REVIEW OF THE APPLICATION OF SATELLITES TO METEOROLOGY

by G. T. Rutherford

Central Office, Bureau of Meteorology, Melbourne

(presented at A. N. Z. A. A. S, Brisbane, May 1961)

Abstract: The increase in meteorological knowledge during the past half-century has not been accompanied by a parallel increase in accuracy of forecasts. This has been due not only to a continuing absence of information from certain vital areas but also to a more fundamental and scientific difficulty of inadequate understanding of meteorological processes, necessitating reliance on empirical and largely subjective forecasting techniques.

In this paper reference is made to the potential of the weather satellite, by television camera and radiation sensor, to remove the former of these limitations by extending the field of observation from the present one-quarter of the earth's surface to the entire globe. The importance of radiation measurements by satellite sensors for extended range forecasting by heat balance considerations is also discussed together with other applications of these measurements.

It is concluded that while availability of observations on a global basis from weather satellites will be a major advance, it will not prove a panacea for all meteorological ills. The additional requirement is a better understanding of meteorological processes. This is still a long term prospect but close study and interpretation of photographed cloud patterns is one avenue which promises to lead to this result and consequently to better weather prediction.

1. INTRODUCTION

The objective of meteorology is to increase understanding of atmospheric processes and to improve ability to predict weather. Since prehistoric times man has noted the connection between clouds and weather and some of the first studies in meteorology were based on efforts to relate certain types of weather to particular cloud types and cloud systems. This was qualitative, highly subjective and considerably dependent on experience and in consequence quickly lost favour with meteorologists as soon as more objective techniques became available.

The basis of these new techniques was to ascertain first what processes were at work in the atmosphere, secondly, why they were at work, and finally what would be their future manifestation as weather. The first step in these new techniques was the sampling of the
atmosphere's structure in the form of weather reports. These were treated in such a way as to present a pattern which was representative of the weather. Sampling and systematic treatment of data in this way commenced about one hundred years ago when meteorological observations from land stations were first plotted on charts. With the advent of more refined techniques the usefulness of these charts became established, and the charts gradually expanded, as communications improved, to include islands and those portions of oceans where weather reports were obtainable from shipping. In addition reports have gradually become available from within the atmosphere itself—from aircraft and more recently from balloons equipped with electronic devices reporting temperature, moisture and pressure at various levels.

In spite of the advances made in the gathering of data the position as a whole has continued to be very unsatisfactory. The increased access to data in the vertical as described above has not been accompanied by a similar increase laterally, particularly over the vast ocean areas. Less than one quarter of the earth's surface is adequately sampled by conventional meteorological techniques and large storms may exist undetected for days in many oceanic regions. This inadequacy of the weather reporting network has been further emphasized by the discovery in recent years on theoretical grounds that such storms may induce similar disturbances in far distant parts of the hemisphere.

A rather more alarming conclusion, however, has arisen from studies of the relationship between data density and forecast accuracy (Allied Res. Ass., 1960). It is apparent that forecast accuracy increases only up to a certain density of weather reports and beyond this point further increase in data density brings little improvement in accuracy. Perhaps the chief reason why this is so is because forecasting methods are still largely empirical and dependent on experience.

These then until the present time have been the two major obstacles to further advances in forecasting; first, the inadequate observational data over vital portions of the earth's surface, and secondly, even where the network has been adequate, we have been confronted by a more fundamental difficulty of a rather ominous gulf between the theory and practice of meteorology. We have not been able to understand why certain processes have been operating and have therefore been unable to predict their future manifestation as weather.

This is the stage at which we have the advent of the rocket and the weather satellite. Research rockets (Conover and Sadler, 1960) have been in use for the past decade and will continue to play a useful part in sounding that part of the atmosphere above the reach of conventional balloons and within which atmospheric drag restricts the use of satellites. The latter in particular provides a new and promising approach.
2. CLOUD OBSERVATIONS BY SATELLITE

The orbiting meteorological satellite with television camera provides not only a supply of cloud data in regions such as oceans from which observations have not hitherto been available, but also in regions of dense network, patterns of cloud manifesting atmospheric processes may be revealed which are not observable at ground stations individually, or detectable by analyses of the reports on charts. The analyses of such systems may well provide a vital link in the understanding of these processes.

It has already been stated that the charting of weather systems is restricted by the density of the network of reporting stations. This applies not only to the vast expanses of the Indian and Southern Oceans in the Southern Hemisphere, but also over wide regions in the Pacific and Atlantic Oceans of the Northern Hemisphere. In all these regions vigorous storms may remain undetected although their overcast cloud patterns may cover hundreds of miles. A major contribution of satellites to meteorology therefore and one which has in fact already been demonstrated, is their ability to locate and track major storms and to detect their birth and decay.

Weather satellite Tiros II (launched November 1960) could be programmed to transmit cloud photographs directly when within range of certain "read-out" stations in U.S.A (Nat. Aer. and Space Admin. 1960). It could be programmed also to instruct one or both of its two television cameras at a specific time in the future to provide about thirty still photographs at half-minute intervals and to record the scanning of these photographs on magnetic tape in the satellite. When the satellite came within range of a read-out station the signals could be transmitted to it from the tape.

The cloud photographs as received at the read-out station are distorted in the sense that:

(a) the surface being photographed is curved,

(b) most pictures are taken at oblique angles, i.e. the camera is not pointed directly downwards,

(c) some lens and electronic distortion exists towards the outer margins of the picture field.

The interpretation of the photographs therefore commences with their "rectification" at the read-out centre (Glaser 1960). This is accomplished on the photographs by means of a computer and line-drawing attachment, which automatically inserts a grid of latitude and longitude lines. The photograph complete with superimposed geographical grid is disseminated to meteorological authorities in various
countries—provided they possess radio-facsimile equipment with the necessary band width. Where countries do not have the necessary equipment for this type of transmission, alternative methods for despatch of the information on the cloud photograph are available (W. M. O. 1961).

The utility of the photograph as a forecasting aid depends on the degree to which it can be accurately interpreted in a meteorological sense, i.e. in terms of horizontal and vertical motions in the atmosphere. Photographs already available (Winston 1960) indicate patterns of linear, circular, spiral or cellular form and these may be related to such features as vortices, fronts, jet streams or other significant meteorological elements. Of these the most immediately impressive is the vortex spiral. This appears to be characteristic of many tropical cyclones and high latitude depressions and is a pattern which could not be observed from ground stations. No two of these patterns are exactly alike and it is likely that their dissimilarities may represent important differences in weather process or structure and be a fruitful field of study.

With regard to cloud patterns in general it appears that the major limitation to confident and objective classification lies in the present inability to determine cloud types and heights. However, there is reason to believe that this, among other data, may be obtainable indirectly through satellite observations other than in the visual part of the earth-atmosphere spectrum.

3. RADIATION OBSERVATIONS BY SATELLITE

The ability to look down at the earth and its atmosphere offers many possibilities and to utilize these to the fullest extent it is necessary to make use of different regions of the electromagnetic spectrum. The earth intercepts energy from the sun in the form of radiation and this intake of energy is balanced (except for long term climatic change) by a compensating loss through radiation from the earth and atmosphere to outer space. The energy "budget" or heat balance is determined then by:

(a) direct radiation from the sun (solar or short wave radiation),

(b) the fraction of the direct radiation which is reflected by earth, clouds and atmosphere,

(c) the fraction of the direct radiation which is converted into heat and ultimately re-radiated back to space (infra-red or long wave radiation).

The net radiant energy received from the sun is not uniformly distributed over the earth's surface and it is known that the excess heat energy received at the tropics is transported poleward by the atmosphere and ocean currents. The differential heating of the earth must be
balanced by this transport of energy to maintain the existing average
temperature equilibrium (Suomi 1958). When the winds are zonal, the
energy transport from the tropics is reduced and energy accumulates in
the tropics. However, when the basic flow changes from zonal to
meridional—characterised on charts by large amplitude waves and quasi-
stationary anticyclones and cyclones—much more energy can flow
poleward. This alternation from zonal to meridional flow is often
difficult to predict although it has a profound effect on the weather in
particular regions. Prolonged periods of weather of a particular type such
as fine weather, droughts, storms and floods are characteristic,
depending on the geography of the locality with respect to the stationary
weather pattern.

Satellite measurements of the radiation components comprising
the heat balance will enable calculation of the net radiation for a given
area of the earth at the time the satellite is overhead. From such
samplings it is hoped that a daily record of net energy transfer will be
available which may be interpreted for its influence on weather systems.
It will be necessary to chart areas of net radiant energy accumulation and
correlate these with changes in potential energy and large scale
processes such as anticyclogenesis and cyclogenesis. This could be
expected to provide most benefit in selected zones where meridional out-
breaks commonly occur. Thus, providing the problems of interpretation
can be overcome the satellite can be expected to contribute a great deal to
long range forecasting, through measurement of the gross infra-red and
solar radiation entering and leaving the earth-atmosphere system.

Aids to short term as well as to long term forecasting may be
indirectly derived also from detailed measurement by satellite of the
infra-red radiation emitted upwards from the earth and atmosphere
(Greenfield and Kellogg 1960). The atmosphere contains certain
constituents which have pronounced absorption and emission bands in the
infra-red region of the spectrum. The interpretation of satellite
measurements of the radiation at particular wavelengths will require much
investigation because of the complexity of the infra-red absorption and
emission spectra and local variations in the relative concentrations of the
gases in the atmosphere.

A start has been made towards collection of radiation data for
this purpose in satellites Vanguard II (Fritz 1959) and Explorers VI and
VII (W. M. O. 1961). This was extended in the satellite Tiros II, which
was equipped with a radiometer containing a set of five sensors which were
sensitive to the following spectral bands:

(a) 0.2 to 6 microns (μ) — to measure reflected
    solar radiation,

(b) 6 to 6.5 microns (μ) — to measure radiation
    from water vapour, which is a good
    absorber at this wavelength,
(c) 8 to 12 microns (\( \mu \)) - to measure radiation from the earth's surface and from thick cloud layers. Water vapour is a weak absorber for this wavelength band,

(d) 8 to 30 microns (\( \mu \)) - to measure the total energy of the infra-red radiation emitted by the earth-atmosphere system,

(e) 0.56 to 0.75 microns (\( \mu \)) - to measure the incoming visual radiation.

The most interesting constituent from the meteorological point of view is water vapour. Water vapour is a poor absorber of radiation of wavelength 8 to 12 \( \mu \). This property may be used to give cloud cover at night (an observation at present beyond the capability of the television satellite cameras which photograph only the sunlit portions of the earth) and also surface temperature, cloud top temperature and approximate height of tops. The 8 to 12 \( \mu \) part of the spectrum has been called the "window" for water vapour since most of the surface and low level radiation in this band escapes through the atmosphere.

This effect is shown qualitatively in Fig. 1.

![Fig. 1 Schematic diagram of emission from atmosphere and earth for water vapour. (After Greenfield and Kellog 1960)](image-url)
In the "window" region a large fraction of the surface radiation will escape through the atmosphere and at least a part of the radiation at each of the lower layers will also escape. However, in a region of the spectrum where the water vapour is highly absorbing the radiation will not be able to penetrate the absorbing layers above them. With increase of height the overlying absorbing gas becomes sufficiently attenuated so that some emission from such layers high in the atmosphere will escape.

Thus from the nature of the radiant energy measurement by the satellite sensor in the 8 to 12 \( \mu \) "window" band an estimation is available of surface (land or sea) temperature in areas where there is no cloud, and of cloud top temperature where the escaping radiation is emitted from the upper surface of cloud. Delineation of these regions would automatically give a crude distribution of the cloud cover. This has been demonstrated by data from Explorer VII (W. M. O. 1961) which has been used to plot patterns of outgoing radiation from the earth-atmosphere system with marked similarity to anticyclones and cyclones in dimension and motion, due primarily to the presence and absence of cloud.

Similarly Fig. 2 shows temperatures over the Tasman Sea area, computed from radiometer measurements in the 8-12 \( \mu \) band from Tiros II in November 1960. The low temperature regions correspond to regions of cloud producing mechanisms in the corresponding M. S. L. chart (Fig. 3).

Difficulties in interpretation are demonstrated by Greenfield and Kellogg who showed that the "transparency" of the "window" is not so effective in the tropics where the higher humidities reduce the amount of escaping radiation.

Another application consists in the use of the 6 to 6.5 \( \mu \) sensor to detect the radiation which is strongly absorbed by water vapour. As shown in Fig. 1, this absorption is largely complete for radiation from low levels but is not effective to stop emission from higher levels. The radiation emitted upwards from the various constituents of the atmosphere depends on the distribution in the vertical of the density and the temperature. A measure of the radiation in the 6 to 6.5 \( \mu \) band will enable determination of the geographical distribution of water vapour at the tropopause level if the tropopause temperature is known, or, vice versa, if an assumed water vapour content of about 0.3 mm is taken for the top layer of the atmosphere, its average temperature may be deduced.

A further observation may be derived from detailed measurement of the infra-red emission in the vertical from the earth-atmosphere system. From an analysis of specific radiation bands, using high resolution spectroscopic equipment, the temperature of particular layers in the atmosphere may be inferred and the vertical temperature profiles obtained. Using these temperatures and high resolution measurements of emitted radiation in the water vapour absorption band, it would then be possible to determine the vertical distribution of water vapour.
Fig. 2 Isotherm pattern computed by radiometer measurements, 8-12 μ band, Tiros II, 1220 GMT, 23rd November 1960

With kind permission of NATIONAL AERONAUTICS AND SPACE ADMINISTRATION, Washington, D.C., U.S.A. See acknowledgement at end of this article for details.
Fig. 3 M.S.L. Analysis, 1200 GMT, 23rd November 1960

With kind permission of NATIONAL AERONAUTICS AND SPACE ADMINISTRATION, Washington, D.C., U.S.A. See acknowledgement at end of this article for details.
Arrangements are already in hand for experimental measurements of atmospheric ozone by spectroscope and total absorption methods at 9.6 μ and 14 μ. A knowledge of the distribution of ozone in the atmosphere is desirable because the ozone layer (30 to 60 Km) may be the connecting link between unusually intense solar emissions and anomalous weather conditions. Alternatively, rockets fitted with radiosonde equipment may be used to record significant temperature changes in this layer which is beyond the reach of conventional balloons (Lally 1960).

4. OTHER SATELLITE OBSERVATIONS

Other types of observation have been suggested as practicable by an orbiting weather satellite in addition to those discussed in the preceding sections.

A satellite equipped with radar could conceivably provide data on the liquid water content of clouds and enable quantitative rainfall prediction on a global basis. Radar of sufficiently short wavelength could also detect clouds and if the cloud layers are sufficiently separated in the vertical the height of the layers could be obtained.

Satellites equipped with storm direction finding equipment could supplement data obtained from a very limited number of surface stations and would prove valuable in the investigation of tornadoes and other severe storms.

Indirectly the satellite may be used to measure winds by locating and tracking the positions of constant level balloons which in the next few years may reasonably be expected to be capable of flying for long periods at levels up to 30 Km. This conception of the satellite in the role of a data-collecting rather than a data-observing tool, is not unlikely for some purposes. For example, should serious difficulty be encountered in equipping the satellite with instruments capable of indirect measurements of meteorological parameters, the function of the satellite could conceivably be to locate the position of electronically equipped constant level balloons and collect from them meteorological data which had been directly measured from the atmosphere.

5. ORBITS OF SATELLITES

Circular rather than eccentric orbits are desirable for meteorological satellites in order to avoid the need for height correction to cloud photographs.

A satellite on an orbit about the equator would be particularly useful for tropical countries, as its observation of weather data as it moved from west to east would be restricted to a certain distance north and south of the Equator, depending on its height. The frequency of observation over any one point on the equator would be determined by the orbital period, which for circular orbits depends largely on the height of the satellite. Thus a satellite at a height of 1000 Km would orbit the
earth in 105 minutes (Wexler 1960) and could observe the earth's surface within an area from $30^\circ$S to $30^\circ$N. A satellite with an orbit time of 24 hours would remain roughly fixed above a given point on the equator and thus could give a continuous record of weather by television to a ground receiver at this locality.

An orbit in a plane inclined to the equatorial plane would give a coverage of the earth greater than an equatorially orbiting satellite. The projection of the orbit on to the earth's surface or sub-satellite path covers increasingly large areas of the earth with increasing inclination of the orbital to the equatorial plane.

A polar orbiting satellite will view the entire earth twice daily - once as it moves northward and again as it moves southward. Going north it would cross all latitudes at the same local time, and going south (after passing the North Pole) at the same local time 12 hours different. For example a satellite launched at local noon towards the north would cover all latitudes at local noon until it passed the North Pole when it would move southward across all latitudes at local midnight.

Due to the difference between the solar and the sidereal day the local time of passage of the satellite across each latitude circle would be about four minutes earlier each day. Since it is desirable to remove diurnal influences from cloud observations this four minute displacement can be adjusted by launching the satellite not towards the Pole but at a small angle away from it so that the precession of the orbit offsets the four minute period. This "quasi-polar" satellite would then always view the earth at the same local time moving north and at the same local time twelve hours different moving south.

It can be readily visualized that a number of satellites moving on circular quasi-polar orbits could be spaced at say $90^\circ$ longitude intervals by launchings at a particular locality at six hour intervals. If the time of one launching coincided with 0001 GMT a wide spread of data would be available for each of the daily synoptic hours as each satellite came overhead.

6. FUTURE U. S. A. METEOROLOGICAL SATELLITE PROGRAMME

The following table indicates the planned satellite programme of the U. S. A. for the period to 1964.
<table>
<thead>
<tr>
<th>Launchings</th>
<th>1961</th>
<th>1962</th>
<th>1963</th>
<th>1964</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tiros III</td>
<td></td>
<td>Nimbus I, II</td>
<td>Nimbus III, IV</td>
<td>Aeros I, II</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Orbit</th>
<th>Inclined (50°)</th>
<th>Quasi-polar</th>
<th>Quasi-polar</th>
<th>Equatorial</th>
</tr>
</thead>
</table>

| Altitude   | 700 Km         | 1100 Km     | 1100 Km     | 36,000 Km  |

<table>
<thead>
<tr>
<th>Orientation</th>
<th>Space, spin stabilized</th>
<th>Earth stabilized</th>
<th>Earth stabilized</th>
<th>Earth stabilized</th>
</tr>
</thead>
</table>

**Measurements**

1. Cloud
2. Radiation
3. Special radiation measurements
4. Radar, sferics and other developments

**7. CONCLUSION**

The artificial satellite promises to become an invaluable tool in detecting cloud formations of small and large scale over regions which have hitherto been blank areas on synoptic charts.

The interpretation of cloud elements and cloud patterns in terms of meteorological processes is a pre-requisite to their use in analysis and forecasting so that the weather features representing such processes can be identified.

The significant feature of vortices is not only the basic similarity of many of these cloud patterns but also the differences that exist in detail. Study of the causes of these differences should lead to a better understanding of atmospheric processes.

Satellite measurements of radiation may, subject to adequate instrument technique and interpretation, indirectly provide information on cloud cover, temperature of the earth's surface, temperature and height of cloud tops, and vertical and horizontal distribution of temperature and water vapour.
When equipped with special radar, satellites may enable estimates of precipitation and of cloud thicknesses and heights.

Upper winds may be determined for various levels by the tracking of constant level balloons by satellites. In some circumstances, also, it may be desirable to use satellites in the role of collectors of data directly measured and transmitted by such balloons fitted with electronic measuring equipment.

In addition to their function in measuring or collecting observations to improve the network of reports available to the meteorologist, both in the vertical and horizontal, the satellite has important implications towards long range forecasting from heat balance considerations. These too will require accurate interpretation before useful application is possible synoptically.

High altitude rockets may well have a useful part to play in the region above the present limit of conventional sounding balloons, which is of particular meteorological interest, viz. the ozone layer.

The quasi-polar circular orbit appears to hold most promise for weather satellites. Such satellites can be launched so as to provide a global cover of data of various kinds at hours coinciding with the present four daily synoptic hours, at 00, 06, 12 and 18 GMT.

From the above points it is evident that it can confidently be anticipated that one of the major limitations to forecast accuracy, viz. the lack of data in vital regions, is likely to be eliminated in the near future. There remains the major problem of interpretation of atmospheric processes in the light of theory so that a firm basis may be established for prediction of processes given prescribed conditions of atmospheric structure and various operating influences. The satellite in this respect cannot be regarded as a panacea for all the ills afflicting the meteorological profession. However, it does provide through its photographs of cloud patterns, the first complete picture of atmospheric processes and the interpretation of these must lead to a more complete understanding of meteorology, and in consequence a better forecasting capability.

ACKNOWLEDGEMENT


The legend to these figures as given by the authors reads:
"Radiation map constructed from apparent blackbody temperatures viewed by 8-12 micron channel of the medium resolution radiometer while passing over the New Zealand area during orbit "0" just after launch, November 23, 1960. The frontal positions were taken from a standard weather map, based upon limited observations, and modified in accordance with the more voluminous radiation data. Marker dots are placed at 1-minute intervals along the sub-satellite path."

We also have to acknowledge our indebtedness to the World Meteorological Organisation for authorizing the use of material in their Report on the Second Meeting of the Panel of Experts on Artificial Satellites, EC-XIII, Doc. 7 (20. II. 1961), from which the figures were actually taken.

REFERENCES

Allied Research Associates 1959 Operational Plan for Project Tiros

Conover, J. H. and Sadler, J. C. 1960 B. A. M. S. Vol. 41 No. 6

Fritz, S. 1959 Weatherwise Vol. 12 No. 4


Lally, V. E. 1960 B. A. M. S. Vol. 41 No. 8

National Aeronautics and Space Administration 1960 News Release, Tiros II


Wexler, H. 1960 W. M. O. Bulletin, Vol. IX No. 1
