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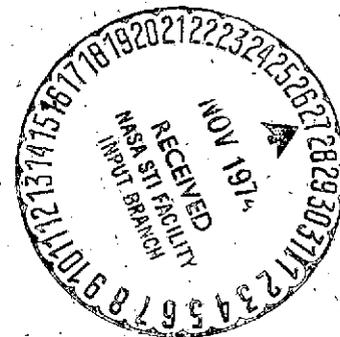
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NOVEMBER 1974



————— **GODDARD SPACE FLIGHT CENTER** —————
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METEOROLOGICAL
SATELLITE ACCOMPLISHMENTS

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W. E. Shenk, and R. Wexler

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TABLE OF CONTENTS

	<u>Page</u>
INTRODUCTION	1
SATELLITES	6
VERTICAL SOUNDING	7
Experimental Satellite Soundings	7
Operational Soundings	11
Retrieval Methods	13
PARAMETER EXTRACTION TECHNIQUE DEVELOPMENT	15
Wind	15
Cloud Parameter Measurement	17
MACROSCALE PHENOMENA	19
General Circulation Studies	19
Extratropical Circulations	21
Tropical Circulations	22
MESOSCALE PHENOMENA	23
Thunderstorms	23
Dust Storms	25
Lake Effects on Cloudiness	25
Fog	26
Terminal Weather Forecasts	26

TABLE OF CONTENTS (Continued)

	<u>Page</u>
HEAT BUDGET OF THE EARTH-ATMOSPHERE SYSTEM AND CLIMATE	26
OCEAN SURFACE AND HYDROLOGY	30
METEOROLOGICAL SATELLITES	34
BIBLIOGRAPHY	37

METEOROLOGICAL
SATELLITE ACCOMPLISHMENTS

INTRODUCTION

The year 1975 marks the fifteenth anniversary of the U. S. meteorological satellite program, which began on April 1, 1960 when the TIROS 1 experimental satellite was launched. Television pictures taken by the spinning TIROS 1, in a near-Earth, non-sun-synchronous orbit, were often oblique and poorly illuminated. Nevertheless, they showed the organization of weather systems with a clarity never before seen and revealed phenomena that previously were unknown. Within a few days of the launch of TIROS 1 the new data were being used operationally to improve weather services (NESS, 1971). At the same time extensive research was carried out to increase our knowledge of the atmosphere and to develop techniques to utilize the new type of data.

In the ensuing years the meteorological satellite program progressed rapidly. Many new types of instruments were developed, e. g., improved camera systems, wide field radiometers, scanning radiometers, quantitative atmospheric sounders, instruments to monitor solar ultraviolet radiation, data collection and platform location systems, data collection and relay systems, and instruments to monitor solar proton and electron fluxes near the Earth. Many instruments contained multispectral bands and remotely sensed over a broad range of frequencies, including the near and far ultraviolet, visible, near and far infrared, and microwave parts of the electromagnetic spectrum. Two basic types of orbits

emerged, viz., (1) polar orbits (sun-synchronous, near-Earth), and (2) geostationary orbits (35,800 km above the equator). Also, two categories of satellites were identified, viz., (1) experimental satellites (operated by the National Aeronautics and Space Administration), and (2) operational satellites (operated by the National Oceanic and Atmospheric Administration).

The Operational system currently provides the following basic services:

- pictures of the entire globe, day and night, every day;
- continuous viewing of the Americas and adjacent oceans, day and night;
- temperature measurements throughout the world, and wind measurements in selected parts of the Atlantic and Pacific Oceans.

Direct-readout images, both in the visible and infrared, are transmitted directly from the NOAA operational satellites and are available to all nations throughout the world (NESS, 1973). These are used in preparing regional weather forecasts of all types, sea ice advisories, and numerous other service products. The Scanning Radiometers (SR) on the NOAA satellites provide the data utilized by the direct automatic picture transmission (APT) service to provide instant weather information, both day and night, in the vicinity of local readout stations. The ground equipment required to receive these images is relatively inexpensive and is used by many countries throughout the world. The Very High Resolution Radiometer (VHRR), having two channels (visible and infrared window) yielding imagery with a resolution of 0.9 km (0.5 n. mi), flew

for the first time on NOAA 2. In addition to a storage capability on the satellite, the VHRR also provides the high-resolution picture transmission service that broadcasts high-resolution imagery to local stations with appropriate equipment for receiving these images. However, the equipment is about 10 times higher in cost than equipment for the APT service from SR (Department of Commerce, et al. 1974).

NOAA 2 was the first operational satellite to include a vertical temperature profile radiometer (VTPR) system, which provides the capability for sounding the atmosphere twice daily from 30 km down to the Earth's surface or to the top of any extensive cloud layer, on a global basis. This system evolved from the initial sounding systems flown on the experimental Nimbus 3 and 4 satellites in 1969 and 1970 (Fritz, et al., 1971). The VTPR on the NOAA 3 satellite for the first time transmitted sounding radiances continuously to provide instant vertical temperature profile and humidity sounding information to local stations around the world that are equipped to receive and process these data.

The World Meteorological Center in Washington uses satellite imagery, temperature soundings, and wind measurements to improve the accuracy of large-scale weather analyses and prognostic charts. These charts are transmitted via facsimile to all U. S. weather stations, both civil and military, and are used as basic guidance material for all weather forecasts. Air Force and Navy weather centrals use the satellite data in much the same way (NESS, 1971). High resolution (0.6 km or 1/3 n. mi.) visible and infrared imagery obtained by

the Defense Meteorological Satellite Program (DMSP), formerly called the Data Acquisition and Processing Program (DAPP), as well as vertical soundings, are now available and complement the NOAA Satellite data (Meyer, 1973; Blankenship and Savage, 1974; Department of Commerce, et al., 1974). U. S. Air Force Weather Service satellites have further demonstrated the capability of monitoring auroral activity on a world wide basis (Rogers et al., 1974). Methods of utilizing satellite data operationally have been discussed by Anderson, et al., (1969, 1971, 1973).

Data from experimental satellites, in addition to NOAA satellites, are also being used operationally. Movie loops from NASA's geostationary satellites ATS-3 (Applications Technology Satellite) and SMS 1 (Synchronous Meteorological Satellite—operational prototype) provide wind velocities daily at two or more levels over the Atlantic Ocean for use in numerical weather predictions. ATS 1 provided similar information over the Pacific Ocean until October 1972 when its picture capability was lost. SMS B, scheduled to be launched in early 1975, will be placed over the Pacific Ocean to provide such data. Subsequent satellites of this type to be operated by NOAA will be called GOES (Geostationary Operational Environmental Satellite). The SMS/GOES satellites, in addition to providing nearly continuous visible and infrared imaging, provide a data collection and relay capability, including weather maps and satellite pictures, for most of the Western Hemisphere except for the polar regions (Department of Commerce, et al., 1974). Immediately after its launch, SMS 1 was positioned over

Latitude 45° W and contributed to the GARP Atlantic Tropical Experiment (GATE), a major experiment of the Global Atmospheric Research Program (GARP).

The Electrically Scanning Microwave Radiometer (ESMR) on the NASA experimental satellite Nimbus 5 senses passive microwave radiation at a wavelength of 1.55 cm. One application of ESMR is to map the extent of sea ice even through the persistent cloud cover of polar regions. The U. S. Navy Fleet Weather Facility uses the Nimbus 5 ESMR data operationally in preparing daily maps of sea ice for dissemination to naval and civilian maritime users (Gloersen, 1974).

The NEMS (Nimbus E Microwave Sounder) flown on Nimbus 5 has demonstrated its ability to sound temperature profiles through clouds. Moreover, the combined data from NEMS and an infrared sounder flown on Nimbus 5 (the Infrared Temperature Profile Radiometer -- ITPR) have been shown to produce better soundings than either data set alone can produce for use in numerical prediction models.

Based on this research, a combined infrared-microwave sounder is planned for the operational prototype satellite TIROS N. This satellite is scheduled to be launched in 1977 as a key part of the international satellite observing system in support of the First GARP Global Experiment (FGGE).

The French Eole satellite, launched on August 16, 1971 by a U. S. Scout rocket as part of a cooperative program, demonstrated the feasibility of tracking and collecting data from a large fleet of free-floating balloons, i. e.,

500 superpressure balloons floating at 200 mb over the Southern Hemisphere (Morel and Bandeen, 1973). Based upon the success of the Eole Project, a data collection and platform location system is planned for the TIROS N and follow-on satellites as a continuing facility for many different users.

SATELLITES

The satellites launched prior to December 1970 were listed by Fritz, et al., (1971), Widger (1967), and Fritz (1963). The satellites launched since December 1970 are listed in this article before the Bibliography. The NOAA satellites are used in daily operations. The Nimbus satellites serve as platforms for new experiments. Further details about them may be found in the Nimbus User's Guides (Goddard Space Flight Center, 1972).

SMS 1 is a prototype of future Geostationary Operational Environmental Satellites (GOES). NASA's ATS 6 is a three-axis-stabilized communications satellite in a geostationary orbit. However, it carries a two-channel (visible and infrared) radiometer that is used for mesoscale and severe storms research.

Although they are not listed in this article as meteorological satellites, the Earth Resources Technology Satellite (ERTS) and Skylab are mentioned briefly. ERTS 1, launched on July 23, 1972, carried very high resolution, multispectral imaging sensors intended for observations of the Earth's surface. However, some interesting results relevant to meteorology have been obtained. For example, Lyons and Pease (1973) have shown that it was possible to detect the long-range (over 50 km) transport of suspected particulate plumes from

steel mills over Lake Michigan and Bowden et al. (1974) have analyzed local atmospheric dynamics associated with a Santa Ana wind condition using ERTS 1 imagery. Also, Otterman (1974) has reported observations in the Sinai-Negev region by ERTS 1 supporting a hypothesized climatic desertification mechanism resulting from the overgrazing of animals. The Skylab unmanned Saturn Workshop was launched on May 14, 1973. Three manned missions were subsequently launched for rendezvous with the Saturn Workshop. Skylab carried an Earth Resources Experiment Package (EREP) consisting of sensors designed primarily for Earth resources survey and oceanography. However, one system, an active-passive radiometer-scatterometer (RADSCAT), obtained measurements of air-sea boundary phenomena of particular relevance to meteorology. For example Moore, et al. (1974) have shown that surface winds over the ocean can be determined to within an rms error of about 2.8 knots from the radar backscatter measurements.

VERTICAL SOUNDING

Experimental Satellite Soundings. The most significant advance in vertical sounding from satellites during the past quadrennium has been the successful use of microwave radiance measurements to determine the vertical temperature profile, total water vapor content, and total liquid water content of the atmosphere. The instrument, NEMS (Nimbus E Microwave Sounder), was flown on Nimbus 5 with a fixed field of view along the nadir and is described in the Nimbus 5 User's

Guide (Staelin et al., 1972). Preliminary results have been reported by Staelin et al. (1973).

The main advantage of the microwave sounder is its ability to sound the atmosphere under all cloud conditions (Staelin et al., 1975). Ice clouds are completely transparent to radiation between 50 and 60 GHz and liquid water clouds have only slight opacity at those frequencies. Except for very thick stratus or during severe storms, the effect of clouds can be neglected. The only weakness in microwave sounding is the variable emissivity of the surface, which limits the accuracy of the retrieved temperature between 1000 and 850 mb (Smith et al., 1974c).

The Nimbus 5 satellite included two other sounders: ITPR, an infrared temperature profile radiometer, and SCR, a selective chopper radiometer, which is an improved version of the one flown on Nimbus 4. Both instruments are described in the Nimbus 5 User's Guide (Smith et al., 1972; Houghton and Smith, 1972). Additional description and some preliminary results have been reported for the ITPR by Smith et al. (1974a) and for the SCR by Barnett et al. (1972) and Ellis et al. (1973).

ITPR differs from the infrared sounders flown previously on Nimbus 3 and 4 in having high spatial resolution (35 km field of view

at nadir), a scanning mirror, and two window channels (3.7 and 11 micrometers). The two window channels, at widely differing wave numbers, make it possible to detect clouds in a single field of view and, by analyzing data in a pair of adjacent fields of view, to obtain both the surface temperature and the effective cloud amount (Smith and Rao, 1972).

The SCR uses CO₂ gas filled cells as additional filters. By subtracting signals through the gas filled cells from signals through an empty cell, a radiance is obtained which corresponds to a weighting function that peaks high in the stratosphere. The instrument includes several CO₂ gas cells at different pressures, yielding weighting functions that extend to 1 mb.

Smith et al. (1974b) have developed a data processing system which amalgamates the data from the three Nimbus 5 instruments and produces a composite vertical sounding. The SCR covers the upper stratosphere while ITPR and NEMS complement each other in covering the troposphere and lower stratosphere. The temperatures retrieved from the amalgamated system were found to be more accurate than from any instrument alone (Smith et al., 1974c).

Sounders developed for the soon-to-be-launched Nimbus F satellite include a scanning microwave sounder (SCAMS), a high resolution

infrared radiation sounder (HIRS), a pressure modulated radiometer (PMR), and a limb radiance inversion radiometer (LRIR).

HIRS differs from TTPR in using cooled detectors to improve responsivity and a double set of sounding channels, one at 15 micrometers and one at 4.3 micrometers. Sounding at 4.3 micrometers is expected to improve the vertical resolution in the lower troposphere. A further use of the two sets of weighting functions, at widely separated wave numbers, is the application of a more effective method for eliminating the effects of clouds at various levels (Chahine, 1974). In principle, it is analogous to the use of the two window channels (at 3.7 and 11 micrometers) in TTPR to detect clouds and solve for the cloud effects on other channels.

SCAMS is essentially a scanning version of NEMS and consequently will increase the coverage of soundings in the presence of extensive cloud cover. By overlapping the coverage of the HIRS sounder, the microwave measurements can be used in combination with the infrared measurements to eliminate the effects of clouds on the infrared.

PMR, like the SCR, uses CO₂ gas filled cells to obtain weighting functions that peak high in the stratosphere and mesosphere. However, instead of differencing signals that proceed along separate optical paths, as in the SCR, there is only a single path through a gas cell in which

the pressure is modulated, thus yielding an AC signal representing the difference in signal between the extreme CO₂ gas cell pressures (Curtis et al., 1974). The PMR avoids the spurious signals that may originate in the SCR from a lack of balance between the two optical paths.

LRIR provides high vertical resolution (but poor horizontal resolution along the line of sight) by scanning the Earth's limb. Because of the effects of clouds and haze, it is virtually useless below about 15 km. In the stratosphere, however, it should provide details of the vertical structure that could not be resolved with downward looking sounders. The principles of this method have been described by Gille and House (1971).

Each of the above methods for obtaining vertical soundings of the atmosphere from satellites has unique features and often the methods complement one another. The physical concepts of these methods have been reviewed by Smith (1972).

Operational Soundings. In moving from the realm of experiment to an operational system, the remote sounding of the atmosphere from satellites has demonstrated the utility as well as the limitations of present day techniques (Fritz, et al., 1972). The current operational instrument, VTPR, has flown on the NOAA 2 and 3 satellites and will continue to serve as the operational sounder until its replacement by a third generation system, TOVS, in 1977. The VTPR data are processed by the NOAA National Environmental Satellite Service, yielding temperature and water vapor profiles over the sea-covered

areas of the globe, on a 600 km scale, at least once per day since its inception in October 1972 (McMillin, et al., 1973).

Comparison of satellite retrieved temperature profiles with radiosonde data reveal RMS differences ranging from 1.5 to 4.0° C between 10 mb and the surface, compared with differences between adjacent pairs of radiosondes ranging from 1.5 to 2.5° C. (The tendency for satellite temperature retrieval errors to be systematic over large areas (Tarakanova, 1974), may have a mitigating effect on the errors introduced when inserted into numerical forecast models.) The largest differences between satellite and radiosonde temperatures occur around the tropopause and near the surface; the smallest differences are in the middle troposphere. A comprehensive analysis of the VTPR data and the results of an extensive research effort to improve the quality and accuracy of the retrievals are contained in a report under preparation by Fleming et al. (1975).

To eliminate or reduce systematic errors associated with instrument degradation, uncertain knowledge of the atmospheric transmission functions, and any systematic bias associated with the retrieval method itself, it is a part of some methods to periodically apply empirical corrections to the radiance measurements and/or the parameters of the retrieval algorithm (Jastrow and Halem, 1973; Smith et al., 1974b; Weinreb and Fleming, 1974). The empirical corrections aim to reduce the mean differences between satellite retrieved temperatures and the radiosonde measurements.

Retrieval Methods. The fundamental limitation to atmospheric sounding by passive measurement of thermal radiation above the atmosphere is the poor vertical resolution of the sounding (Conrath, 1972; Chow, 1975). The satellite measured radiances provide practically no information on fine structure in the vertical profile smaller than 5 or 6 kilometers. The fine structure that does show up in a retrieval (e.g., in the vicinity of the tropopause) is basically the structure contained in the initial guess (Hogan and Grossman, 1972; Strand, 1973). In principle, one could circumvent this fundamental limitation on vertical resolution by increasing the number of channels and decreasing measurement noise, but this would require accuracy in the transmission functions well beyond what one can hope to obtain with our uncertain knowledge of the concentrations of minor gaseous constituents of the atmosphere and the variability of the aerosol component. The uncertain knowledge of atmospheric composition at any given time and place, coupled with our imperfect understanding of molecular transitions and line broadening, places severe limits on the accuracy of calculated transmission functions (Stowe, 1974). This limits the number of independent channels and hence the vertical resolution. (A comprehensive compilation of line parameters for atmospheric transmission function calculations has been made available by McClatchey et al., 1973.)

The degree of success that is achieved in inverting radiances to obtain temperature profiles is due in large measure to the consistent behavior of the atmosphere in any given season and latitudinal zone. Atmospheric temperatures

vary from place to place and day to day but there is a remarkable similarity of structure. Information on the "expected" vertical profile (e.g., a forecast or a climatological mean) or statistical information (e.g., mean temperatures and covariances, which include information on vertical correlations) is often part of the input, along with the measured radiances, in the retrieval program. The "expected" profile is used as an initial guess in iterative methods of inversion, or as a reference profile from which deviations are calculated by direct inversion. Statistical information enters in either of two forms that are equivalent in principle: (1) a set of regression coefficients which empirically relate temperature at a particular height to the set of measured radiances; or (2) the use of an inverse operator that depends upon the covariances. Various inversion methods described in the literature have been reviewed and compared by Fleming and Smith (1972), Conrath and Revah, (1972), and Rodgers (1972). No method stands out as being superior to the others under all circumstances. Each has advantages and disadvantages. Statistical methods use little computer time and produce good results where reliable statistical information is available and the atmosphere tends to be consistent. Iterative methods work well where reasonably good forecasts are available. The use of a statistical solution as the initial guess in an iterative scheme has also proved successful (Smith et al., 1974a and 1974b).

A procedure for evaluating the usefulness of satellite retrieved temperatures, in terms of their information content, was applied to the Nimbus 4 SIRS-B

data by Brodrick and Hayden (1972). Their results show definite usefulness at 200 mb and moderate usefulness at 300 and 500 mb for conditions of no clouds, or small amounts of clouds.

PARAMETER EXTRACTION TECHNIQUE DEVELOPMENT

Wind. Considerable progress has been made in measuring cloud displacement from a series of geosynchronous satellite images. Once a level is assigned to the displacements, a wind vector is obtained. These vectors are now being derived operationally by NOAA and inserted into numerical models.

Hubert and Whitney (1971), comparing rawinsonde reports with cloud motions, found that cumulus cloud vectors over water corresponded equally well with the 0.9 km and 1.6 km rawins and cirrus clouds over land and water compared best with the 9 km winds. The median vector deviation of the winds from the cloud motions was 4 and 8 m/sec at 0.9 and 9 km, respectively. Wiegman, et al., (1971) found a 4.5 m/sec vector difference between cirrus motions associated with jet streams and the rawinsonde winds at the level of the minimum vector difference between the two data sources. From simultaneous aircraft cloud tracking and wind measurements of cumulus ensembles over tropical waters, Shenk et al. (1974) have reported a vector deviation of 1 m/sec between the cloud movement and the wind at about 950 mb (cloud base). Vector differences of 3-4 m/sec were found at the cloud center (typically near 800 mb) and the top (generally 650 mb). Hubert (1974) has suggested 1-2 m/sec vector differences between cloud motions and 850 mb rawins based on independent analyses

of the measurements from each source. For a case study using sequential airplane photographs near Springfield, Missouri Fujita, et al. (1973) found that the best comparison between cumulus cloud motions and the wind was 300 m below the cloud base. Viezee, et al. (1972) compared vorticity determined from middle level cloud motions with concurrent NMC analyses and found a good correlation at 700 mb.

Other remote sensing methods besides cloud tracking have been suggested to obtain the winds. Sun glitter patterns viewed from a geosynchronous satellite have been used by Levanon (1971) to obtain surface wind velocities. Wind directions, accurate to $\pm 20^\circ$ at 400 mb, have been obtained from Nimbus 4 $6.7 \mu\text{m}$ imagery by Steranka et al. (1973). Endlich, et al. (1972) have proposed a method of measuring winds in cloud free areas with isentropic analyses of temperature and water vapor profiles. The thermal support for a jet streak was determined by Togstad and Horn (1974) from simulated temperature profiles. They also concluded that $0.05\text{--}0.1 \text{ ergs/cm}^2 \text{ sec sr cm}^{-1}$ radiance measurement accuracies gave far superior wind determination results than $0.25 \text{ ergs/cm}^2 \text{ sec sr cm}^{-1}$.

Numerous methods ranging from manual to almost fully automatic exist for the calculation of winds from cloud displacements. The key steps in the procedure are registration of an image series, cloud selection, calculation of cloud displacements, and the altitude assignment of the displacement. An objective two-step registration procedure has been developed by Endlich, et al.

(1971) where the initial coarse registration is done by matching the earth's disc and the more precise step involves landmark matching. Chang, et al. (1973) describe a method developed at the University of Chicago where the registration is done manually and the cloud displacements are calculated by a computer. Phillips and Smith (1972) describe a man-computer interactive wind extraction system (called WINDCO) that was used at the University of Wisconsin. All of the steps are objective with the exception of cloud selection. A second generation system, called the Man-Computer Interactive Data Access System (McIDAS) is now in use at Wisconsin. Leese et al. (1971a) described a technique where two dimensional cross correlation methods could be employed to calculate cloud displacements. This method, which tracks a pattern within a specified area, is now an important part of the NOAA procedure that derives winds from low clouds. It is completely objective except for a post editing step to remove motions that do not appear to represent the wind. Wolf, et al. (1973) describe a possible prototype wind extraction procedure for the Global Atmospheric Research Program (GARP). A unique feature of this system is a clustering program (called ISODATA) which isolates and tracks brightness centers.

Cloud Parameter Measurement. During the 1971-1974 period there has been an emphasis on the development of multispectral methods for cloud type identification. Lo and Johnson (1971) have combined Nimbus 2 Medium Resolution Infrared Radiometer (MRIR) 6.4-6.9 μm and 10-11 μm channels with bivariate frequency distribution methods to determine cloud type. A combination of

0.5-0.7 μm and 10.5-12.5 μm channels plus feature extraction procedures were successfully used by Booth (1973) to describe 8 cloud type categories. Shenk and Holub (1972) developed a four channel Nimbus 3 MRIR procedure for ocean areas that identifies ten cloud type categories.

Lo and Johnson (1971) estimated cloud cover from probability density distributions of the differences between the earth surface temperature and the corresponding Nimbus 2 10-11 μm channel equivalent blackbody temperature (T_{BB} 's). The effect that sensor spatial resolution has on estimating cloud amounts has been simulated by Shenk and Salomonson (1972a). For a sensor with infinite sensitivity they found that the ratio between the areal size of the cloud and the instantaneous field of view of an instrument had to be >1000 before the cloud amount estimates were within 10% of the true cloud amounts. Shenk (1971) generally verified these results with comparisons of ESSA-3 and ATS-3 images with concurrent high resolution Apollo 6 photographs. Park, et al. (1974) have demonstrated that brightness measurements can be used to estimate cloud type heights, especially for well developed cumulonimbus. Greaves (1973) developed a relationship between ground and satellite derived cloud amount frequency distributions. This relationship was used in a statistical modelling technique to describe global cloudiness. Koffler et al. (1973) have developed a 10.5-12.5 μm method of operationally estimating cloud type heights. Effective emissivities of cirrus clouds between 0.1-1.0 were determined by Davis, et al. (1973) when radiometrically determined cloud heights were compared with heights

representing the level of best fit between the cloud motion vectors and winds measured from rawinsondes. Shenk and Curran (1973) developed a method to determine cirrus cloud top temperatures where the 10-11 μm cirrus cloud emissivity was estimated from cloud brightness. Pichel (1973) described an artificial stereo technique which uses a 10.5-12.5 μm response as a spatial modulation signal to produce a stereo pair from a visible channel image. The infrared data in a second image is shifted accordingly. Shenk and Holub (1971) have performed stereographic analyses from image pairs of Apollo 6 photography.

MACROSCALE PHENOMENA

General Circulation Studies. During the autumn major cloud bands were observed by ESSA satellites to extend from North Pacific tropical storms to higher latitudes, from about 10° to 60° N. The bands are associated with tropospheric warming to the south and cooling to the north resulting in increasing zonal westerlies during and after cloud band formation. The bands are visual manifestations of energy injection from the tropics to middle latitudes, contributing to the autumnal buildup of circulation in the Northern Hemisphere (Ericksen and Winston 1972).

During February 1971 trade winds over the Pacific were strong with fast upper westerlies and well developed upper level troughs north and south of the equator. The ITCZ as observed by ATS-1 was weak over the Pacific and convection was largely confined to the three tropical continental areas. In contrast, during February 1969, the circulation was much weaker and the high

level mid-oceanic troughs were also weak. Tropical convection was more intense over the central and eastern Pacific. Dynamic instability in the subtropical jet may play an important part in regulating the intensity of the tropical circulation (Krueger and Winston 1974).

An analysis of GHOST and EOLE constant level balloons at 100 and 200 mb in the southern hemisphere show the following results: (1) There is a 30 cm sec⁻¹ poleward flow in winter-spring and an equatorward flow in summer-autumn; (2) During the west wind phase of the quasi-biennial zonal wind oscillation in the low tropical stratosphere, there is a 10 cm sec⁻¹ poleward flow at 200 mb. The flow is opposite during the east wind phase. This indicates a circulation link between tropical and temperate latitudes (Angell 1974). From an analysis of EOLE balloon data, Morel and Bandeen (1973) reported on various climatological aspects of the Southern Hemisphere general circulation and on new estimates of the rms divergence of the 200-mb flow, together with its scale dependence, which was found to be a logarithmic law.

ESSA photographs show persistent maxima of early vortex developments in the western South Atlantic and in the central South Pacific. The depressions in these areas extend into lower latitudes than elsewhere in the hemisphere (Streten and Troup 1973).

Radiances from Nimbus 3 SIRS show that winter polar stratospheric warmings are accompanied by relatively small stratospheric cooling in the tropics and summer hemisphere (Fritz and Soules 1972). Solar heating of the

tropical stratosphere would produce large temperature gradients. Atmospheric motions reduce these gradients to the relatively small gradients observed by satellites (Fritz, 1974).

Nagle and Hayden (1971) developed a quasi-objective method for deriving 500 mb heights with the aid of ESSA photographs. The 6.7 μm channel of the Nimbus 4 Temperature Humidity Infrared Radiometer (THIR) allows an improved streamline analysis at the 400 mb level and provides an improved analysis of regions of subsidence and moisture transport (Steranka et al. 1973). The global distribution of total ozone, obtained from the Nimbus Infrared Interferometer Spectrometer (IRIS), provides information on upper tropospheric circulation patterns (Prabhakara et al. 1973).

Extratropical Circulations. Wilheit et al. (1973), Allison et al. (1974a), Sabatini and Merritt (1973) and Theon (1973) have demonstrated the value of the Nimbus 5 ESMR (19.35 GHz) for delineating the rainfall areas of extratropical cyclones over oceans. The ESMR measurements were much more definitive in locating the precipitation areas than the corresponding THIR 11 μm information. Holub and Shenk (1973) have traced the life cycle of an Atlantic extratropical cyclone with Nimbus 3 MRIR measurements. The 0.2-4.0 μm , 6.5-7.0 μm , 10-11 μm , and 20-23 μm channels were used to estimate the positions of jet streams, detect secondary cyclogenesis and study the evolution of the cloud types within the storm circulation. A 10-level diagnostic atmospheric model was used by Rodgers et al. (1973) to examine (1) the spatial and temporal

relationships that existed between radiometrically observed water vapor patterns as seen by the Nimbus 4 THIR 6.7 μ m channel and conventionally derived water vapor patterns and (2) the upper and middle tropospheric water vapor budget and its relationship to the same satellite data.

Parmenter (1973) has shown the value of ESSA andITOS visual and infrared data for East Coast snowstorm forecasting. Shenk et al. (1973) have developed a statistical method for estimating the central pressure and intensity of extratropical cyclones. Woods et al., (1973) used Nimbus 4 SIRS data to delineate areas of clear air turbulence at 9 km over the North Atlantic Ocean.

Tropical Circulations. Dvorak (1973) developed a technique for using satellite pictures to detect changes in tropical cyclone intensity, and for forecasting 24 hour intensity changes. Fett and Brand (1974) described a method to predict 24 hour movement of tropical cyclones using consecutive daily satellite views. Studies of Hurricane Camille, 1969 by Bradbury (1971) and Shenk and Rodgers (1974) used ATS-3 with composited ground radar and Nimbus 3 MRIR and HRIR data respectively to describe the dynamics of the storm over the Gulf of Mexico and the United States. Balogun (1973) studied the spatial distribution of tropical cyclone cloud cover with development and made harmonic analyses of cloud cover estimates. Sikdar et al. (1972) made time series of areal cloud coverage from ESSA data over the central Pacific and determined marked geographical variations of tropical disturbance activity. Sikdar and Suomi (1972) developed an objective technique for estimating the mass and energy exchange in convection systems using cirrus outflow area change from ATS-1 data. Fujita (1972b) used

time integrated ATS-3 pictures to detect cloud changes during the modification processes of Hurricane Ginger, 1971, in the Atlantic Ocean. Allison et al. (1974b) used Nimbus 5 ESMR (19.35 GHz) data to make semi-quantitative measurements of tropical cyclone rainfall during the 1973 season.

MESOSCALE PHENOMENA

Thunderstorms. Since the geosynchronous satellites were launched measurements have been available with a time scale that is useful for research on thunderstorms. A sizeable portion of the effort has been on identifying conditions that can produce severe local storms and detecting these storms. The probability of thunderstorm growth later in the day is greatest where it is clear in the morning (Weiss and Purdom, 1974). Cloudy areas are less favored because the surface heating is retarded. Purdom (1973) has discovered thin lines of cumulus (called arc clouds) that move along the leading edge of meso-high areas produced by existing thunderstorms. New thunderstorm formation is more likely along these lines than elsewhere and an especially vigorous storm can occur where two or more lines intersect or where a line intersects another boundary such as a front. Convective mass transports have been calculated from a three layer convective model by Sikdar, et al. (1971) using a series of ATS-3 images to measure the growth rates of convective complexes. The fluxes for the severe storms of April 19 and 23, 1968 were higher by at least one order of magnitude than those for a moderate storm. Ninomiya (1971a), analyzing conventional and ATS-3 measurements, found that the pre-existing flow at cirrus

levels over storm areas changed dramatically into outflow as the storms developed. The outflow was induced and maintained by convective warming. When the storms were mature the outflow extended to about 500 km from the storms. A warm core existed in the outflow accompanied by significant convergence below 700 mb. Ninomiya (1971b) has reported that a dry region has formed to the rear of a storm area caused by an increased thermal gradient to the left of the warm mid-tropospheric core of the storm. Similar dry areas have been observed in Nimbus 4 THIR 6.7 μ m imagery by Allison, et. al (1972).

Extremely high thunderstorm cloud tops have been measured. Using stereographic methods Shenk, et al. (1975) found the maximum height of the top of a large dome over Mississippi to be 22.4 km where a tornado had occurred 1.5 hours before the Apollo satellite pass.

A significant cloud feature of a strong thunderstorm is a small dome that protrudes above the cirrostratus anvil. From aircraft measurements Shenk (1973) has calculated that the average size of the domes when they reach their highest point is 1.4 and 6 km in the vertical and horizontal dimensions respectively. The maximum upward vertical motion was 27 m/sec averaged over 30 sec. Fujita (1972a) has indicated that there is a tendency for tornado formation during the collapsing portion of a dome life cycle. Based on a combination of conventional, laboratory, aircraft and satellite evidence Fujita (1974) has concluded that: (1) tornadoes are associated with the downdraft stage of a thunderstorm and with a periodic frequency (perhaps 45 minutes) in the vigor of the

domes, (2) hailstorms can be detected based on the height of the domes, (3) ordinary thunderstorms have moderate size domes with periodic frequencies of 15-20 minutes, and (4) rainstorms have insignificant domes since there are no intense updrafts. A mechanism of tornado formation has been postulated by Fujita (1973) where a twisting downdraft has been produced by precipitation overloading. A dome at the top of a storm precedes the overloading and a small area of cirrus sometimes remains after the dome has collapsed.

Dust Storms. Dust storms produce changes in a scene that is radiometrically viewed from a satellite that can lead to their detection. Ing (1972) has shown that the deserts of central Asia appear less distinct in visible ESSA 9 images when a dust storm is in progress. Shenk and Curran (1974) found that daytime 11 μm infrared measurements were lower than surrounding areas in dust storm conditions because the surface material is mixed with the air immediately above it resulting in lower equivalent blackbody temperatures.

Lake Effects on Cloudiness. Heavy snow showers can occur in the lee of the Great Lakes when cold air passes over the relatively warm water. Ferguson (1971) showed that ESSA 8 photographs were useful for depicting the position of the clouds associated with these showers as well as for locating clouds that indicated positive vorticity advection which can enhance shower intensity. Enlarged cloud bands were found by Holroyd (1971). These bands, probably associated with heavier activity, had preferred origin points and appeared to be generated by frictional differences between land and water, by the geometry of

the body of warm water with respect to the prevailing wind, and by certain urban influences.

Fog. Gurka (1974) has developed an objective method of predicting the dissipation time of fog. The dissipation time was related to the brightness of the stratus cloud. A correlation coefficient of 0.92 was calculated.

Terminal Weather Forecasts. With geosynchronous satellite data Sikula and Vonder Haar (1973) have demonstrated that 4-6 hour air terminal weather forecasts of ceiling and cloud cover had skill exceeding persistence or climatology forecasts.

HEAT BUDGET OF THE EARTH-ATMOSPHERE SYSTEM AND CLIMATE

During the past four years many studies have been carried out using measurements of emitted long-wave and reflected solar radiation acquired by medium resolution scanning and low resolution spherical or flat plat radiometers flown on both experimental and operational satellites since 1962.

Vonder Haar and Suomi (1971) analyzed a data set, largely from low resolution radiometers on many satellites representing 39 months during the five-year period 1962-66, and presented the first satellite measurements of planetary albedo and radiation budget for all four seasons and the annual case. They found the earth-atmosphere system to be warmer and darker (albedo: 30%) than previously believed, especially in tropical regions.

Data from the Medium Resolution Infrared Radiometer (MRIR) experiment on Nimbus 3 provided the first synoptic scale view of the global radiation

budget during four seasons (April 1969–February 1970). The Nimbus 3 results show a warmer (255 K vs. 250 K) and darker (albedo: 28–29% vs. 35%) planet than was previously believed, with most of the radiative energy input in excess of those older results in tropical regions, thus requiring higher poleward energy transport (Vonder Haar et al., 1972a; Raschke et al., 1973a; Raschke et al., 1973b). These results essentially confirm the earlier results of Vonder Haar and Suomi (1971).

Raschke et al. (1973a) discussed the complete radiation budget experiment using data from the MRIR on Nimbus 3, the extensive data reduction method (including assumptions), and results during the period April 1969–February 1970. Raschke et al. (1973b) presented measurements of reflected solar radiation and emitted thermal radiation taken with the MRIR on Nimbus 3 for ten semi-monthly periods, April 1969–February 1970. Results on the planetary albedo, the amount of absorbed solar radiation, the infrared radiation lost to space, and the radiation balance of the earth-atmosphere system were discussed at various scales: global, hemispherical, and zonal averages, as well as annual polar and global maps.

Vonder Haar et al. (1972b) discussed satellite measurements of solar energy absorption on global and planetary scales. Vonder Haar (1972) discussed the natural variation of satellite radiation budget measurements over 17 seasons and the implications with respect to the energetics of the atmosphere and oceans. He concluded that low and medium resolution radiometric measurements existing

at that time permitted studies at the planetary and synoptic scales, but that new measurements from new sensors were needed to study global climate and meso-scale phenomena.

Vonder Haar and Raschke (1973) discussed the Nimbus 3 MRIR results within the framework of the earlier satellite measurements, especially with regard to interannual variations. Ellis (1972) compared 35 months of satellite data on the north-to-south gradient of net radiation with parameters defining the intensity of the general circulation. He found that the interannual variations in the gradient of net radiation and the intensity of the general circulation appeared to be related, with the latter lagging the former by 3 months.

Vonder Haar and Oort (1973) combined measurements of the earth's radiation budget from satellites with atmospheric energy transport summaries to show the required transport by the oceans between equator and pole. The results showed that the ocean must transport more energy than previously believed, i. e., for the region 0° - 70° N the ocean contribution averages 40%.

Winston et al. (1972) applied a regression analysis to data from the first Satellite Infrared Spectrometer (SIRS-A) flown on Nimbus 3 to obtain monthly, seasonal, and annual mean global charts and zonally averaged values of outgoing long-wave radiation for the period May 1969-April 1970. These results generally agree well with the corresponding results by other workers discussed previously, but differences do exist suggesting the need for further refinements in one or more of the areas of instrumental calibration, data

processing, and analysis techniques. A review of the satellite measurements of albedo and outgoing long-wave radiation by many workers and of possible reasons for the differences that do exist has been presented by Gruber (1973b).

Satellite photography has been utilized in climatological studies of cloud, snow, and ice cover and applied to other studies for specialized purposes. A four-year archive of daily brightness values derived from the Advanced Vidicon Camera Systems of meteorological satellites was used to prepare a climatology of daytime cloudiness over the globe (Miller and Feddes, 1971). An analysis of a year of brightness data from the ESSA 9 and ITOS 1 satellites revealed a region of persistent cloudiness in the circumpolar trough 50° - 60° S, and indicated that meteorological buoys might be needed in that region to augment remote satellite sensing of temperature profiles. These results are applicable to the planning of the global observing system for GARP. Inasmuch as cloud cover is the primary variable influencing changes in the earth's radiation budget, these results are also useful in developing methods to parameterize the effects of cloudiness on the energy budget of the atmosphere (Downey et al., 1972).

In a study of snow and ice boundary maps produced by NOAA from operational satellite photography, Kukla and Kukla (1974) concluded that snow and pack-ice cover in the Northern Hemisphere has expanded in recent years, producing a significant change in the hemispheric heat balance at the same time anomalous weather patterns were noted.

Kellogg (1974) has discussed the types of satellite measurements that have in the past and will increasingly in the future make possible a better understanding of the Earth's present climate and possible causes of future climatic change.

OCEAN SURFACE AND HYDROLOGY

Sea surface temperature analyses by Warnecke et al., (1971), Maul and Hansen (1972) and Arnold et al. (1971) using Nimbus 2 High Resolution Infrared Radiometer (HRIR) data (3.4-4.2 μm) indicated the feasibility of detecting major current boundaries and upwelling regions on a global scale. Atmospheric correction models, instrumental noise filtering, and data averaging techniques were described by Vukovich (1971), Hanson (1972), and Maul (1973). An objective composite histogram method to derive sea surface temperatures was described by Rao et al. (1972) which yielded 2° to 3° K RMS differences when compared with ship observations. Shenk and Saolmonson (1972b) used a multi-spectral technique with Nimbus 2 Medium Resolution Infrared Radiometer (MRIR) data to detect the presence of clear skies and determined a 1.0-1.5° K RMS difference with ship reports in mid-latitudes. Prabhakara et al. (1974) demonstrated the use of Nimbus 3 and 4 Infrared Interferometer Spectrometer (IRIS) spectral data (11-13 μm) to determine sea surface temperature within 1° K of ship measurements. The differential absorption properties of water vapor in two "window" channels enable the estimation of the water vapor correction for the sea surface measurements.

An operational computer automated technique for global monitoring of sea surface temperatures was developed by Leese et al. (1971b) using the ITOS 1 Scanning Radiometer (SR) (10.5-12.5 μ m). Cloud contamination was found to be the largest source of error for this system. The present program uses the NOAA-3 VTPR sounding to derive moisture coefficients which are then used to correct the SR sea surface temperature data. Stumpf (1974) reported on the production of a weekly experimental gulf stream analysis from NOAA 2 Very High Resolution Radiometer (VHRR) data for use by the maritime community. Stevenson and Miller (1974) used NOAA 2 direct-readout Scanning Radiometer (SR) data, corrected for atmospheric attenuation and demonstrated that certain optimum sea surface temperatures related to maximum tuna fish catches off the U. S. west coast in good agreement with biological research vessel data. Huh (1973) demonstrated the operational utility of the High Resolution Infrared Radiometer images (8-13 μ m) of the U. S. Air Force Defense Meteorological Satellite Program (DMSP) to delineate the thermal patterns which outline currents, distinctive water masses and oceanic fronts.

The feasibility of measuring sea surface winds and roughness was demonstrated by Levanon (1971) by using sun glitter measurements from a geostationary satellite. Strong et al. (1974), using NOAA 2 VHRR (0.6-0.7 μ m) visual data detected streamers of increased ocean brightness in low surface wind areas in the lee of the Lesser Antilles. Strong and De Rycke (1973) and Richardson et al. (1973) used this same data to detect the Loop Current in the

Gulf of Mexico, the borders of the Gulf Stream, and associated eddies. Sabatini (1974) determined realistic surface wind speed gradients in the Mediterranean Sea by using Nimbus 5 Electrically Scanning Microwave Radiometer (ESMR) data under a variety of weather conditions. Cardone et al. (1973) made Radiometer-Scatterometer (RADSCAT) measurements on SKYLAB over Hurricane Ava, 1973, and obtained results which tend to confirm the approximately square law relation between the scattering coefficient for horizontal polarization and the wind speed.

Curran (1972) has shown that chlorophyll concentrations in the oceans cannot be detected from satellites by remote sensing in the visible spectrum without explicit correction for the atmospheric aerosol concentration along the line of sight.

Sea ice surveillance by use ofITOS 1 and ESSA 9 five-day Composite Minimum Brightness (CMB) charts was reported by McClain and Baliles (1971). By use of these CMB charts, Kukla and Kukla (1974) noted a 12% increase in snow and pack ice cover in the Northern Hemisphere from 1968 to 1971-74. The snow covered grasslands and ice fields reflect 80% of solar insolation, cause strong radiative cooling aloft, and inhibit surface heat exchange processes. These factors may be important in explaining anomalous global weather patterns from 1972 to 1974. Vonder Haar (1973) described the patterns and extremes of albedo measurements over polar snow and ice fields using Nimbus 3 MRIR (0.3-3 μm) data. Barnes et al. (1972) showed that Nimbus 2 HRIR and NOAA 2

SR were capable of mapping gross ice boundaries during periods of polar darkness. McClain (1974) studied sea ice in the Arctic and Antarctic using NOAA 2 VHRR data and described the operational limitations of the data. Seasonal polar sea ice boundaries and changes in sea ice compactness have been observed under all-weather conditions by the Nimbus 5 Electrically Scanning Microwave Radiometer (ESMR) (Gloersen et al., 1973a; Campbell et al., 1973). Weekly ice limit charts have been produced by the U. S. Navy for military, commercial, and international use (Gloersen et al., 1973b).

The detection of thawing snow cover was described by Strong et al. (1971) using the Nimbus 3 HRIR (3.4-4.2 μm day) and the Image Dissector Camera System (IDCS, 0.5-0.7 μm). Snow field estimates were made by Barnes and Bowley (1972) using Nimbus 4 THIR (11 μm) and ITOS 1 Direct-Readout SR (10.5 to 12.5 μm) data over relatively flat terrain.

Major soil moisture distributions and watershed changes were described by Sabatini et al. (1971), Merritt and Hall (1973), and Salomonson and MacLeod (1972) by use of Nimbus 3 HRIR images (0.7 to 1.3 μm). Nimbus 5 ESMR data indicated broad regions of low brightness temperature (high soil moisture content) which outlined the Mississippi flood plain prior to the major 1973 Spring flood disaster (Schmugge et al., 1974). Regional flood and watershed physiography mapping was demonstrated by Salomonson and Rango (1974) and Rango et al. (1974) by use of NOAA 2 VHRR and ERTS-1 (0.8-1.1 μm) data, in which regions of excessive soil moisture, vegetation stress, and standing water were

shown as areas of abnormally low reflectance. Eagleman (1974) found good correlation between surface soil moisture content in 5 data sets over the midwest U. S. with Skylab S-194 RADSCAT (L Band 21 cm) data. Grosh et al. (1973) using ATS-3 data, demonstrated that areas of bright clouds are proportional to the stream run-off measured below the cloud system. Barrett (1973, Sikdar (1972), Woodley et al. (1972), Griffith and Woodley (1974), Follansbee (1973), and Gruber (1973a) used ATS-3 and/or NOAA visual imagery to estimate hourly and daily rainfall from satellite cloud brightness and categories and radar data.

METEOROLOGICAL SATELLITES

NOAA 1: launched December 11, 1970;

Nominal orbit: sun synchronous (polar orbiting);

Altitude: 1455 km (785 n. miles) approximately;

Camera: Advanced Vidicon Camera System (AVCS);

Radiometers: Scanning Radiometer (SR), Omni-Directional (Flat Plate)

Radiometer;

NOAA 2: launched October 15, 1972;

Nominal orbit: sun synchronous (polar orbiting);

Altitude: 1455 km (785 n. miles) approximately;

Radiometers: Scanning Radiometer (SR), Very High Resolution Radiometer

(VHRR), Vertical Temperature Profile Radiometer (VTPR);

Solar Proton Monitor (SPM);

Nimbus 5: launched December 11, 1972;

Nominal orbit: sun synchronous (polar orbiting);

Altitude: 1100 km (595 n. miles) approximately;

Radiometers: Temperature-Humidity Infrared Radiometer (THIR), Electrically Scanning Microwave Radiometer (ESMR), Selective Chopper Radiometer (SCR), Infrared Temperature Profile Radiometer (ITPR), Surface Composition Mapping Radiometer (SCMR); Nimbus E Microwave Sounder (NEMS);

NOAA 3: launched November 6, 1973;

Nominal orbit: sun synchronous (polar orbiting);

Altitude: 1510 km (815 n. miles) approximately;

Radiometers: Scanning Radiometer (SR), Very High Resolution Radiometer (VHRR), Vertical Temperature Profile Radiometer (VTPR);

Solar Proton Monitor (SPM);

SMS 1: launched May 17, 1974;

Nominal orbit: geostationary;

Altitude: 35,800 km (19,300 n. miles) approximately;

Radiometer: Visible and Infrared Spin-Scan Radiometer (VISSR);

Space Environment Monitor (SEM);

Communications: Data Collection and Relay System;

ATS 6: launched May 30, 1974;

Nominal orbit: geostationary;

Altitude: 35,800 km (19,300 n. miles) approximately;

Radiometer: Geostationary Very High Resolution Radiometer (GVHRR);

Communications: Data Collection System;

NOAA 4: to be launched in late 1974;

Nominal orbit: sun synchronous (polar orbiting);

Nominal altitude: 1460 km (790 n. miles)

Radiometers: Scanning Radiometer (SR), Very High Resolution Radiometer

(VHRR), Vertical Temperature Profile Radiometer (VTPR);

Solar Proton Monitor (SPM).

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