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Reprinted for private circulation from
BULLETIN OF THE ATOMIC SCIENTISTS
Vol. XVII, Nos. 5–6, May–June 1961
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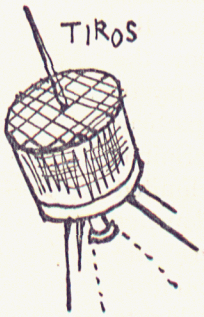
Meteorological Satellites



H. WEXLER and D. S. JOHNSON

FOR THE first time in history, there exists an observing platform which can detect atmospheric conditions long before local meteorologists relying on conventional techniques may be aware of them. This platform is the meteorological satellite, which, even in its present primitive stage, has already contributed significantly to meteorological developments through depiction of cloud systems and their interpretation for daily weather prediction, and by collecting basic physical data such as measurements of the radiative exchange between the Earth and Sun and space. Future observations will include the temperatures of cloud tops and the Earth's surface, the average temperatures of layers of the clear atmosphere, concentrations of water vapor, ozone and other properties not yet envisaged.

Man is immersed in a working fluid of a global extension—the Earth's atmosphere—a fluid so massive that there are nearly 2 million tons of it for each person on Earth. From above, it is penetrated by energetic particles and radiations, and from beneath, deformed, restrained, heated and cooled as it passes over the irregular Earth surface in its endless quest to equalize its energy imbalances, thus creating wind and weather. The atmosphere performs countless cycles of interrelated phenomena of every size, from global to microscopic. They are all important. For example, those actions involving water vapor—which comprises only about 0.2 per cent of the total mass of the atmosphere—nevertheless have such a profound effect on our planet's heat balance that without them the mean temperature of the Earth would drop by 40 degrees centigrade.

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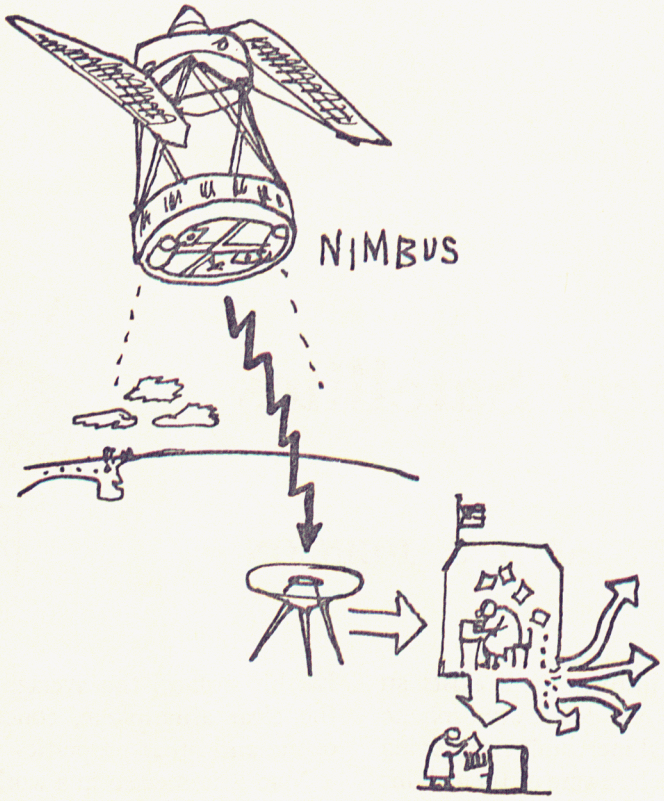
Meteorologists have traditionally been handicapped by having only fragmentary knowledge of what is going on in the atmosphere at any time. About a century ago, national meteorological services were established to provide forecasts to the public. As observing networks expanded geographically and in altitude, meteorologists continued their audacious attempts to predict the future state of a three-dimensional system whose initial state was inadequately known. Because of insistent public demand, the forecaster makes his daily predictions and up to a certain point is generally successful. His successes, however, are generally limited to forecasts for not more than a few days in the future and for areas in the midst of or close to a fairly dense observing network so that unknown disturbances from distant and sparsely observed regions have not had time to exert significant influence. Even so, disturbances such as tornadoes or severe thunderstorms can develop suddenly or slip through the mesh of observing stations.



Pictures of such storms, continuous in space and time, can now be provided by the proper distribution of surface radars and meteorological satellites. Radar observations show the three-dimensional array of many cloud types, particularly those with precipitating particles, over limited areas (200–300 kilometer radius) surrounding the radar set. In Earth-orbiting satellites, meteorologists have for the first time an observing platform with a capability commensurate with the global extent of the atmosphere, not only in observing what is going on but in communicating observations and warnings over the entire world.

Until recently, high altitude photographs of large cloud systems for meteorological research have been available as the result of a relatively few rocket flights. The V-2 rocket photographs at White Sands, New Mexico, in 1947 were among the first; then followed the Aerobee photograph of an upper cyclonic vortex over Texas in October 1954. In August 1959, pictures obtained from an Atlas nose cone showed a frontal cloud system 3000 kilometers long, extensive lines of tropical clouds, and cellular cloud patterns over the north Atlantic ocean. In April–June 1960, 14,000 high quality cloud photographs were obtained over the world between 55 degrees north and 55 degrees south latitude by the meteorological satellite Tiros I. These revealed spiral cloud bands associated with cyclonic vortices 800 to 1500 kilometers in diameter, cellular arrangements of cumuliform clouds 50 to 80 kilometers in diameter resembling in appearance the Bénard cells studied in the laboratory, and frontal cloud patterns which confirm in a remarkable manner the classical Norwegian model of cyclone families. In general, the cloud pictures from the Tiros satellites reveal an unexpectedly high degree of organization and unsuspected scales of local activity in atmospheric motions. Full interpretation of these natural "weather maps" will require intensified empirical, laboratory, and theoretical research in the dynamics of convection and vortex flow.

The Tiros I photographs also illustrate in a dramatic way the potential usefulness of satellites in the detection of severe storms by photographing the unique spiral cloud structure of a hurricane near New Zealand and a large cumulonimbus cloud system in the midwestern United States which later produced tornadoes. Snow and ice areas over land and oceans were also observed.

Cloud observations from satellites, once they serve their immediate forecast use, are valuable in meteorological research. They can be used to establish for the first time a truly global cloud census, to draw average charts of world cloud cover by months or other periods, and to note long-time variations in cloud amount and distribution. The world cloud cover is the most important component in determining the Earth's albedo and serves as a natural thermostat to keep the world temperature within narrow limits. A larger than average cloud cover can reflect more solar radiation and cool the Earth, thus reducing the convection currents and cloud cover. A smaller cloud cover will enable more solar radiation to heat the Earth's surface and thus cause more clouds to form.

A second Tiros satellite was successfully placed in orbit on November 23, 1960 and produced useful cloud photographs for more than two months.

In addition to the television cameras identical to those used on Tiros I, Tiros II carries two sets of radiation sensors. One radiation instrument relies on the mo-

tion of the satellite to scan the Earth with five sensors having a spatial resolution of about 50 kilometers and designed to measure reflected solar radiation from the Earth and hence the albedo; infrared radiation from the Earth; emission of the atmosphere in the 6.3 micron water vapor band; temperature of the Earth's surface or the cloud tops; low resolution cloud cover in visible light for comparison.

In the second experiment, two sensors, having a resolution of about 800 kilometers, view a portion of the Earth in the center of the area depicted by the wide angle television camera. One sensor responds to the terrestrial radiation emitted by the Earth and atmosphere while the other measures the radiation as well as the reflected and scattered solar radiation.

Observations from these radiation sensors are still under study but a preliminary analysis indicates that much of the data are of excellent quality and should reveal useful information concerning the radiative sources and sinks in the atmosphere, the surface and cloud temperatures and thus the approximate heights of cloud tops. The radiation sensors on Tiros II represent a continuation and extension of the low resolution solar and terrestrial radiation measurements made from the Explorer VII satellite which was launched on October 13, 1959. The data for Explorer VII are still in process of analysis, but some interesting preliminary charts of outgoing radiation from the Earth to space have already been drawn.

These satellite observations of radiation will be used to study weather developments and motions of atmospheric disturbances as related to the radiation balance, and to compute net radiation gains and losses over the Earth—a possible aid to long range weather prediction. It is known that poleward transport of excess energy from the tropics can vary considerably. When winds are blowing mostly from the west or east, the energy flow away from the tropics is inhibited. But when the flow pattern changes from this "high index" condition to meridional or "low index" flow pattern (typically characterized by large quasi-stationary anticyclonic and cyclonic vortices), poleward energy flow is promoted, giving rise to rather prolonged spells of the same general weather type—fair weather, droughts, floods, storms—depending on geographic location with respect to the stalled weather pattern.

Observations of unusual solar radiations, energetic particles, and meteoric dust from space should be readily available from satellites for correlation with unusual weather behavior. World weather charts should make it possible to study contrasts and similarities in northern and southern hemispheric circulation patterns, and to see whether one hemisphere precedes the other in assuming anomalous patterns or whether both react simultaneously to a common external excitation such as unusual solar radiations or meteoric dust. Also, observation of compositions and circulations of atmospheres of other planets by space probes, planetary satellites and landings, will permit comparisons with the terrestrial atmosphere and will assist in the separating out of phenomena common to all planetary atmospheres from those characteristic of a particular planet.

Climatic Changes

Much climatic warming, which has attracted considerable attention in recent years, is confined to rather restricted areas of the Earth, particularly to the north Atlantic subarctic region and the eastern and central United States. Other regions, such as the northwestern United States and parts of central Canada, have cooled appreciably during the past 40 or 50 years. But whether the Earth as a whole is warming or cooling cannot be determined from the present inadequate observation networks. Measurements over periods of a year or longer of the incoming solar radiation and the fraction that is reflected by the atmosphere, clouds, and Earth's surface (Earth albedo), as well as the outgoing infrared radiation from the Earth and the atmosphere should enable us to learn whether the Earth is receiving more energy than it returns to space or vice versa.

The difficulties of detecting changes in energy budget of some of these components by conventional means are illustrated by the following. On the average, each square centimeter of the Earth's surface and the atmospheric column above annually receives from the Sun about 175,000 gram calories. If there were complete radiative balance (as most textbooks in meteorology assume) there should be an equal return of energy to space. But if, averaged over a year, there were a one per cent excess of energy received by the Earth, what would this mean in terms of heating the oceans, melting the glaciers, and warming the atmosphere? If all the extra energy were concentrated in heating the oceans and nothing else, this would raise their average temperature by 0.006 degrees centigrade, which could not be detected by present observing techniques.

Imagine that the excess energy resulting from the imbalance of incoming and outgoing energy streams were concentrated in the atmosphere. This would raise the average atmospheric temperature by seven degrees centigrade—an amount believed to be the difference in world air temperature between that of the last ice age and the present time—a difference readily detectable even by our present observation networks.

Actually the excess (or deficit) of energy would be partitioned among atmosphere, oceans, glaciers and land in some unknown manner. Determination of the overall global energy budget plus that of such individual components as the atmosphere and glaciers (with the aid of greatly expanded observation networks) would permit determination of the energy budget changes of oceans and land masses. Thus the advent of satellites will unveil a new tool by which meteorologists may soon learn

more about the energy exchanges of the planet Earth with Sun and space, and how the exchanges, in turn, may be translated into the climate trends on which man's existence depends so crucially.

Operational Use of Satallite Data

Although significant improvements in meteorological analysis and forecasting will most likely result from a broad research program to which meteorological satellite data will contribute, it has already been possible to utilize cloud data from the Tiros satellites to a limited degree in meteorological operations. While operational use of data is considered to be experimental, it has already indicated the potential of even such simple analyses as cloud maps. They are particularly valuable in filling in the vast distances on weather maps between existing conventional observing stations, particularly over the oceans and other data-sparse areas of the world.

While the radiation data from the Tiros II satellite are not yet being used in meteorological operations, preliminary study of these data indicates they will be operationally useful as soon as rapid processing and analysis techniques are established. For example, the radiation measurements made in the eight to 12 micron water vapor "window" show promise of indicating in a gross sense the world's cloud distribution at night, complementing the existing daytime cloud observations obtained by the vidicon type television cameras. The correlation between the various radiation temperatures and weather patterns indicates that these data will be operationally useful in an empirical sense even though much research is required before the full import of these data in a quantitative, physical sense will be known.

The nature of the orbit and type of stabilization of the Tiros satellites do not permit the observation of the whole globe on a daily basis. The Nimbus satellite now under development by the National Aeronautics and Space Administration is designed to overcome these limitations in observational coverage inherent in the Tiros satellite. The quasi-polar orbit planned for Nimbus will bring the entire Earth into its view twice each day—a great impetus to the operational use of satellite data. By an active stabilization system, one axis of the satellite will always be normal to the Earth's surface.

Operational Meteorological Satellite System

The initial operational system might utilize a single Nimbus-type satellite launched so that on each orbit the satellite will cross the equator at the ascending node (northbound) at local noon and again at the descending node at local midnight. Presently available television cameras could produce cloud pictures over the entire solar illuminated portion of the Earth once each day with a resolution of about 0.8 to 2.4 kilometers. The cloud distribution over the portion of Earth in darkness could be determined by a scanning infrared radiometer.

A second Nimbus satellite might be launched so that one satellite crosses the equator at the ascending node at 9 a.m. local solar time and the second at 3 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).

The complexity and tremendous volume of data expected from even the early experimental Nimbus satellities will require the use of a costly ground station for satellite control and data reception. Only one such station would be required if it were located at a point poleward of about 80 degrees latitude. Initially, two or more ground stations probably will be used, utilizing existing facilities as much as possible. Wide bandwidth communications will be required to speed all of the data to a central analysis facility, such as the National Meteorological Center in Washington, D.C. Meteorologists, assisted by high-speed data processing equipment, would reduce the observational data and prepare analyses for both national and international use. The analyzed satellite observations would be distributed to field forecast centers by teletypewriter and high quality facsimile equipment.

While limited amounts of satellite data could be transmitted to other nations of the world via existing teletypewriter circuits, the global nature of satellite observations indicates the need for more adequate global meteorological communications. Indeed the large volume of data expected from meteorological satellites, when added to the ever increasing number of conventional meteorological observations, sharply emphasizes the urgency of providing greatly improved communications in support of meteorology. Communication satellites now under development offer promise of providing a means for the worldwide dissemination of meteorological data for the benefit of all mankind.

It also appears feasible to measure the vertical distribution of precipitation beneath the satellite by use of radar carried by polar orbiting satellites. Such data would greatly enhance the value of the cloud pictures because of the added knowledge of vertical distribution of cloud layers not obtainable from the cloud pictures alone and the ability to determine something of the intensity of storm systems as indicated by the intensity of precipita-

tion. The height of the freezing level in the atmosphere could also be inferred from the characteristic radar echo produced when ice and snow begin to melt after falling below the freezing level in the atmosphere. Further engineering development may ultimately permit the use of radar for detection of clouds, including measurements of the height of the bases and tops of various cloud layers beneath the satellite.

Theoretical studies have recently shown that the mean temperature of several layers of the atmosphere in at least the high troposphere and stratosphere can be determined from a series of high resolution spectrometric measurements of the radiation emitted by the Earth's atmosphere in various portions of the 15-micron carbon dioxide band. A spectrometer for this experiment is now under development. The same spectrometer is also being designed to measure the radiation received in a narrow spectral interval centered at 11.1 microns. The gaseous atmosphere is transparent to radiation at this wavelength so that the radiation received by the instrument would be proportional to the temperature of the Earth's surface or cloud tops within the field of view of the instrument.

Great strides have been made in recent years in utilizing digital computers to numerically predict the weather by solving simplified forms of the equations of atmospheric motion. The procedures presently used require quantitative observations as input to the computer. The aforementioned temperature measurements will likely contribute to numerical prediction as will the vertical velocity field as deduced from cloud pictures.

Present numerical prediction models require upper air wind velocities and some parameter directly related to the height of selected constant pressure surfaces in the atmosphere. It has been suggested that balloons be injected into the atmosphere which will move with the wind on surfaces of constant density. A network of balloons circling the globe at three different levels and equipped with temperature sensors would go a long way toward permitting numerical prediction on a global basis. Polar orbiting meteorological satellites might be used for locating the balloons with respect to the Earth's surface and receiving the temperature data from the balloons. The change in the position of a given balloon between observations would yield the mean wind during that period. The observational data could be processed at a central location before international dissemination.

A polar orbiting satellite system of the Nimbus type, while providing rather frequent observations of the whole globe, 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, 35,700 kilometers above the surface, will appear to be stationary. Four such satellites equally spaced about the equator would provide a system of observing platforms capable of viewing all of the Earth's surface continuously in the zone between 60 degrees north and south latitude. The observational coverage of these "stationary" satellites would be complemented in the polar areas by the Nimbus type of satellite.

It only appears feasible to obtain cloud observations from stationary satellites because of their great altitude above the Earth's surface. These satellites might be equipped with low resolution cameras which would provide a new global cloud map (except for polar areas) every few minutes to any station having the proper receiving equipment and located within "line of sight" 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.

International Aspects

It is quite clear from the foregoing that the advent of meteorological satellites will have a strong impact on operational and research meteorology throughout the world. In promoting international cooperation in these areas, it is anticipated that the World Meteorological Organization (WMO) and the Committee on Space Research (COSPAR) will play important roles.

The World Meteorological Organzation, affiliated with UNESCO 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 worldwide 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.

In this framework of international cooperation in meteorology extending back 83 years, the appearance of meteorological satellites presents some novel aspects and opportunities. First, 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 are truly global in their range and thus enable the meteorologists of the launching country to observe atmospheric phenomena over their area and outside areas more rapidly and more completely than can be done by local meteorologists and to make some measurements which cannot be done at all by conventional means no matter how dense the station network is. Since some of the phenomena observed by meteorological satellites may have rapid and serious consequences to the safety of the population and to the economy of a nation, it is imperative that meteorological

satellite information be conveyed speedily to all the nations. This can be done in several ways:

—*Read-out of data by the launching country* which relays data summaries on international meteorological circuits by means of coded messages or by facsimile. This system of notification introduces delays of several hours which may seriously limit the value of the information.

—*Read-out of data by individual nations or groups of nations.* This would seem to be the most efficient way of disseminating such information and putting it to immediate use but, as indicated earlier, involves rather expensive equipment of the order of $3 million or more per receiving station 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.

—*Communication satellites.* Here the launching nation could receive the information from its read-out stations and transmit it in digested and analyzed form to other nations via communication satellites. Raw information from meteorological satellites might also be relayed via communication satellites directly to central processing centers not in line of sight of the meteorological satellites.

A small beginning has been made in limited international release of meteorological satellite information from Tiros II. Whenever meaningful data were obtained for the southern hemisphere, these were transmitted by word message to the International Antarctic Analysis Center at Melbourne, Australia where meteorologists of several nations (including the U.S.) are cooperating in studying the meteorology of a major portion of the southern hemisphere. Also daily transmissions of cloud charts by U.S. Navy radio facsimile were beamed abroad for fleet units and received by other nations within range of these transmissions. The WMO informed its member countries of these transmissions and provided pertinent communication information.

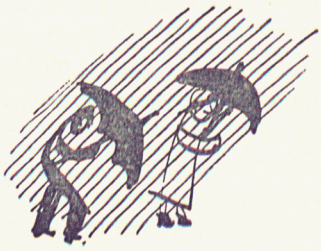
WMO can play an important role by keeping its members informed of the launchings of meteorological satellites, their orbits, heights, periods, characteristics of the sensing equipment, frequency and power of the radio transmissions, etc. It could encourage the member countries to participate in the program either by launching meteorological satellites in desirable orbits which supplement those launched by other countries, by assisting in the tracking and receiving of the transmitted data and by taking valuable auxiliary observations such as additional upper air soundings, cloud observations, etc. The WMO could also promote the dissemination of such data and stimulate their use and interpretation by distributing literature and arranging for the visits of meteorologists trained in the new techniques or by sending meteorologists to countries which have launched meteorological satellites.

COSPAR, the nongovernmental Committee on Space Research organized by the International Council of Scientific Unions (ICSU) which sponsored the International Geophysical Year, could encourage and coordinate meteorological satellite experiments and could, because of its broad representation from the international scientific community, draw upon a wealth of knowledge to suggest new meteorological experiments and to promote the design, development and testing of new observing techniques. These techniques, based on developments in the fields of spectroscopy, electro-magnetic radiation, particle dynamics, etc., may depart widely from conventional meteorological instrumentation.

The interplay of the various scientific disciplines engaged in research in space may lead to the unexpected development of valuable new tools and concepts in meteorology. These might include detailed observations of radiations and energetic particles from the Sun and space which affect the Earth's atmosphere, and observations of atmospheric properties of other planets, as discussed previously.

World Data Centers, containing meteorological satellite data for research purposes by all meteorologists, would also be maintained. World Data Center A, Asheville, North Carolina, is now receiving data from U.S. meteorological satellites.

In considering a world system of meteorological satellites for both operational and research use, the question of financial support arises. Who would pay for the satellites? Will this be done by individual countries or will there be a sharing of the costs by many countries, with a few countries designated to do the launching? For the foreseeable future, it is likely that costs of the meteorological satellites will be borne by individual launching countries but other countries might establish their own read-out stations. However, it is interesting that Dr. A. Viaut, president of the WMO, on the occasion of its tenth 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.



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March 20, 2009