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Meteorological measurements from satellites — A review

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ABSTRACT. Experiments carried out from meteorological satellites during the last ten years have convincingly demonstrated that efficient and economical global observations of meteorological parameters can be made from orbiting spacecraft by "remote sensing", *i.e.*, by measuring the radiation emitted and reflected by the earth and atmosphere.

1. Introduction

Two types of radiation measurements are made from meteorological satellites, namely, (1) a continuous imaging of radiation intensities in wide spectral bands in the visible and infrared over the entire globe with television cameras to obtain cloud pictures, and (2) quantitative measurements of the intensity, polarisation and angular and spectral variations of the received radiation with scanning radiometers to obtain surface and cloud top temperatures, the radiation balance, the amounts and vertical profiles of water vapour, ozone and temperature in the atmosphere. The experiments for sounding the atmosphere from satellites represent a major breakthrough of long-term importance in meteorological observational techniques. Meteorological satellites now form an indispensable and integral part of a global weather observing system and are likely to increase in importance with the development of improved sensors and better methods of data processing and dissemination.

2. Weather satellites

The concept of using satellites for weather observations was first discussed by Greenfield and Kellogg (1951) wexler (1954) and Singer (1957) The first meteorological experiments were made on Vanguard 2 (Hanel 1961) and Explorer 7 in 1958 (Suomi 1961). The first satellites designed purely for meteorological purposes were the Tiros for the identification and tracking of weather systems on a synoptic basis and were followed by the ESSA series of satellites, the Soviet Cosmos satellites and the highly sophisticated and versatile Nimbus research satellites, which provided meteorologists with global data on a scale not imagined possible before.

The limitations of Tiros are well known. They were experimental and had only vidicon cameras and simple radiometers but led to rapid changes in spacecraft technology and data transmission and processing techniques and the evolution of the first operational meteorological satellite, ESSA, launched in 1966. The ESSA series were mainly earth imaging and had either APT or AVCS cameras systems. The present ESSA satellites are being replaced by the improved Tiros operational satellite system, ITOS, which will combine stored data and APT both day and night in a single earth stabilised vehicle with longer design life. Two two-channel radiometers (SR), one in the $0 \cdot 5$–$0 \cdot 7 \mu$ band and the other in the 10–12 μ band, will ultimately replace the AVCS and APT cameras for operational day and night time viewing and to give cloud top and surface temperature data.

The first geostationary satellite ATS-1 was launched in 1966 and ATS-1 and ATS-3 have provided continuous cloud pictures every 20 minutes of the whole earth visible to the spacecraft from a distance of 37,000 km. The first Geostationary Operational Environmental Satellite (GOES) to be launched in 1972, will have a ten-channel telescope with 8 channels in the visible and 2 in the infrared, to give high quality, near real time and frequent observations by day and night.

The Nimbus series of research satellites have provided us with most of the quantitative observations made so far from earth-orbiting satellites. These highly sophisticated and versatile spacecraft are so designed that it can be pointed to the earth at all times with an accuracy of 1° and can store 10^{12} bits of information per orbit and carry about numerous complex experiments. Nimbus 3 had

TABLE 1

Nimbus IV meteorological experiments

Experiment	Spectral bands (Microns)	Main purpose
Temperature Humidity Infrared Radiometer (THIR)	10·5-12·5	Daytime and night-time surface and cloud top temperatures and cloud mapping
	6·5-7·0	Atmospheric water vapour mapping
Infrared Interferometer Spectrometer (IRIS)	8-20	Atmospheric temperature profile, O3, water vapour surface temperature and minor Atmospheric gases
Satellite Infrared Spectrometer (SIRS)	11	Surface and cloud top temperatures
	13-15	Atmospheric temperature profile
	19-36	Atmospheric humidity Profile
Monitor of Ultraviolet Solar Energy (MUSE)	0·12	Monitor changes in solar radiation
	0·16	
	0·18	
	0·21	
	0·26	
Selective Chopper Radiometer (SCR)	13·15	Atmospheric temperature profile
Filter Wedge Spectrometer (FWS)	1·2-2·4 3·2-6·4	Atmospheric water vapour
Backscatter Ultraviolet Spectrometer (BUV)	0·25-0·34	Atmospheric ozone distribution
Image Dissector Camera System (IDCS)	0·45-0·65	Daytime cloud mapping
Interrogation, Recording, Location System (IRLS)	—	Data collection from platforms

Taken from Nimbus IV User's Guide published by NASA, March 1970

six and Nimbus 4 nine experiments and Nimbus 5 will carry 15. The list of meteorological experiments on Nimbus 4 is given in Table 1.

3. Technological requirements

The need for continuous earth orientation implies the precise stabilization of satellite radiation sensors with respect of the centre of the earth. It is this stabilization requirement, with an accuracy of $\pm 1°$ in all three axes, which is partially responsible for the complexity and expense of meteorological remote sensing satellites.

The orbital characteristics of remote sensing spacecraft are determined by the requirements of geography and temporal coverage as well as by the

limitations in the sensitivity and response time of the sensors. Geosynchronous orbits are best for the study of mesoscale meteorological systems where continuous coverage on the shortest possible time scale is required. The very great distance of the satellite from the earth requires sensors with high energy-gathering power and only sensors, operating in the visible part of the spectrum provide the spatial resolution of the few km required. The sensitivity of radiometric sensors is limited by their angular field of view, the diameter of the radiation gathering apparatus and the dwell time of the detectors on each viewed element. Radiometric sensors of great absolute accuracy in narrow spectral intervals in the longwave infrared cannot yet be accommodated on geosynchronous spacecraft. So, for any global observation system for total coverage using quantitative, spectrometric remote sensors at long wave lengths, both low altitude earth orbiting satellites in high inclination orbits covering the entire earth in 12 hours as well as geosynchronous satellites will be necessary.

The main advantage of the earth imaging satellites is the high spatial resolution of the images given by the television cameras. A Nimbus television camera can give a resolution of a fraction of a km on the surface of the earth. The spectral resolution of scanning radiometers used for imaging of quantitative radiation intensities depends largely on the spectral band used and is limited by the minimum acceptance angle of the detector for a given radiometric accuracy and an instrument of a given size and scanning speed. In the visible range, very high spatial resolution is possible and in the infrared near 4μ and 11μ, the possible angular resolution of $0·5°$ permit continuous global mapping of cloud formation and earth surface and cloud top temperatures with a spatial resolution of 5 to 10 km and a radiometric accuracy of 1 to 2 °K. In other atmospheric windows $6·3\mu$, 15μ and $19-23\mu$, maximum angular resolution for global mapping of average moisture or temperature patterns is $1°$, corresponding to about 20 km on the surface of the earth from an altitude of 1500 km. In the microwave window at wavelengths larger than $1·6$ cm, the best achievable angular resolution is 3 to 5°, which corresponds to 50 to 80 km.

In order to relate measured radiation quantities to meteorological parameters uniquely, (1) the spacecraft sensory systems must have the necessary accuracy, resolution, calibration and geographical coverage for the measurements and (2) theoretical or empirical models must be available which permit rigorous analytical derivation of meteorological parameters from the radiation measurements. While satellite instrumentation is sufficiently advanced to satisfy the first condition,

TABLE 2

Parameters defining the state of the atmosphere

Parameters	Method	Resolution and accuracy	Qualifications
Atmospheric temperature and water vapour	(a) Infrared spectrometry	Complete profiles $\pm$ 2°C or $\pm$ 10 per cent R.H. Spatial resolution 100-200 km	Above dense cloud tops, to surface in clear areas, perhaps to surface in areas 50% or less cloudy
	(b) Microwave spectrometry	Do.	Surface emissivity and cloud transparency problems not resolved
Pressure, Density	(a) Refraction of visible star light	Complete profile $\pm$1%	Above cloud tops and haze only Nighttime only
	(b) Radio occultation	Perhaps better than $\pm$1%	Severe systems requirements: multisatellites, high tracking accuracy
	(c) Absorption by gases	—	
Winds	(a) Inference from cloud and moisture patterns	Coarse $\pm$ 20m/sec $\pm$ 20° Better from ATS cloud picture	Restricted to altitudes and locations where appropriate cloud patterns exist
	(b) Inference from ocean wave patterns (radar)	Very coarse	Near Surface winds over oceans only
	(c) IRLS, GHOST, EOLE *in-situ* devices	—	
Surface temperature	Infared scanning radiometry and spectrometry	Temperature $\pm$1°C Spatial 10 × 10 km	Cloud tops only — spatial resolution and frequency of observation depends largely on satellite system characteristics, capacity of data storage number and height of satellites
Cloudiness	TV imaging and radiometric scanning, AVCS, APT, IDCS, HRIR, manned spacecraft	1 × 1 km day 10 × 10 km night (can be improved)	
Precipitation	Scanning microwave	50 × 50 km	Depends strongly on underlying surface, may be feasible over oceans only
Radiation Balance	Radiometry, IR and visible	5 × 5 km or coarser	Top of the atmosphere only
Ozone	(a) UV spectrometry	$\pm$ 20 % above 15 km Very coarse height resolution	Sunset and sunrise only
	(b) Backscatter	Complete profile $\pm$5% above 15 km	Depends on reflectance of underlying surface
	(c) Infrared spectrometry	Very coarse height resolution Spatial resolution about 200 × 200 km (all methods)	Depends strongly on underlying surface above cloud and haze only (all methods)
Sferic	(a) Radio emission	Thunderstorm counts with very coarse directional resolution	
	(b) Visible lightning detection	Thunderstorm counts with higher directional resolution than radio method	

problems regarding the second seriously limit the usefulness of satellite radiation measurements.

4. Meteorological parameters

The parameters defining the state of the atmosphere and the methods used to derive the parameters are given in Table 2.

4.1. *Atmospheric temperature*

It was King in 1958 and Kaplan in 1959 who first pointed out that the temperature structure of the atmosphere can be inferred from the measurements of the earth's radiance in the CO_2 absorption band centred at 15μ. Techniques of obtaining the vertical profiles of temperatures have since been developed from measurements of the upwelling infrared radiation and are now well established. Computed mean temperature errors range from 1 to 2°K. Two alternative systems have been developed by NASA and ESSA. The Infrared Interferometer Spectrometer (IRIS) developed by Hanel at the Goddard Space Flight Centre continuously samples the spectrum of the earth's radiation between

5-20μ to determine the amount of ozone and water vapour and to infer the vertical profile of temperature in the atmosphere. The Satellite Infrared Spectrometer (SIRS) developed by Wark and Hilleary at the National Environmental Satellite Centre (1960, 1966) measures the infrared energy radiated by the atmosphere in 7 channels in the 15μ absorption band of CO_2 to give temperatures at various levels in the atmosphere. Both have given comparable data. SIRS also senses the cloud top temperatures with an eight channel and in the absence of clouds the surface temperatures. IRIS failed on 23 July 1969.

The derived soundings in their quality and accuracy are comparable to those from the conventional radiosonde and at higher levels in the stratosphere more accurate. Two methods are used to derive temperature profiles from measured radiation values. With the least-squares regression method developed by Smith and Woolf (1969) good agreement is found at all levels from surface to 10 mb, including the troposphere. But the results are not satisfactory in areas where no radiosonde data are available. The direct method, using climatological mean data from radiosonde and rocketsonde measurements are carbon dioxide transmittance functions give profiles too warm by 2-3°C in the middle and upper troposphere. Somewhat larger errors are introduced near the surface over hot land areas in the daytime. Both errors are caused by errors in the transmittance function for CO_2 and water vapour. By empirical corrections to the theoretically derived transmittance functions, it has recently been possible to eliminate both these errors. In the stratosphere, the data are degraded possibly because of the poor quality of radiosonde data resulting from solar and thermal radiation effects on radiosondes.

The main drawbacks in the vertical sounding of temperature from satellites are (1) below clouds, which are larger than the viewing aperture, the satellite is blind, simulated clear air soundings have to be used to correct for them; (2) the soundings represent a mean value over a large area; SIRS measures radiance over a 225 km square area and during the 8 seconds of sampling the spacecraft travels about 50 km; (3) over the tropics, the accuracy will be least due to increased moisture and haze. Temperature changes in the lower troposphere in the tropics are also so subtle that satellite soundings in the lower tropical troposphere may be of little value. The need for accurate radiosondes therefore remains.

More than 90 per cent of the SIRS soundings now requires some adjustment because of clouds. Future instruments will have a small field of view of about 50 km square and will greatly increase the number of soundings in clear-air regions. Considerably more study and development are required to improve the techniques of retrieving temperature from radiation measurements and to perfect methods for incorporating them effectively and on a real-time basis in numerical weather analysis and forecast routines. When the atmospheric transmittance functions become better known, the direct method will eventually replace the regression method.

4.2. Surface temperature

The techniques of measuring surface temperature remotely is well-established. But small uncertainties exist in the emissivity of the sea surface and in correcting for optically active gases and particulates in the atmosphere. It does not appear possible at present to reduce the errors to the value 0·25° required for air-sea interaction studies.

4.3. Water vapour

From simultaneous measurements of radiation up-welling within different spectral ranges of deficient absorptivity of water vapour, a vertical profile can be determined if the temperature profile is known. The method developed for determination of temperature profile can be applied to the inference of water vapour content and distribution.

Water vapour has several absorption bands in the near infrared (1·2—4 μ), middle infrared (6·3 μ) and for infrared ($>$18 μ), with lines extending into the microwave region (1·35 cm). All these lines and bands possess sufficient strength to measure water vapour content and distribution in the troposphere.

But all particles in the atmosphere (water droplets, ice crystals, aerosols) scatter, absorb and emit radiation at these wavelengths and accurate interpretation of infrared measurements is possible only in the clean atmosphere above cloud surface.

In the microwave region the effect of particles on droplets of thin, non-precipitating clouds is small but in either case the emittance measurement in the water vapour band must be accompanied by measurements in a spectrally adjacent window to account for the radiance from the surface underlying the atmospheric water vapour. It is assumed that the emissivity of the surface is the same in the water vapour and window regions. Since this assumption is not known to be valid in the microwave region, and because of the large emissivity of land surfaces and because of the relative transparency of the 1·35 cm water vapour line, microwave measurements of water vapour are likely only over the oceans.

The 6·5 to 7·0 μ band of the MRIR covering the 6·7 μ water vapour absorption and the 20 to 23 μ band provides information on water vapour distribution in the upper and lower troposphere.

Measurements of the global distribution of water vapour have been made since Tiros was launched in 1960, from infrared radiation measurements in the water-vapour bands from small, medium and high resolution infrared radiometers. New sensors used on Nimbus-4 and planned for future missions for temperature and humidity measurements are :

(1) The Temperature Humidity Infrared Radiometer (THIR) to measure infrared radiation in two narrow bands 10-12 μ and at 6·3 μ to furnish surface or cloud top temperatures,

(2) SIRS-B, to measure infrared radiation emitted by CO_2 and H_2O and by the surface and cloud tops in narrow spectral channels in the 15 μ CO_2, 18-36 μ H_2O rotation bands between 18-36 μ and 11·1μ window to obtain vertical profiles of temperature and humidity,

(3) IRIS, similar to SIRS-B to measure the intensity of the earth's spectral radiance in the continuous wavelength interval 8-40 μ, in the 15 μ CO_2 band for temperature, profile in the 10-11 μ bands for surface and cloud top temperatures, 20-40 μ H_2O band for water vapour profile and in the 8-10 μ O_3 absorption band for ozone determination;

(4) Filter Wedge Spectrometer (FWS) to measure water vapour profile from the 3·7 μ radiation;

(5) Selective Chopper Radiometer (SCR) to measure the vertical temperature profile to 50 km water vapour distribution and cloud cover;

(6) Microwave Spectrometer (MWS) to measure atmospheric temperature at 3 levels and liquid water and water vapour in troposphere; and

(7) Electrically Sensing Microwave Radiometer (ESMR) to measure liquid water content, and the thickness and water content of clouds.

4.4. *Pressure/Density*

There seems to be no immediate prospect of measuring pressure directly from satellites. Direct methods under study are refraction of stellar images, refraction of microwaves and absorption of laser or reflected sunlight by molecular constituents. The indirect method is to derive pressure and density from thermal profiles.

By measuring the amount of refraction of visible starlight viewed during occultation from a satellite can provide a density profile but the technique will operate only at night and above cloud tops and haze. The radio occultation method would eliminate difficulties due to clouds and is a "natural", as it gives volume samples 1 km × 1 km and can probably detect small density gradients in the tropics.

4.5. *Winds*

No method has been developed to measure winds precisely and directly by remote sensing. Wind fields may, however, be derived from other remotely measured parameters, such as jet streams, cells and eddies, mountain waves, cirrus streams, tropical cyclones and cloud lines, ice and lithometeors. Estimation of high level winds from individual pictures of thunderstorms and high and low level winds from ATS cloud pictures is now routine. The main limitation of the method is that clouds must exist at the required level and in the required location. In addition, the clouds must move with the wind. The spin-can camera on ATS satellite has made it possible to measure cloud displacement with considerable precision but much remains to be done.

4.6. *Precipitation*

Precipitation can be inferred from radiation measurements by various methods. Since all precipitation is accompanied by clouds, it is important to operate at a wavelength where clouds can be penetrated or where precipitating clouds can be distinguished from non-precipitating clouds. This is possible at wave-lengths longer than 1·6 cm. A multi-channel scanning microwave radiometer operating between 1-2 cm could provide maps of the existence and horizontal extent of precipitation areas. The Microwave Spectrometer (MWS) and the Electrically Scanning Microwave Radiometer (ESMR) will measure liquid water content and provide information on ice and water clouds, thickness and water content of clouds, areas of precipitation and morphology of ice cover. Over water a qualitative indication of the amount of rainfall as well as a measurement of the vertically integrated moisture field can be obtained.

4.7. *Radiation balance*

The radiation balance is the meteorological parameter that was first measured from a meteorological satellite and the present sophisticated radiometers can measure radiation emitted

by the earth and atmosphere with a radiometric accuracy of better than one per cent at an angular resolution of better than one degree. While there is not much difficulty in correlating the spectrally and angularly restricted radiation measurements in the 4-30 μ region to the total emitted flux, there is still considerable difficulty in deriving accurate values of the total reflected solar radiation from narrow beam measurements. The solar constant has been measured with an accuracy of 2 per cent. Satellite measurements of solar flux are now possible from sun-oriented spacecraft or earth-oriented satellites, by radiometric scanning of the sun. Nimbus already has this facility for monitoring the sun for about 20 minutes during each orbit in the range 1700-3000 Å. Present instrumental accuracies, spatial resolutions and reliability in the analytical models permit the combination of terrestrial and absorbed solar radiation to give the distribution of net energy in the earth-atmosphere system on a planetary scale.

4.8. *Ozone*

Ozone concentrations can be determined by any one of the following three methods —

(1) the occultation technique, by measuring the absorption of direct radiation (solar, lunar, stellar) as it passes through the atmosphere from the source to the satellite.

(2) by measuring the absorption by ozone in radiation scattered upwards by the earth's atmosphere, and

(3) by measuring long-wave radiation emitted by ozone.

The occultation technique has been successfully carried out, by observing the whole solar disc from a spinning satellite in ultra-violet wavelengths in the Hartley band to give ozone concentrations down to 30 km. Using visible radiation in the Chappuis bands measurement to an accuracy of 10 per cent down to 15 km are possible. The second technique is similar to SIRS and uses 10-15 wavelengths between 2500 to 3500 Å to give the total ozone content and its vertical profile.

4.9. *Sferics*

The probable locations of thunderstorms can often be identified even in overcast areas by computer enhancement methods. Nimbus satellites are being used to carry out an experiment for the location of atmospherics due to thunderstorm activity.

The techniques naturally suggested are radio emission and visible lightning detection to give thunderstorm counts with fairly satisfactory direction resolution.

During the past several years, many techniques have been suggested for the detection of sferics from earth orbiting satellites. Ground-based and airborne experiments indicate that there is adequate power in UHF sferics for detection at satellite altitudes. UHF is preferred because the ionosphere is transparent to it and the associated antenna are smaller. The experiments proposed are field strength experiments or mapping experiments. In addition to a measure of the field strength, the first will give a rough mapping of thunderstorm activity along the path of the satellite. The second will provide a mapping of thunderstorm activity within an area comparable to that viewed by a TV picture, with a spatial resolution of about 50 km, using interferometers with an angular resolution of 2-3°.

Sferics measurements can thus give the global distribution of thunderstorm activity and the intensity of thermal convection of great importance in the tropics. This is based on the fact that the frequency of occurrence of UHF noise pulses seems to be related to the vertical rate of cloud development.

5. Conclusion

The development of satellite techniques for the measurement of meteorological parameters during the last ten years has been spectacular. While early meteorological satellites proved that systematic remote sensing of meteorological parameters on a global scale is feasible, recent achievements have shown that they can measure the vertical temperature structure of the lower stratosphere and troposphere above cloud tops, the vertical distribution of water vapour in the troposphere above clouds, global measurements of the total amount and vertical distribution of ozone in the stratosphere, the intensity and frequency of electrical emissions from thunderstorms and convective cells and the exact balance of radiative flux at the top of the atmosphere. Remote sensing techniques have thus developed in three distinct phases; first the observation of cloud formations from low altitudes and from geosynchronous altitudes, second, the observations of atmospheric temperature, humidity and ozone above cloud level, and third unlimited observation of density and pressure as well as temperature, humidity, ozone etc. Development of techniques for the measurement of temperature, ozone and water vapour profiles even in the presence of thin clouds, of precipitation patterns with microwave techniques and of density and pressure distributions in the troposphere should give us unlimited continuous observations of all main parameters on a global scale. There is, however, no expectation of obtaining direct measurements of the wind field by remote sensing in the foreseeable future. Wind fields must be

inferred indirectly from cloud observations or be derived from the density, pressure and tempera- ture profiles or obtained by tracking platforms in the atmosphere.

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DISCUSSION

Prof. K.R. Ramanathan remarked that this method of evaluating the temperature profile is similar to the method of estimating ozone. This is better as Raleigh scattering is less. However, temperature profile below clouds cannot be determined.

Gr. Capt. S. Das Sarma : Would the errors of temperatures at SST flying levels be within the tolerance limits of $\pm 1°C$?

Miss A. Mani : Yes.