all by conventional means no matter how dense the ground-base observing network is. Because some of the phenomena observed by meteorological satellites may seriously affect the safety of peoples and their economies within a day or two, or even hours after they are sighted, it is imperative that meteorological satellite information be conveyed speedily to all nations. This can be done in several ways:

A launching country can relay data summaries on international meteorological circuits by means of coded messages or by facsimile, as is now being done with TIROS observations. This system of notification can introduce delays of several hours which may limit the operational value of the information.

Individual nations or groups of nations may receive the data directly from the satellite. This would seem to be the most efficient way of disseminating such information and putting it to immediate use but, as indicated earlier, this involves rather expensive ground equipment and

would complicate the satellite instrumentation if all data were to be transmitted in this manner. A more realistic possibility would be the continuous transmission of some of the data (such as cloud pictures over a limited area) with the remaining data being received and processed at a central location before international transmission.

Finally, the development of radio communication satellites will afford another solution. The launching nation could, after receiving the information from its satellite data receiving stations, transmit the observations in digested and analyzed form to other nations via communication satellites. Unprocessed information from meteorological satellites might also be relayed by communication satellites directly to central processing centers not within radio reception range of the meteorological satellites. The large volume of data expected from the Operational Meteorological Satellite System, when added to the ever-increasing number of conventional meteorological observations, suggests that communication satellites offer the only promise of providing an adequate means for the world-wide dissemination of weather data.

In the future, one can visualize an international weather service, including a World Meteorological Center where global data would be processed and analyzed for distribution to regional and local centers. It is interesting that Dr. A. Viaut, President of the WMO, on the occasion of its 10th anniversary, stated "It would not be realistic to mention—except as an ideal not likely to be attained for a very long time yet—the possibility of a single world meteorological budget." Until this day arrives there is ample opportunity for continued increase of international cooperation in meteorology, and it is expected that meteorological satellites will contribute strongly to this movement.

EDITOR'S NOTE: *Lectures in the Space Science series were originally prepared for Forum in the early part of 1961 and were broadcast in 1962. Although revisions have been made by the authors, continued developments in the space sciences require continued revisions of these texts, which would delay their publication still further. The texts as printed may, therefore, be out-of-date as regards certain extremely recent developments in the space sciences. They do, however, represent the thinking of scientists involved in space research as of the early part of 1962.*

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