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Honors Night Dinner Address
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THE SATELLITE AND METEOROLOGY*

by

Harry Wexler**

Since the satellite will be the first vehicle contrived by man which will be entirely out of the influence of weather it may at first glance appear rather startling that this same vehicle will introduce a revolutionary chapter in meteorological science -- not only by improving global weather observing and forecasting, but by providing a better understanding of the atmosphere and its ways. There are many things that meteorologists do not know about the atmosphere, but one thing they are sure of is this -- that the atmosphere is indivisible -- that meteorological events occurring far away will ultimately affect local weather. This global aspect of meteorology lends itself admirably to an observation platform of truly global capability -- the Earth satellite.

A foretaste of the future was revealed on March 7, 1947, when a V-2 picture of the Earth was taken from 100 miles up[1] (Fig. 1). Although this picture reveals some interesting examples of organized cumulus cloud patterns which show a good deal of fine structure and also some fuzzy patches of cirrus clouds, no storm happens to be in the field of view -- a circumstance deliberately chosen to avoid cloud interference with visual tracking of the rocket.

Another example, this time when a storm happened quite fortuitously to be in the field of view, occurred at 1815 GMT on October 5, 1954 at White Sands when an Aerobee rocket was launched into a hole in the cloud deck[2]. Figure 2 shows the area covered by a composite photo pieced together by Mr. Berg of the Naval Research Laboratory. This picture (Fig. 3) covers an area of 1¼ million square miles and has a distance along the horizon of 2800 miles. The curved edge is not the profile of the Earth. Note the spiral cloud bands -- the characteristic signature of a hurricane -- although no sign of a hurricane was noted on the surface weather map shown in Figure 4. This indicates a weak low pressure disturbance near Del Rio Texas which had moved in from the Gulf of Mexico a day or two earlier and produced heavy rains but no wind speeds higher than 35 miles per hour at any time in its previous life history.

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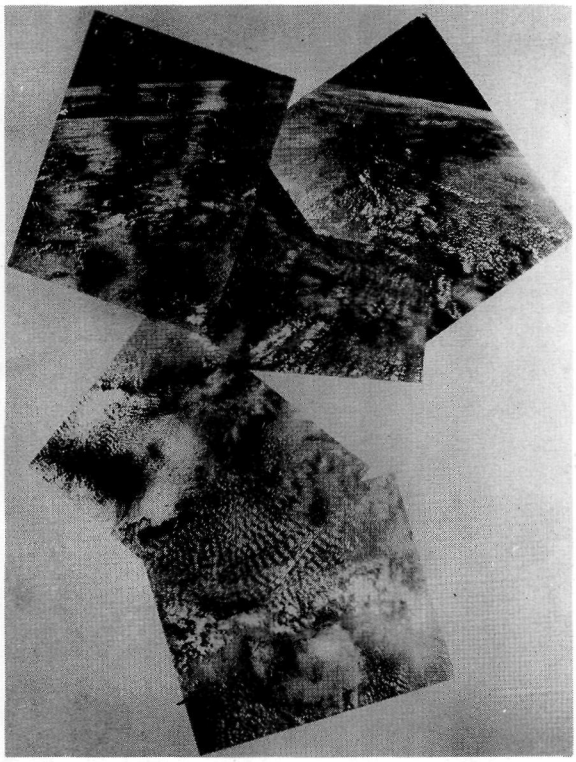


Fig. 1 Composite Picture of Photographs taken at an Altitude of about 100 Miles (V-2 flight, 7 March 1947)

Fig. 2 Outline of Area Shown in Fig. 3 (Discrepancies between the mosaic and this diagram are due to distortion resulting from mounting)

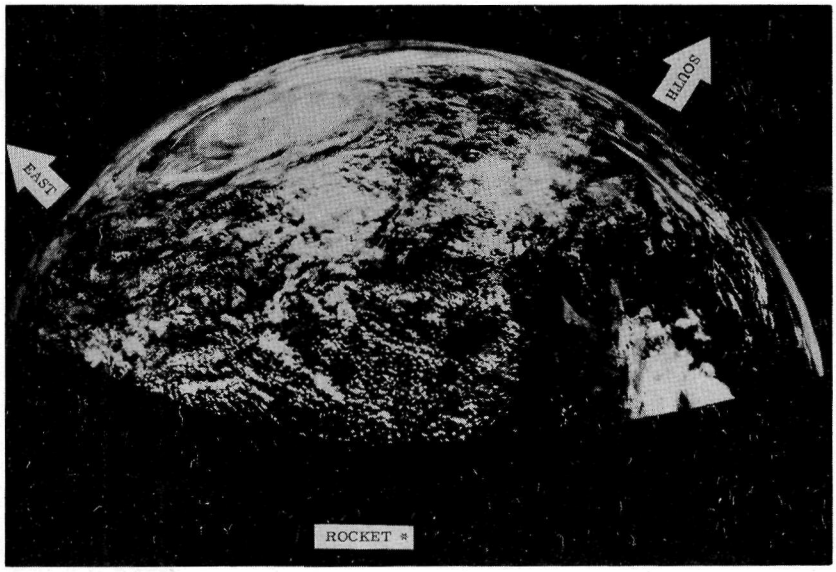


Fig. 3 Mosaic composed of Approximately 90 Frames taken by Telephoto Lens at an Altitude of about 100 miles over White Sands, N.Mex., 5 Oct. 1954. (Tropical Storm is slightly left of center and a second vortex is in lower right. The area of this mosaic is outlined in Fig. 2

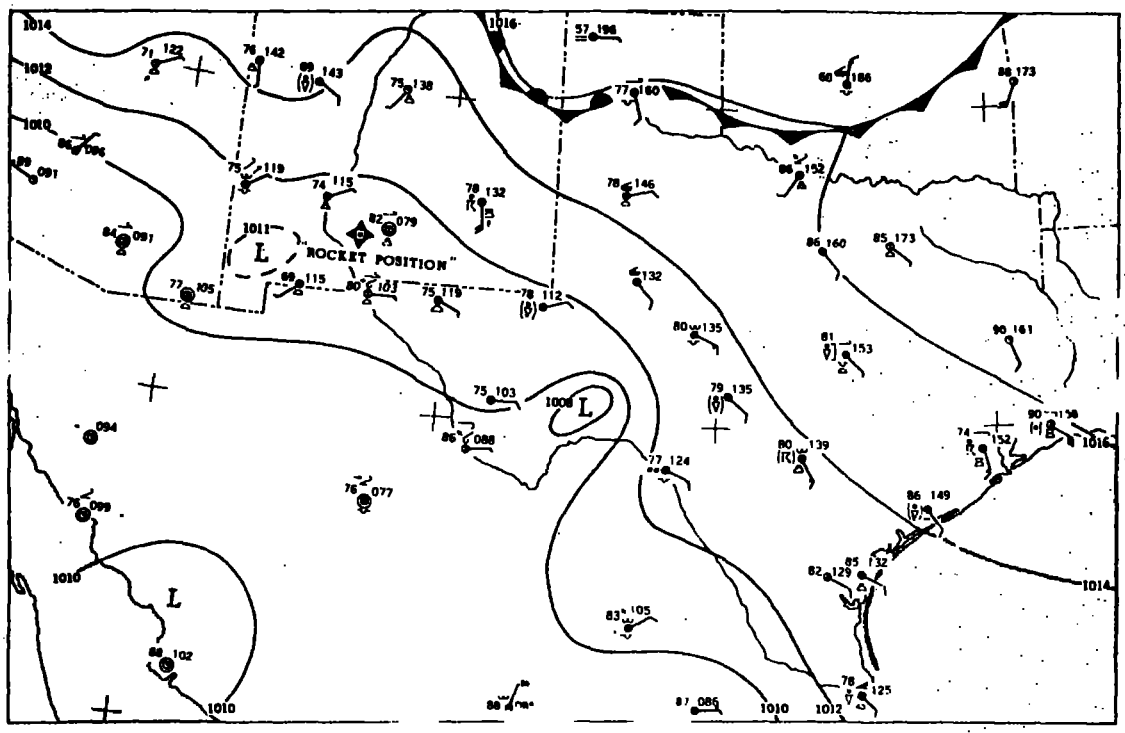


Fig. 4 Surface Weather Map for 1830 GMT, 5 Oct. 1954

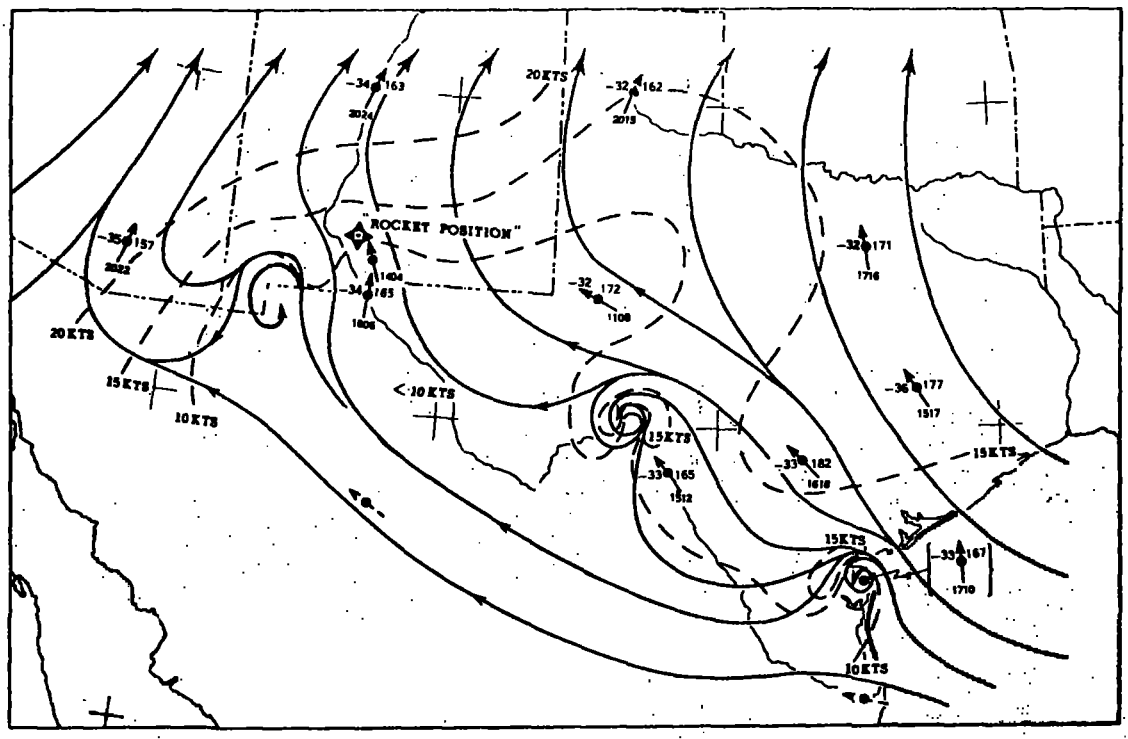


Fig. 5 Streamlines (solid lines) and Lines of Equal Wind Speed (dashed lines) at the Pressure Surface of 300 millibars for 1830 GMT, 5 Oct. 1954

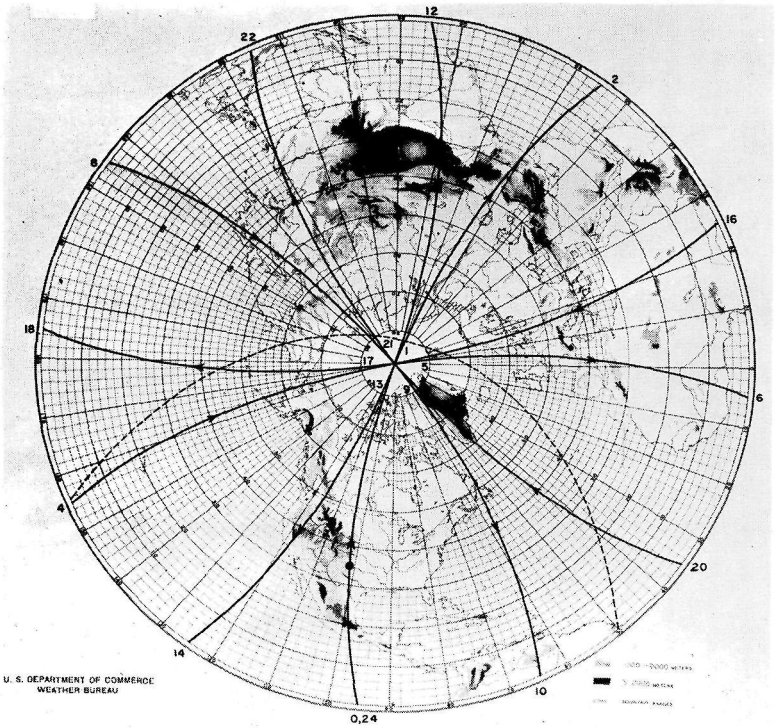
No one had suspected from sparse meteorological evidence available along the Mexican border that above the Earth's surface there was a small, intense vortex, perhaps approaching hurricane intensity. It was only the fortuitous rocket launching and the picture taken from it which later revealed the existence of this upper vortex. When all the data -- rocket and meteorological -- were put together three vortices were revealed (Fig. 5), the center one being the large one initially indicated by the rocket photo. The vortex to the west of El Paso however, was first suspected from the few meteorological observations available near there and then identified on the rocket photograph as a rather ill-defined circular cloud pattern.

Having had our imaginations stimulated by such chance photos from research rockets we can proceed to lay down some criteria for a satellite vehicle for meteorological purposes. First, it should be located far enough away from the Earth to have an instantaneous field of view comparable to North America and adjacent ocean areas -- similar to the area covered by the weather forecaster's "working" chart. Second, it should not be so high that the cloud areas and geographical features are not readily identifiable. Third, the vehicle should move in such a manner as to have the same cloud system in sight at least twice in a 12-hour period so as to obtain a track of the storm associated with the cloud system.

Such a vehicle is one which is located at two Earth's radii from the Earth's center or about 4,000 miles from the surface and which has a period of rotation about the Earth of 4 hours. If the Earth were not rotating the vehicle would move in the same meridional plane through the North and South Poles. But since the Earth does rotate as the vehicle moves, its path relative to the Earth's surface is a series of curves shown in Figure 6.

Let us assume that at noon on March 21 the vehicle is directed poleward from the Equator at the 95th meridian west, at "0" hour. If there are no external perturbations, the orbit of the vehicle is always maintained in a plane parallel to its initial orbitary plane, but attached to the center of the Earth in its motion through space. The Earth rotates under the vehicle in such a way that as the vehicle proceeds northwards, it crosses all latitudes at noon and after one hour it passes over the North Pole; afterwards it then moves southward at all latitudes at midnight. At 2 hours it is again at the Equator, at 3 at the South Pole, after which it enters into the daylight hemisphere again crossing all latitudes at noon in its northward passage. At 4 hours, it crosses the Equator at the 155th meridian, west, and repeats a similar path on the Earth's surface, but displaced westward from its initial path. In 24 hours it returns to its initial point of departure after having made both a daylight (noon-time) and night (midnight) surveillance of the entire Earth's surface.

Twenty minutes after its departure on its first leg,



--- Satellite's horizon in Northern Hemisphere when satellite is over Amarillo, Texas (large dot).

Fig. 6 Series of Curves (solid lines) Indicating Path of Satellite (4,000 miles altitude; 4 hour period of rotation about the earth)

Fig. 7 Portrayal of Features of Earth's Surface and Hypothetical Cloud Systems as they might appear on a Black and White TV Picture taken from a Satellite 4000 miles above Amarillo, Texas

when the vehicle has moved over Amarillo, Texas, its horizon will enclose an area almost identical to that of the weather chart used in preparation of weather forecasts for North America and adjacent oceans; this horizon in the Northern Hemisphere is indicated by the dashed line shown in Figure 6.

What would be seen from the vehicle at some 4,000 miles above Amarillo, Texas, if it were exactly noon, this time on June 21? An attempt has been made to portray the scene below under the assumption that the sun is directly overhead. The surface features of the Earth were first drawn by taking into account its normal color and reflectivity of sunlight, and the scattering and depleting effects on the passage of light through the Earth's atmosphere. Albedo values were assigned to various cloud types and their brightnesses computed. A colored drawing was made but is not shown here; however, a black and white photo of it is given in Figure 7 which contains the following major features:

(a) A cyclone family of three storms in various stages of development extending from Hudson Bay southwestward to Texas.

(b) The northeastern part of another such cyclone family whose oldest member is in the Gulf of Alaska, the remaining members to the southwest being invisible.

(c) A small hurricane embedded in "streets" of trade cumuli north of Puerto Rico.

(d) The Intertropic Convergence Zone (or Equatorial Front) -- a zone of interaction between the north east trades of the Northern Hemisphere and the southeast trades of the Southern Hemisphere -- extending west of Isthmus of Panama to the mid-Pacific.

(e) A "line-squall" -- favorite breeding-ground of severe wind storms and tornadoes -- in the eastern U.S. moving ahead of the cold front and surrounded on both sides by the cauliflower-like cumulus congestus.

(f) Scattered cumulus clouds of varying thicknesses over the heated land areas -- especially in the mountains and other areas where dynamic effects encourage the lifting of air in vertical columns.

(g) Altocumulus lenticularis or lens-shaped clouds, formed by lifting of wide layers of moist air over mountains and usually found where the "jet stream" crosses mountains, as over the northern

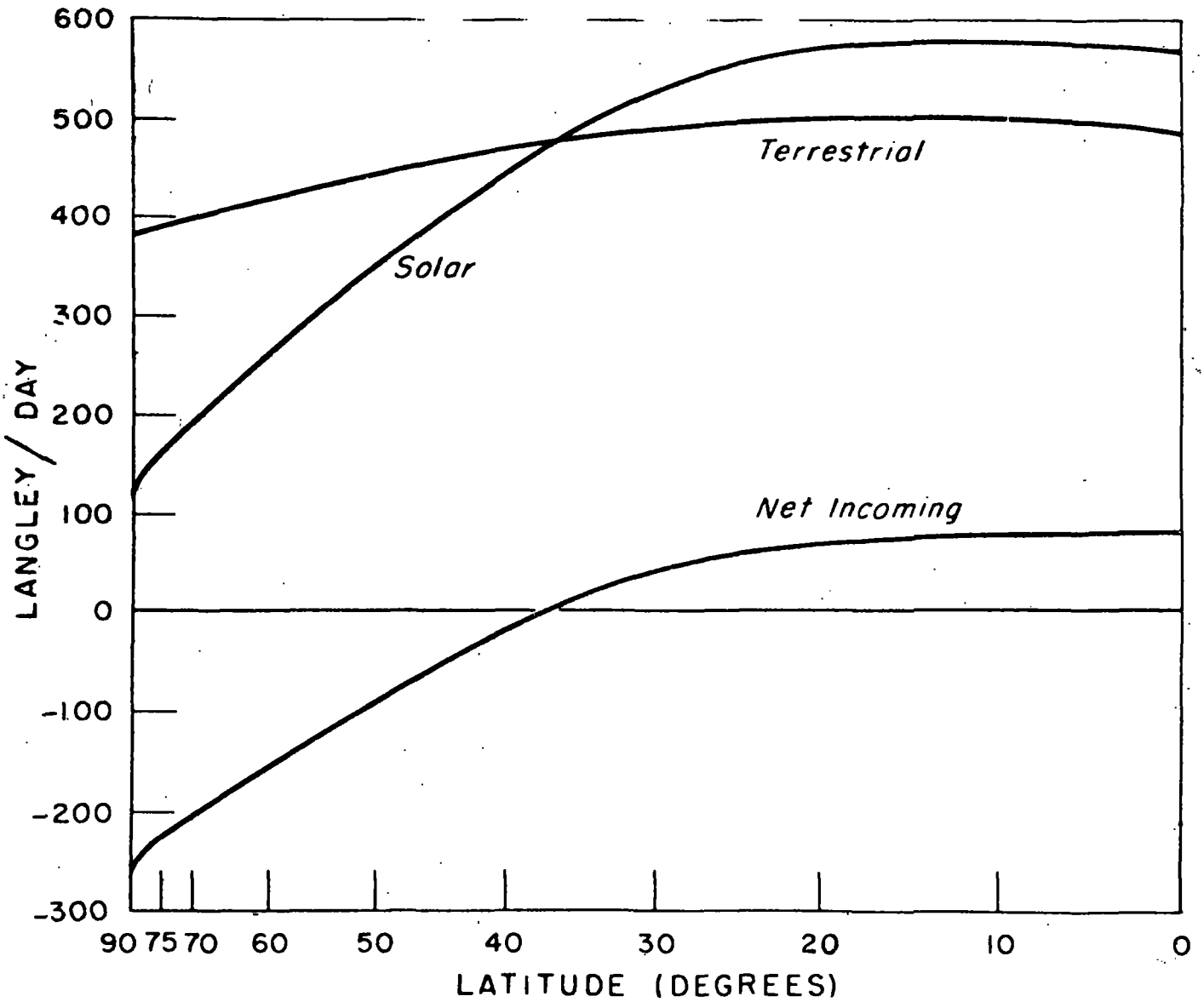


Fig. 8 Annual Mean Radiation

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Canadian Rockies.

(h) Low stratus and fog found off the southern and lower California coasts, over the Great Lakes, and the Newfoundland area -- formed by passage of warm moist air over cold surfaces.

The cumulus cloud systems over the oceans will tend to fall in fairly regular patterns of "streets" -- even more so than was observed over the rough terrain in Figure 1. The regularity and detail of the ocean cloud systems in the present sketch are exaggerated, but their breakdown into a more irregular pattern over land is in the right direction. The centers of the anticyclonic or "high pressure" areas are marked by little or no cloud.

This then is the hypothetical picture visible from the 4,000 mile high vehicle over Amarillo, Texas. Some of these clouds, such as the trade cumuli, could undoubtedly be observed on almost any day and others, such as the hurricane, seen only rarely. The cyclone families would be observed daily but their location, the number of individual storms, size and intensity would vary geographically. A meteorologist, given a clear picture of the cloud distribution, as here protrayed, could without difficulty sketch in a very useful weather chart showing location of the various stormy and fair weather areas; in fact, he would have a much better idea of the large-scale weather distribution than his Earth-bound colleague, who is forced to rely on scattered observations taken at or near the Earth's surface.

As for obtaining two or more "fixes" on storms within 12 hours, this would be possible as the vehicle makes successive passages toward the Poles -- and the closer to the Pole the storm is located the more such fixes could be made. For example, the large fully developed storm depicted over Hudson Bay in Figure 7 would be visible first on one leg of the path, again 4 hours later on the next leg, and again 4 hours later on a third leg. This would, by reference to known surface features, facilitate tracking of the storm in the 12-hour interval. A word of caution is necessary because the clouds, which on one hand make possible the visual identification of the storm, will hinder its location with respect to known surface features. Nor would trying to track the storm by observing the edge of its cloud shield necessarily give accurate results, because the changing cloud pattern associated with such large, usually dissipating storms may give spurious motions as clouds form on one side and dissipate on the other. Thus, there will not be too good an accuracy in tracking these large storms, but this is usually slow anyway. On the other hand, the smaller incipient or developing storm, so important for future weather developments, is faster moving and has a less extensive cloud system associated with it so that more accurate fixes should be possible. The hurricane, with its cloud bands similar to the arms

of a spiral nebula, and its open "eye" at the center, might be a much easier storm to detect and follow accurately. Cloud systems associated with cold fronts and squall-lines will also lend themselves to accurate tracking.

Figure 7 thus shows what a black and white TV picture of a hypothetical weather situation might look like.

Now that we've described the "ideal" weather satellite which of course will not be available for some years, what would we be willing to settle for in the immediate future -- say during the International Geophysical Year? Oddly enough the first meteorological experiment which will be conducted on an IGY satellite, probably in the spring of 1958, will be one which will contribute more to the basic knowledge of the energy input and output of the atmosphere than to improvement of forecasting, although practical benefits here may very well result too.

The two fundamental curves of solar energy absorbed by the Earth and its atmosphere and the energy emitted to space by Earth and atmosphere are shown in Figure 8. These curves were computed[3] from average conditions of temperature, moisture and cloudiness, observed mostly in one sector of theEarth where observations are quite numerous, namely, the North American sector. These curves are supposed to represent conditions typical of the entire Northern Hemisphere averaged over a year. The third curve in Figure 8 shows the net incoming radiation.

We see that the Tropics receive more radiation from the sun than they emit to space whereas the reverse is true in higher latitudes -- the cross-over point being about 38° latitude. Under the assumption that there is no appreciable energy transport across the Equator, the accumulation of energy in low latitudes increases the poleward energy transport which reaches its maximum at 38° latitude and then dwindles away to zero at the Pole.

These transports of excess energy from the Tropics can vary a good deal. For example, in a 2 months' period, energy transports across the 15° and 30° latitude circles varied from 0 to 200% of that needed to balance energy losses at higher latitudes[4]. When winds are blowing mostly from the west or east then the energy transport from the Tropics to the Poles will be reduced and energy can accumulate in the Tropics. However,when the basic flow pattern breaks down from zonal to meridional flow, characterized by large quasi-stationary high and low pressure areas, much more energy can be bled off from the Tropics. This alternation of flow from predominantly zonal flow -- with its rather inefficient poleward energy transport-- to the highly efficient meridional motions associated with large anticyclones and cyclones, often occurs in a still unpredictable manner. These alternations very profoundly affect the weather at a given locality. For example, when the change

takes place from a so-called "high index" or zonal flow pattern to the "low index" or meridional flow pattern and persists in the latter state, this gives rise to rather prolonged spells of the same weather-type, such as fair weather, droughts, floods, and storms -- depending where a particular geographical region is in relation to the stalled weather pattern.

It would be valuable to measure the net energy gain over the Tropics, directly and systematically with time, to see how it varies and whether its variations can be correlated with weather changes -- both short (period of weeks) and long (period of years) -- which might be associated with changes in climate.

A possible means of making these measurements has recently been proposed by Professor V. Suomi of the University of Wisconsin, and the writer to the Earth Satellite Panel of the United States National Committee for the International Geophysical Year. This proposal is based upon the placing of tiny spheres of the size of ping-pong balls on the four ends of the radio antenna of the satellite, three of these spheres each to have different reflecting characteristics. For example, one would be white to visible radiation but black to infrared; the other would be black to visible radiation and grey to infrared; whereas the third would be black to both visible and infrared. By measuring the temperature of these three spheres each 30 seconds or about every 150 miles along the track, we could solve three simultaneous equations to find the incoming solar radiation, the reflected solar radiation and, finally, the infrared radiation sent to space by the Earth and atmosphere. The difference between the useful incoming solar radiation (the part not reflected by the Earth and its atmosphere) and the outgoing infrared radiation would give the net gain of radiation in portions of the tropical belt between latitudes 35 north and 35 south -- the band expected to be covered by the IGY satellites. By keeping a daily account of this energy difference over this belt we can note its time variations. We could then correlate these net energy variations with atmospheric flow disturbances of the major type described above. By noting the build-up of energy in the equatorial regions, perhaps past a certain critical value, we might be provided an early clue as to the impending major changes in atmospheric circulation from essentially zonal to essentially meridional flow.

In addition to the energy aspects, the distribution of albedo, or reflectivity from the Earth and atmosphere, would be determined by means of the radio of the reflected solar radiation to the incoming radiation as the satellite moves along its path. This would undoubtedly reveal albedo variations caused by differences between land, ocean, snow covered areas, and, most important, clouds. It should be possible to identify the presence of large cloud areas, particularly over the oceans where the brightness would generally otherwise be low. It

should also be possible to distinguish the bright, high-reaching clouds associated with active storm areas or incipient hurricanes from the duller clouds.

Thus if our plans go forth as expected and the equipment works successfully, we would expect to receive from the IGY satellite a good deal of basic information about the energy budget of the important tropical belt of the atmosphere and at the same time some practical aids for forecasting in the meteorologically unknown region over the tropical oceans where hurricanes breed. Ultimately of course, by means of vehicles orbiting on a pole-to-pole trajectory we would want to measure the entire global energy budget and to see whether the Earth as a whole gains or loses energy over long periods and whether the gains or losses can be correlated with warming and other climatic changes that have occurred over large portions of the Earth's surface. Also a pole-to-pole orbit would for the first time provide a truly global weather patrol which should detect major storms anywhere on the Earth's surface. To insure continuous surveillance of all storms on Earth we should have 3 or 4 weather satellites moving along different pole-to-pole orbits at the same time.

You astronauts, who are pioneering in making man a truly three-dimensional animal, will contribute greatly to the development of meteorology.

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