METEOROLOGICAL PARAMETERS DERIVED FROM SPACE-BASED OBSERVING SYSTEMS - FGGE AND AFTER

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1. INTRODUCTION

The political impetus for the Global Atmospheric Research Programme (GARP) and the World Weather Watch (WWW) stemmed from two United Nations resolutions, 1721 (XVI) of December 1961 and 1802 (XVII) of December 1962. "Noting with gratification the marked progress for meteorological science and technology opened up by the advances in outer space," resolution 1721 recommended, "the early and comprehensive study, in the light of developments in outer space, of measures (a) to advance the state of atmospheric science and technology so as to provide greater knowledge of basic physical forces affecting climate and the possibility of large-scale weather modification, (b) to develop existing weather forecasting capabilities and to help Member States make effective use of such capabilities through regional meteorological centres." These became the closely related WMO/ICSU GARP and WMO WWW programmes respectively, of which the First GARP Global Experiment (FGGE) is a cornerstone.

While the emphasis in the United Nations resolutions was on the impact of space technology, which rankled many meteorologists and other scientists at the time, subsequent events, and particularly the results of the FGGE, have shown the pivotal role satellites are playing in both global observations and communications. The first Study Conference on the Global Atmospheric Research Programme (ICSU/IUGG Committee on Atmospheric Sciences, 1967) already established the broad outlines of the scientific basis for and structure of the FGGE. Both ICSU and the WMO received the report of the Study Conference with enthusiasm, approved the GARP, and established the Joint Organizing Committee (JOC) and Joint Planning Staff (JPS) to plan and coordinate the Programme. The ICSU Committee on Space Research (COSPAR) collaborated in the Study Conference and subsequently established its Working Group VI to provide system and space technology planning support to the international effort.

The 1967 Study Conference set forth the first tentative data requirements for a global experiment and called for further study; the COSPAR participants responded with a preliminary assessment of the observing technology which might be used. An iteration process thus began between the atmospheric scientists and the technologists in developing the observational requirements for the FGGE which were scientifically sound, and the development of an observing system, heavily dependent on satellites, which could come close enough to meeting the requirements that the experiment would be worthwhile.

COSPAR Working Group VI (1969) gave the JOC its first full evaluation of the potential of a space-based observing system. This information contributed to the further planning by the JOC and the JPS, resulting in the JOC (1969) report on the planning of the First GARP Global Experiment. Some modest refinements of the tentative requirements developed at the 1967 Study Conference were introduced.

COSPAR Working Group 6 (1971) again reported to the JOC on the feasibility of the FGGE and the criticality of initiating systems planning. The JOC (1973) set forth the objectives and plans for FGGE which, by that time, were quite well developed. The observational requirements had been refined, but not radically changed from 1967, as the result of numerical experimentation and model developments. Planning of a composite observing system, visualized by COSPAR Working Group 6, in which the data output of various subsystems would be combined, had evolved to the point that it became a firm part of the FGGE Plan. This 1973 report described in considerable detail the observing system components and their expected performance. By this time, the match between requirements and expected data was considered close enough to proceed with the experiment. Indeed, the development of the necessary satellites and special observing systems already had begun.

2. OBSERVATIONAL REQUIREMENTS

The JOC report of 1973 gave the minimum requirements for the basic state parameters in data-sparse regions, summarized in Table 1. The analysis in the report of satellite performance expected after 1976 indicated that none of these requirements, with the possible exception of sea surface temperature, could be met. These expectations also are indicated in Table 1. The horizontal resolutions indicated for satellite observations were the maximum expected. The satellite operators did not commit to providing data with these resolutions during FGGE.

3. SATELLITE COVERAGE DURING FGGE

Global coverage by both geostationary and polar orbiting satellites was essential during the FGGE for both remote sensing and data collection functions. Geostationary satellites were needed to provide:

- Winds estimated from observed cloud motions at one or two levels (approximately 850-900 and 200-300mb) in tropical and mid-latitude areas;
- Relay of AIREPS by the Aircraft to Satellite Data Relay (ASDAR) system.

The polar orbiting satellites (TIROS-N and NOAA-6) provided:

- Vertical temperature soundings;
- Total atmospheric water vapour;
- Sea surface temperatures;
- Location and collection of data from drifting buoys and the Tropical Constant Level (stratospheric) Balloon System.

As an example of satellite data coverage during FGGE, Figure 1 shows the FGGE level II-B data collected for the time 12 GMT ±3 Hr, 15 June 1979. The coverage of satellite winds is given on the two upper left maps for high and low levels; satellite temperature soundings (SATEMS) are shown on the upper right map. The absence of the second polar orbiting satellite is clearly reflected in the latter map.

3.1 Geostationary Satellites

Five geostationary satellites operated throughout the FGGE year with only minor interruptions and were located at:

0° longitude	METEOSAT
60°E	GOES-Indian Ocean
140°E	GMS
135°W	GOES-West
75°W	GOES-East

to cover the tropical and mid-latitude regions as specified in the FGGE requirements (Figure 2). The total number of wind vectors produced averaged 178,000 per month, with the lowest number being 131,200 in April and the highest 207,300 in June 1979 (Joint Planning Staff for GARP (JPS), 1980 and 1982). All except GOES-Indian Ocean were equipped for data relay and operated reliably throughout FGGE in support of the ASDAR system.

Table 1

Data Requirements and Satellite Expectations for FGGE

(from Joint Organizing Committee for GARP, 1973)

Parameter	Requirement	Satellite
Temperature (highest priority, mid and high latitudes)		
Horizontal resolution	500km	30km
Vertical resolution	4/3 levels*	7 levels
Accuracy	± 1C	1-2C
Wind (highest priority, tropics)		
Horizontal resolution	500km	low 500km high 500km
Vertical resolution	4/3 levels*	2 levels
Accuracy	± 3m/s (mid-high lat.) ± 2m/s (tropics)	?
Relative Humidity		
Horizontal	500km	30km
Vertical resolution	2 deg. freedom in trop.	3 layers
Accuracy	± 30%	20-30%
Sea Surface Temperature**		
Horizontal resolution	500km	2km
Accuracy	±1C	1C
Surface Pressure (except in tropics)		
Horizontal resolution	500km	No
Accuracy	±0.3% (3mb)	No

* Number of levels in troposphere/stratosphere
** Can be three-day averages

Minimum of one observation a day (except SST), two preferred.

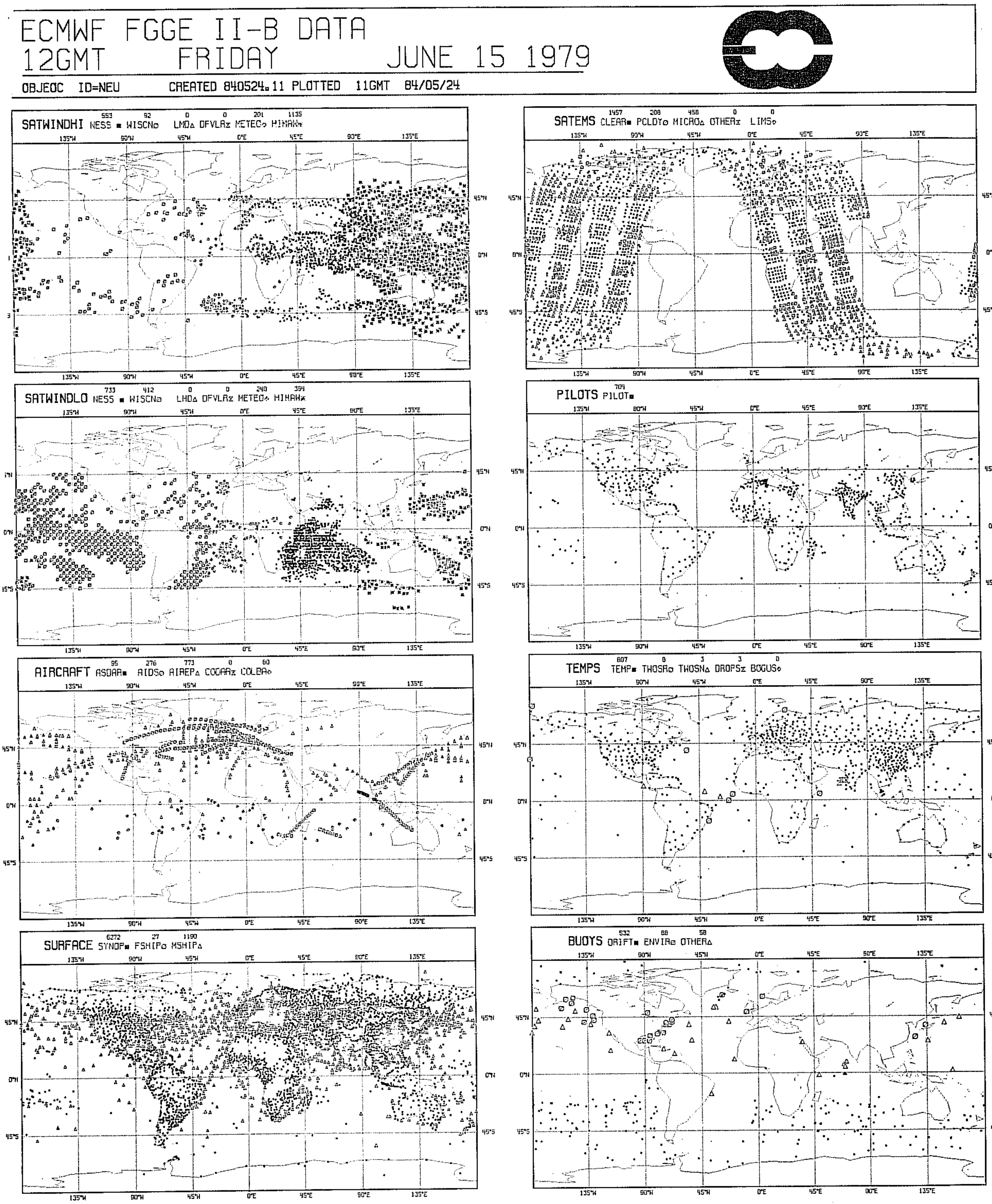

Fig. 1. Maps of FGGE II-B data by ECMWF for 12GMT ± 3HR 15 June 1979.

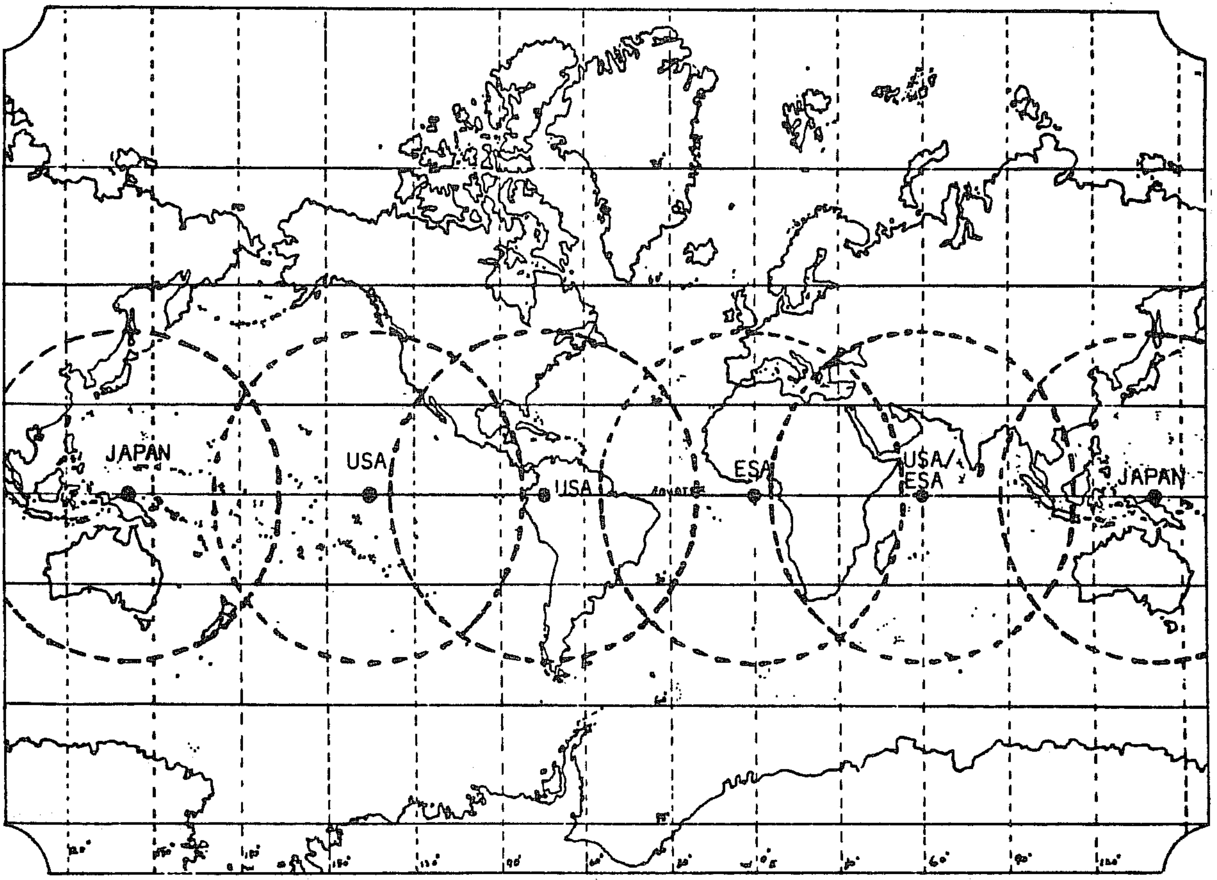

Fig. 2. Coverage of the five geostationary satellites for wind extraction during FGGE. (Circles 50° latitude radius from each subsatellite point).

3.2 Polar Orbiting Satellites

The basic FGGE sounding and sea surface temperature data from polar orbiting satellites were provided by:

NOAA-5	1 December 1978 - 28 February 1979 (except SSTs through 31 January)
TIROS-N	1 January - 30 November 1979
NOAA-6	16 October - 30 November 1979 (except no SSTs from NOAA-6).

Soundings were missed entirely on one day during the FGGE year and sea surface temperatures on six days (JPS, 1980 and 1982).

It had been planned to have both TIROS-N and NOAA-6 operating throughout the FGGE year. Unfortunately, due to technical difficulties in developing the new TIROS-N series, the satellites were not launched until 13 October 1978 and 27 June 1979, respectively. The check-out of the spacecraft and ground systems, data processing and algorithms, and derivation of correlation coefficients delayed the routine production of data to 1 January and 16 October 1979, respectively. Thus, during the first month of FGGE the soundings were derived from the Vertical Temperature Profile Radiometer (VTPR) and sea surface temperatures from the two-channel Very High Resolution Radiometer (VHRR), both inferior to the TIROS Operational Vertical Sounder (TOVS) and Advanced Very High Resolution Radiometer (AVHRR) flown on TIROS-N and NOAA-6 (Schwalb, 1978; WMO, 1975). TIROS-N and NOAA-6 also carried the ARGOS data collection and platform location system which operated flawlessly throughout FGGE in support of the drifting buoy system in the Southern Hemisphere and the Tropical Constant Level Baloon System.

3.3 Derivation and Evaluation of Quantitative Satellite Data

It is not the intention of this paper to cover in any detail the methods of observation and data processing used to derive quantitative data from satellite-observed radiances for use in numerical prediction. The remainder of this paper will briefly summarize the observational methods, review the accuracies and representativeness, and indicate the outlook for improvements in the near future of upper air winds, temperature and water vapour soundings, and sea surface temperatures.

Since most of the satellites and data processing systems used for FGGE were quite new, the processing techniques had not been refined or stabilised. Changes to improve the data quality were introduced during the year. In most cases, the earlier data were not reprocessed because of lack of computing capacity. Also, significant processing improvements were introduced in the 1981-1983 period. Thus, the quantitative data derived from satellite observations today are considerably better than those for the FGGE year. These differences should be kept in mind when using and evaluating the FGGE data sets.

It is common to evaluate the quality of quantitative atmospheric data derived from satellite observations by comparing them with in situ observations. Satellite cloud-drift winds are compared primarily with radio-wind observations, satellite temperature soundings with radiosonde observations, and sea surface temperatures with those measured by ships and buoys. It also is usual to refer to observed differences between satellite and in situ observations as "errors" in the former. However, the observed differences include the effects of the

o different nature of the two classes of observation: satellites provide volume and time (for winds) averages (area for surface temperature) while in situ observations are close to instantaneous point readings;

Table 2

Estimated Observation Errors at the Synoptic Scale for Different FGGE Observing Systems (Bengtsson, 1983)

Level	Layer-mean Temperature (K)				Level Wind (mps)				
		Satellite					Cloud-Drift Winds		
mb	radio sonde	clear	ptly cldy	cldy	radio wind pilot ASDAR AIDS	AIREPS	GOES	METEO SAT	GMS
10	4.5	2.0	2.0	2.0					
20	3.8	2.0	2.0	2.0					
30	3.2	1.9	1.9	1.9					
50	2.7	1.8	1.8	1.8					
70	2.3	1.7	1.7	1.7	4	6			
100	2.1	1.7	1.7	1.7	4	6			
150	2.1	1.7	1.7	1.7	4	6			
200	2.0	1.7	1.9	1.9	4	6	8	8	13
250	1.8	1.7	1.9	1.9	4	6	8	8	13
300	1.6	2.0	2.1	2.3	4	6	8	8	13
400	1.5	1.8	1.9	2.1	4	5	7	8	10
500	1.2	1.5	1.5	1.5	4	4	7	8	10
700	1.1	1.9	2.1	2.2	3	3	5	8	6
850	1.1	2.6	2.6	2.6	2	2	4	7	6
1000	-	-	-	-	2	2	4	7	6

The estimated accuracies are representative for the synoptic scale

- non simultaneity in space and time of the two sets of data; often no attempt is made to even interpolate the observations to the same location and time for comparison; and
- errors in the in situ observations, as well as the errors in the satellite data which we wish to determine.

Thus, it is important when comparing satellite performance evaluations to determine to what extent the above factors have been taken into account (Bengtsson and Morel, 1974). In some cases, objective analysis schemes have been used as the standard to which the individual sets of in situ and satellite observations are compared (Bengtsson, et al, 1982; Bengtsson, 1983; Broderick and Thomasell, 1984). Table 2, from Bengtsson (1983) shows the results of an assessment by the European Centre for Medium-Range Weather Forecasts (ECMWF) of the quality of observational data collected during the FGGE. The accuracies are estimated with respect to the representativeness of the observations at the synoptic scale. Therefore, the error estimates include the contributions from smaller scales as well as instrumental errors. The ECMWF compared the FGGE observations to special reference observations, such as special, high quality radiosondes and also by examining their fit to the analyses. Table 2, then, presents the results of one approach to the problem of comparing the accuracy of various satellite and in situ observations in the absence of any acceptable absolute measurement standard appropriate to the time and space scales of interest.

4. GEOSTATIONARY SATELLITE WINDS

4.1 The Method

Upper air winds are derived from a sequence of geostationary satellite images, usually acquired at 30 minute intervals. High clouds, in most cases, are tracked manually by observing the motion of small cloud elements over a period of one and a half to two and a half hours in duration. On the other hand, the displacements of low clouds are determined by automated systems (GMS only since 1 April 1982) involving cross-correlation of the cloud patterns in two images adjacent in time (Leese, et al, 1971). The low cloud determinations are edited objectively and manually to eliminate unsuitable cloud tracers. Generally, low level winds are not produced over land because of the danger of topographic and thermal influences on the apparent movement of the clouds. Hubert (1979) provides a summary of the wind derivation techniques used with GMS, GOES and METEOSAT data.

The main problem in obtaining winds from cloud motions is in estimating the altitude to which each wind derivation will be ascribed. This is not as critical for the low-level vectors as for the high-level, since relatively small cumulus clouds usually are used as low-level tracers, and the vertical shear in the wind through the cloud layer usually is small. Low level winds are assigned to a fixed level (900 mb for GOES and 850 mb for GMS).

It is another matter for the high-level winds. The cloud targets extend over a large range of altitudes and vary as to cloud type. Wind shears can be large over the range of altitudes involved. Many of the cloud targets are thin, whose cloud top (infrared) emissivity can be highly variable and subject to large errors of estimation. The latter is important in the case of the GOES and METEOSAT high-level winds in which satellite-observed infrared temperatures are used to estimate cloud heights (Hubert, 1979). Until December 21, 1981, Japan assigned GMS high-level winds to the seasonal climatological tropopause height. Only in the extreme can high clouds be expected to reach as high as the tropopause. Thus, one would expect the GMS high-level winds to underestimate the wind which actually existed at the estimated altitude. This would be particularly pronounced in winter. The altitude for GMS high-level winds now is assigned to a climatological level determined statistically from past levels of best fit with radio-winds (Hamada, 1982). Table 3 depicts the pressure-heights assigned as a function of latitude and season. As can be seen from Figure 4, beginning in 1982, there has been some improvement in the GMS high-level winds.

4.2 Accuracy

Whitney (1983) has compared the relative performance of the GMS and GOES winds, and their departure from radio-winds for the period 1979 (northern hemisphere) summer through 1982 (January) winter. Figure 3, from Whiteny, shows the RMS vector differences between GMS and GOES-West, and GOES-East and GOES-West, for cloud motions viewed by each pair of satellites at approximately the same time and over the common coverage area of the two satellites. The vector differences have varied little over the period of comparison. The RMS vector differences never exceeded 11 mps for high clouds and 6 mps for low. In the period since 1982 winter, these maxima have remained below 6 and 5 mps respectively. High cloud direction differences have remained less than 5° in the mean and below 10° for the low cloud targets. Of course, the altitude estimates do not affect these satellite-to-satellite comparisons.

Figure 4 is based on Whitney's and the satellite operators'comparisons with radio-wind observations. METEOSAT data have been added to Whitney's data and the period extended to the beginning of 1979 to embrace the FGGE observing year and through January-February 1984 (CGMS, 1979 - 1984). GOES and METEOSAT low-level winds depart by about 6 mps (RMS vector difference) throughout the comparison period; the high-level GOES wind departures show some winter-summer seasonal differences, but recently have leveled out at about

Table 3

Pressure-Altitude Assignment for GMS High-level Winds Initiated in 1982

NORTHERN HEMISPHERE SEASON

Latitude	Winter	Spring	Summer	Autumn
50N				
	400mb	300mb	250mb	300mb
35N				
	400	300	200	300
25N				
	200	200	200	200
25S				
	200	300	400	300
35S				
	250	300	400	300
50S				

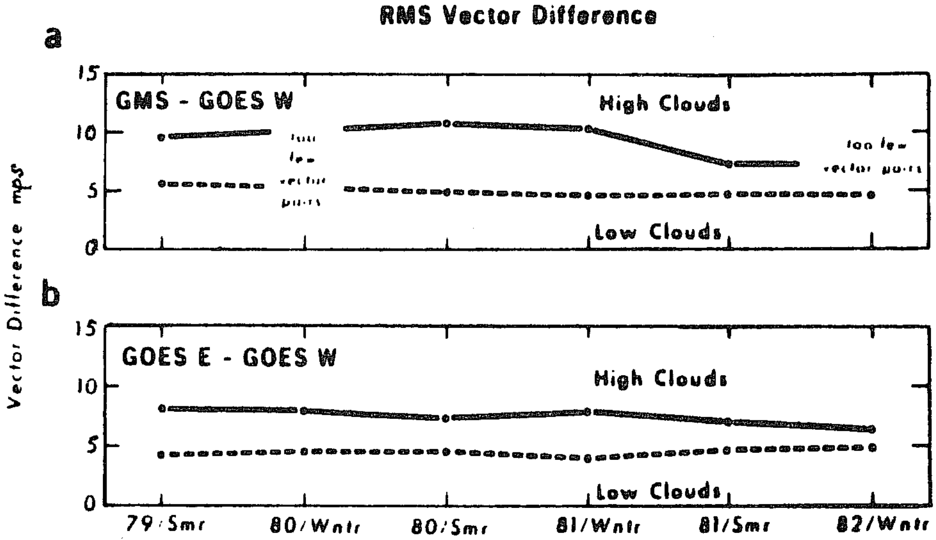

Fig. 3. Comparison of RMS vector differences for high- and low-cloud motion vectors viewed simultaneously by GMS and GOES-W, and by GOES-E and GOES-W (from Whitney, 1983).

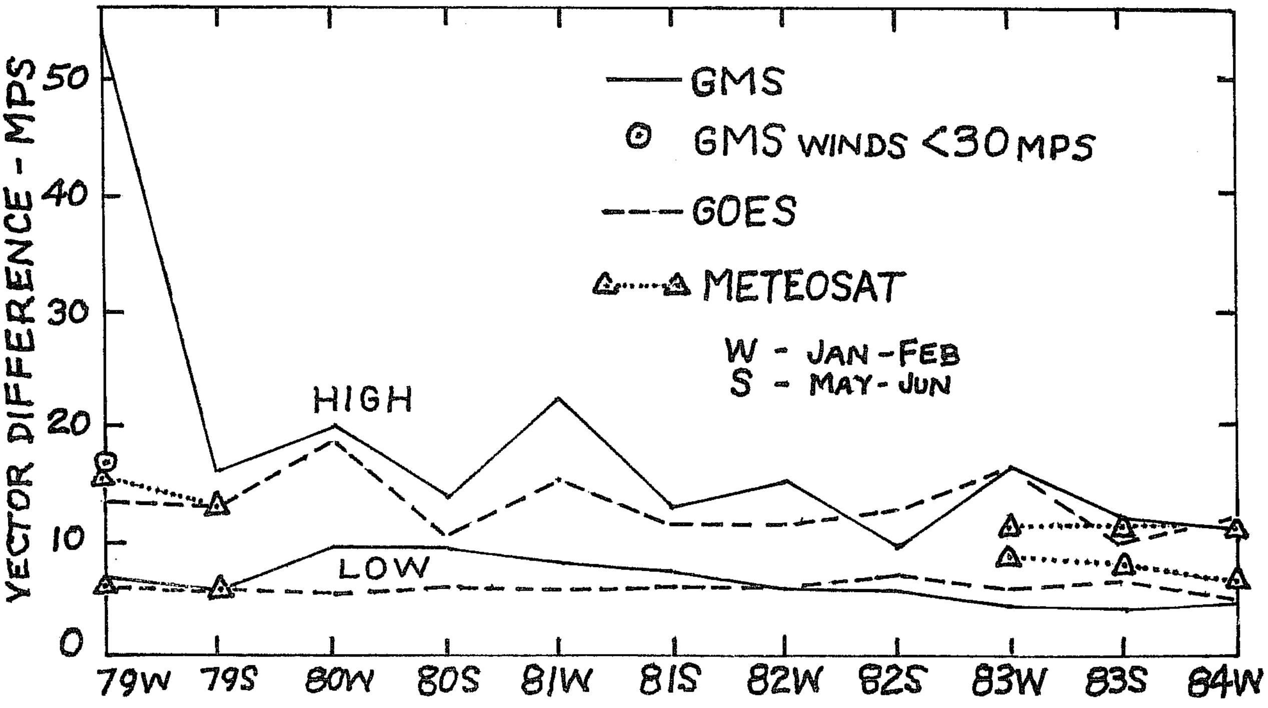

Fig. 4. Comparison of high- and low-cloud wind estimates from GMS, GOES and METEOSAT with radio-wind observations.

12 mps, with similar values for METEOSAT. GMS departures are somewhat larger prior to 1982: 6-9 mps for low-level, and ranging from 12 to 22 mps, except more than 50 mps in January 1979, for high-level winds.* However, with the introduction of the new altitude determination scheme, it appears that the GMS high-level winds now are comparable to GOES and METEOSAT.

4.3 Representativeness

These comparisons with radio-wind observations imply larger "errors" than those quoted by ECMWF (Table 2). However, it must be remembered that the geostationary satellite wind estimates are integrated over space (the volume of each cloud target) and time (1 - 2 1/2 hours), while the radio-wind is nearly instantaneous in space and time. Further, in order to achieve a reasonable statistical sample, a fairly large space-time window is allowed for each satellite-to-satellite and radio-wind-to-satellite comparison.

Arnold (1956) presented wind comparisons derived from nearly simultaneous pairs of pilot balloon wind observations taken at selected distances from each other. The standard deviation of the winds at all levels observed for all of the pairs as a function of distance was:

Distance (km)	0.5	5	110	180	480	600
Difference (mps)	0.6	0.9	3.4	4.3	7.8	8.0

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* The Japanese comparisons of high-level GMS winds with radio-winds for the period January (winter) 1980 through June (summer) 1981 were significantly in error because of the inclusion of some bad radio-wind reports. Corrected information became available in April 1984 (Japan Working Paper No. 2 for XIII meeting of Coordination on Geostationary Meteorological Satellites - CGMS). This corrected information is used in Figure 4.

Double-theodolite serial ascents from the same location gave the time variability of the wind. The standard deviations for winds separated by about 30 sec, 5 min (range 1-10min), and 90 min (range 50min-2h), were 0.5, 0.6 and 2.2 mps respectively. Any variations with height were masked by observational errors. Based on this study, one should expect vector differences between satellite winds and radio-winds in the range of 4-8 mps due only to the difference in sampling and location of observations used in the comparisons.

In another study, Bauer (1976) used radio-wind observations for three adjacent observing times over the contiguous United States and southern Canada to examine the variability within the data set. Each "base" radio-wind observation was compared, in turn, with the two or three closest (maximum separation of 660 km) observations taken at the same time. The two or three adjacent observations were extrapolated to the location of the base observation and the extrapolated values of the u and v components compared with those of the base observation. The mean absolute values of the differences from 2184 comparisons based on 270 radio-wind ascents are 4.2 and 5.1 mps respectively for the u and v components. This can be interpreted as the "noise" in a set of nearly simultaneous radio-wind observations, reflecting both the higher frequency components of atmospheric motion and the average errors in the observations themselves.

The Bauer study gives results on radio-wind variability which are very similar to those of Arnold. When compared to Whitney's data in Figure 3, which can be considered the "noise" level for cloud winds ignoring altitude errors, the performance of the two systems is quite similar. Also, the results in Figure 4, when adjusted by the results of Arnold and Bauer, are close to the ECMWF estimates of error for cloud winds compared to radio-winds (Table 2).

4.4 The Altitude Problem

Mention should be made of the problems associated with estimating the height to which the wind vectors determined from cloud motion measurements should be ascribed. There are two questions which must be considered: (1) At what altitude does the observed cloud motion best represent the air motion? (2) How well is this level estimated from satellite data? Hasler et al (1979) show that most cumulus cloud-winds over oceans, except near frontal zones, should be assigned to the altitude of the cloud base. The height range for 64 clouds studied was 977 to 898 mb, with an average of 936 mb and standard deviation of 19 mb. Thus, the use of 900 mb for GOES low-level winds appears to be appropriate. It was found that the motion of cumulus clouds associated with frontal zones (18 cases) and cirrus clouds (5 cases) correlated best with the mean wind through the entire cloud layer, with a mean vector difference between the clouds and wind of 2.5 and 1.7 mps respectively. Ascribing the wind vector to the mid-cloud level in each case was nearly as good.

How well can these levels be determined? As already indicated, the use of a fixed level of about 900 mb seems to be satisfactory for small low-level cumulus clouds. There does not seem to be an operationally satisfactory solution for mid- and upper-level clouds. Hubert (1979) compared mid- and upper-level cloud winds to the "level of best fit" with respect to a radio-wind observation nearby in space and time. The pressure level of best fit then was compared to that assigned in the GOES cloud-wind process. Figure 5 gives the resulting distributions of the pressure height differences as a function of latitude zone. The RMS error at all latitudes is about 50 mb and there is little bias around zero pressure difference.

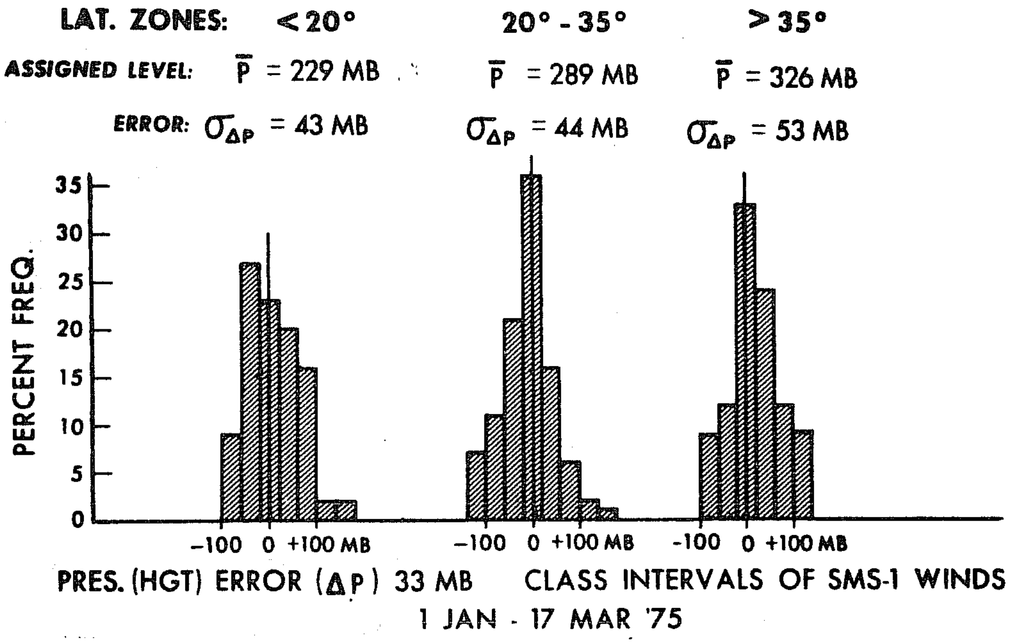

Fig. 5. Pressure-height deviations between those assigned to mid- or upper-level cloud-winds and those associated with the "level of best fit" to the wind profiles from nearly adjacent radio-wind stations (from Hubert, 1979).

In regions of overlap in the coverage of two adjacent satellites, stereo techniques can be used to measure cloud top altitudes. Hasler (1981) finds differences of about 500 m in the stereo altitudes compared to aircraft measurements for cloud tops associated with Hurricane Frederick. Such accuracy would be excellent for layer type clouds. However, the areas where stereo can be used are limited to the overlap regions, a small part of the global coverage, and very precise synchronization of the scanning of the two images in each pair is required. The coverage limitation and operational problems have limited the use of stereo to selected cases for research.

Multi-channel infrared images also can be used to help discriminate the altitude of clouds. The METEOSAT has two infrared channels and both are used in the European Space Agency's automated wind processing scheme (Hubert, 1979). Menzel et al (1983) use three carbon dioxide absorption channels on the GOES Visible and Infrared Spin-Scan Radiometer (VISSR) Atmospheric Sounder (VAS) to provide vertical "temperature-slicing" to differentiate between high (350-100 mb), middle (650-350) and low (surface - 650 mb) cloud levels. The CO_2 radiances themselves are used to derive cloud-top pressures independent of knowledge of fractional cloud cover or the cloud emittance. In two case studies, the carbon dioxide heights were found to be within about 50 mb RMS of the heights from radiosonde, bi-spectral and stereo measurements. These initial results encourage additional study.

5. SATELLITE TEMPERATURE SOUNDINGS

Since the soundings produced from radiances measured by the TIROS Operational Vertical Sounder (TOVS) on TIROS-N and NOAA-6 dominated the FGGE observational year, beginning 1 January, only data produced by TOVS will be considered here.

5.1 The Method

For a general discussion of the principles of remote sounding, see Hayden (1979). Smith, et al (1979) have summarized the general characteristics of TOVS and the data processing system utilized during the early part of FGGE. While a number of changes were introduced into the processing system during the observing year, the most significant ones, discussed below, were not introduced until later.

The TOVS includes three main components: the High-resolution Infrared Radiation Sounder (HIRS), the Microwave Sounding Unit (MSU) and the Stratospheric Sounding Unit (SSU). Their basic characteristics are summarized in Table 4. The instruments are described in considerable detail by Schwalb (1978). The vertical resolution of the radiance observed in each channel is demonstrated in Figure 6. Each curve shows the sensitivity of the radiance measurement in the indicated channel to the variation of temperature with pressure in the atmospheric column. These "weighting functions" are affected somewhat by the water vapour and ozone content of the atmosphere, and weakly by atmospheric temperature.

There are four principal steps in the data processing (Smith et al, 1979): preprocessing, TIROS Atmospheric Radiance Module (TARM), TIROS Stratospheric Mapper (TSM), and the TIROS Retrieval (TRET) Module. In the preprocessing module, the calibration and earth location data, and satellite sensor telemetry are processed to produce calibrated, corrected and earth located sounding radiances for further processing. Ancillary data, such as solar zenith angle and terrain elevations; initial guess values of surface emissivity, skin temperature and albedo; and regression coefficients used in the "limb" corrections and other sets used in subsequent processing, are added to the basic data file.

Table 4

Basic Characteristics of the TIROS Operational Vertical Sounder (TOVS)

(Based on Schwalb, 1978, Smith et al, 1979, and WMO, 1975.)

Sensor	No of Channels	Band	Function	Spatial(3) Resolution	Samples per Scan line(4)	Length of Scan line
HIRS	(20)	(um)		20 km	56	2250km
	7	13.4-15	Temperature			
	1	11.1	Surface Temp(1)			
	1	9.7	Total ozone			
	3	6.7-8.3	Water vapour			
	5	4.2-4.6	Temperature			
	2	3.7-4.0	Surface Temp(1)			
	1	0.7	Cloud (2)			
MSU	(4)	(GHz)		110	11	2250
	1	50.3	Surface emissivity, cloud attenuation			
	3	53.7-58	Temperature			
SSU	3	15.0um	Stratospheric temperature	147	8	1500

(1) 3.7-4.0 um channels are used with the 11.1 um channel to detect cloud contamination and to derive the surface temperature under partly cloudy conditions.

(2) 0.7 um channel is used during the day with the 4.0 and 11.1 um infrared window channels to detect cloud-free data sets.

(3) Resolution at the subsatellite point.

(4) All three subsystems scan across the satellite track. The scans are contiguous along the orbital path at the ends of the scan lines of each instrument.

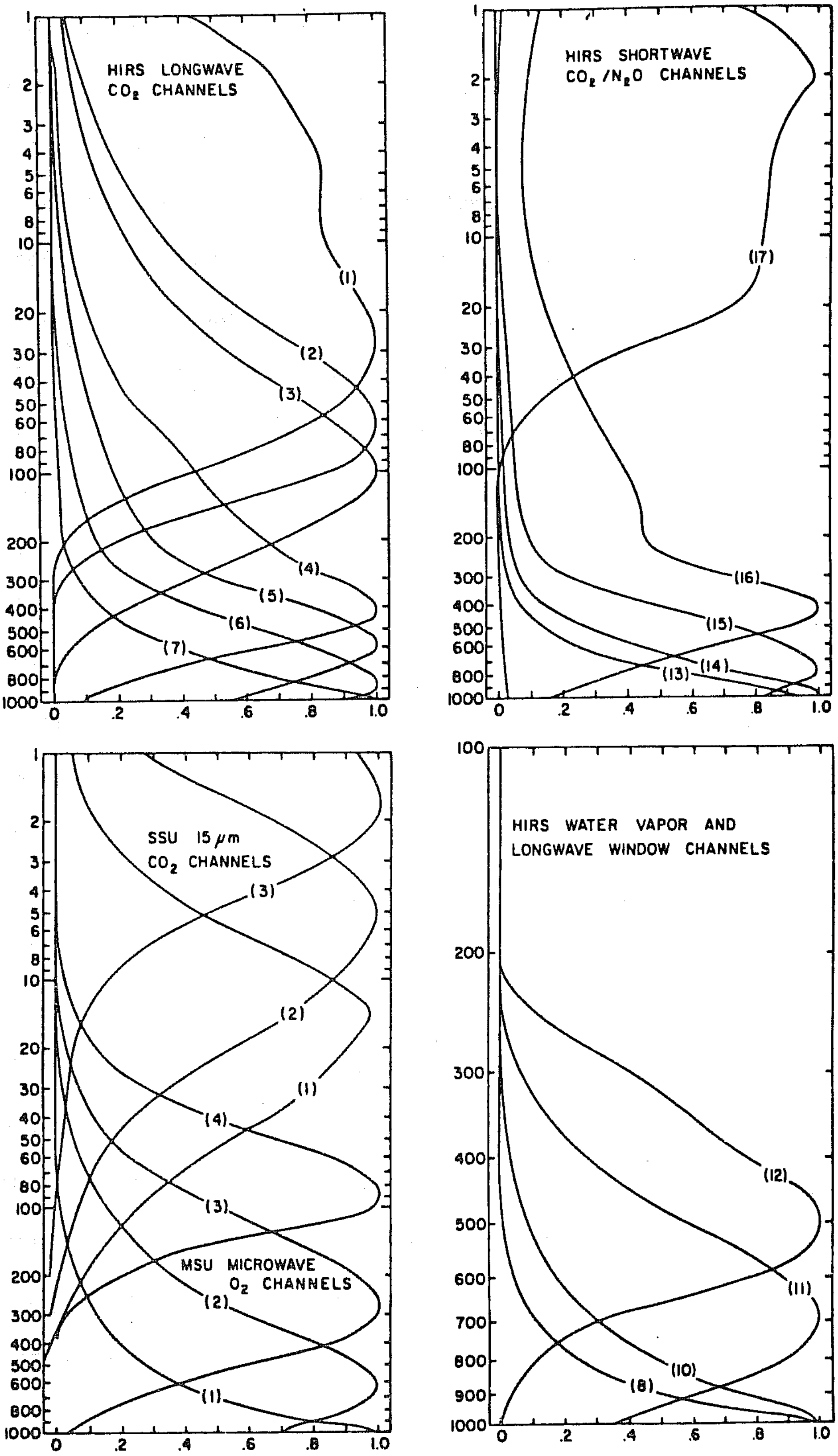

Fig. 6. TOVS weighting functions (normalized), indicative of the sensitivity of each channel to the variation of temperature with pressure-height in the atmospheric column (from Smith et al., 1979).

The TARM (McMillin and Dean, 1982) is a very important component in the sounding processing. It operates on 7 by 9 arrays of HIRS scan spots and associated MSU data to extract the true thermal emission of the atmosphere within the volume being sampled by each array. This often has been referred to as the derivation of "clear-column" radiances. A complex objective analysis scheme is used to detect if there are truly clear scan spots within the array. If there are at least four, they are averaged to produce a radiance set for a "clear" sounding which is located at the centroid of the individual clear scan spots. If there are not a minimum of four clear spots, the array is processed to determine if there are enough partly cloudy areas which can pass a complex series of quality tests to be acceptable for further processing as a "partly cloudy" sounding. Finally, those arrays which fail these tests are classified as "cloudy". In the latter cases, the MSU channels and the four channels of HIRS which sense radiation from the highest part of the atmospheric column, those presumed not to be contaminated by cloud, are compiled for subsequent processing in the retrieval module as "cloudy" soundings. The use of a 7 by 9 array of HIRS fields of view in TARM gives a nominal horizontal resolution of the resulting soundings of about 250 km.

The cross-track scan of the SSU is 1500 km compared to 2250 km for HIRS and MSU. In order to have SSU radiances available for temperature retrieval at all sounding locations determined in TARM, the TIROS Stratospheric Mapper (TSM) produces a latitude-longitude grid-point analysis of SSU radiances for adjacent orbits from which they can be interpolated to the sounding locations in the TARM output. The SSU data also are adjusted for limb effects in the TSM.

The TIROS Retrieval (TRET) module produces vertical profiles of temperature and water vapour mixing ratio, and layer mean virtual temperatures from the output of TARM and TSM. Estimates of total ozone content and the vertical distribution of cloudiness within the sounding volume also are obtained. The basic temperature retrieval technique used is the statistical eigenvector regression method (Smith and Woolf, 1976) below 100mb, and multiple linear regression above 100 mb. The regression coefficients are derived from a sample of quasi-coincident measured radiances and radiosonde observations, they are updated on a weekly basis.

Because of the low vertical resolution of the MSU, the "cloudy" retrievals, which depend upon only the three microwave channels in the troposphere, are less accurate than the "clear" and "partly cloudy" soundings. During the period through 9 June 1980, the TARM procedure of Smith and Woolf (1976) was used. With this method, 42% of the soundings were "cloudy" and produced with the microwave method (McMillin and Dean, 1982). The new TARM procedure of McMillin and Dean, reduced the number of "cloudy" soundings during the same time period to 21% of the total. This perhaps is a more important result than the improvement in the quality of the "partly cloudy" soundings. The new TARM-2 was introduced operationally on 10 June 1980. The accuracy of the remaining "cloudy" soundings was improved by operational changes introduced on 13 February and in July-August 1980.

5.2 Accuracy

Phillips et al (1979) and Gruber and Watkins (1982) have examined the performance of the TOVS and compared the satellite soundings with those obtained by radiosondes. The comparison statistics for TIROS-N during 1979 are summarized in Table 5. Phillips et al, compared only ocean soundings

Table 5 A

Comparison of TIROS-N soundings with radiosondes 1979

30 - 60°N LATITUDE

LAYER (cb)	30 JAN-28 FEB(1)			29 MAR-27 APR(1)			JULY-AUG (2)			SEPT-NOV (2)		
	N	Mean	RMS	N	Mean	RMS	N	Mean	RMS	N	Mean	RMS
	Mostly Clear			Mostly Clear			Clear			Clear		
100-85	39	-2.1	2.9	91	-0.6	2.3	334	-0.1	2.0	1390	0.7	2.7
85-70	43	0.7	2.1	97	-0.2	1.4	991	0.0	1.3	3463	0.2	1.9
70-50	45	1.3	2.6	97	0.1	1.7	989	-0.3	1.0	3418	0.1	1.5
50-40	43	0.9	2.2	94	0.3	1.8	985	-0.5	1.4	3403	0.1	1.9
40-30	39	0.6	2.2	97	0.8	2.2	986	-0.8	1.7	3381	0.1	1.9
30-20	39	-0.0	2.2	98	0.6	2.0	988	-0.6	1.8	3390	0.0	2.2
20-10	37	-0.3	1.8	98	0.2	1.8	983	0.4	1.9	3424	-0.1	2.0
	Mostly Cloudy			Mostly Cloudy			Cloudy			Cloudy		
100-85	41	-2.1	4.0	19	1.6	3.1	137	2.8	3.9	535	-0.5	3.6
85-70	47	1.5	3.1	22	1.5	2.4	293	-1.0	2.7	1488	-0.1	2.7
70-50	46	2.1	3.3	22	0.3	2.4	289	-0.9	1.7	1475	0.1	2.0
50-40	44	2.0	3.3	20	0.3	2.5	289	-1.3	2.3	1469	-0.2	2.5
40-30	45	1.6	3.1	20	0.3	2.4	291	-1.6	2.6	1457	-0.3	2.6
30-20	43	1.3	2.8	21	0.9	1.9	292	-0.2	2.7	1464	0.0	2.6
20-10	41	-0.3	1.6	15	0.0	1.6	284	0.0	2.0	1474	0.2	2.1

30°N - 30°S LATITUDE

LAYER (cb)	30 JAN-28 FEB(1)			29 MAR-27 APR(1)			JULY-AUG (2)			SEPT-NOV (2)		
	N	Mean	RMS	N	Mean	RMS	N	Mean	RMS	N	Mean	RMS
	Mostly Clear			Mostly Clear			Clear			Clear		
100-85	26	-0.5	1.0	60	-0.1	1.4				1708	0.2	1.9
85-70	29	0.4	0.8	64	0.7	1.3				3334	0.2	1.8
70-50	31	0.2	0.9	69	-0.4	1.5				3298	-0.1	1.3
50-40	31	0.7	1.1	64	-0.2	1.6				3290	-0.1	1.6
40-30	30	1.0	1.9	61	0.1	1.3				3227	-0.1	1.6
30-20	29	0.5	1.6	60	0.5	1.4				3206	0.0	1.7
20-10	28	0.9	1.6	50	1.4	2.0				3234	0.0	2.0
	Mostly Cloudy			Mostly Cloudy			Cloudy			Cloudy		
100-85	8	1.3	2.6	TOO FEW REPORTS						636	-1.1	3.0
85-70	8	0.9	1.9							1175	-0.8	2.8
70-50	7	0.1	1.1							1159	-0.6	1.5
50-40	8	-1.0	1.5							1142	-0.9	2.0
40-30	7	-2.1	2.2							1134	-1.3	2.2
30-20	6	-0.5	2.6							1071	-1.2	2.4
20-10	6	3.6	3.9							1150	0.1	2.2

(1), (2) See Table 5 B

Table 5 B

Comparison of TIROS-N soundings with radiosondes 1979

30 - 60°S LATITUDE

LAYER (cb)	30 JAN-28 FEB(1)			29 MAR-27 APR(1)			JULY-AUG (2)			SEPT-NOV (2)		
	N	Mean	RMS	N	Mean	RMS	N	Mean	RMS	N	Mean	RMS
	Mostly Clear			Mostly Clear			Clear			Clear		
100-85	14	1.2	2.7	39	-1.0	3.3				883	-0.5	2.8
85-70	12	-0.1	1.5	39	-0.5	2.1				1679	0.0	2.4
70-50	12	-1.1	1.8	38	-1.2	2.1				1620	0.1	1.9
50-40	14	-1.4	2.2	38	-1.3	2.7				1624	0.1	2.1
40-30	14	-0.4	2.0	36	-1.5	2.8				1607	0.3	2.2
30-20	13	-0.6	2.0	36	0.5	2.1				1658	0.7	2.6
20-10	9	-0.1	2.0	30	-0.1	2.2				1568	-0.2	2.2
	Mostly Cloudy			Mostly Cloudy			Cloudy			Cloudy		
100-85	12	2.2	3.4	9	-2.8	3.7				364	0.4	3.3
85-70	14	1.0	2.5	10	-2.4	2.8				708	-0.6	2.7
70-50	11	-1.1	1.8	8	-0.7	1.5				685	-0.8	2.4
50-40	11	-1.7	2.2	9	-1.5	1.8				688	-1.1	2.7
40-30	13	-2.0	2.9	11	-2.0	2.4				689	-0.8	2.5
30-20	12	1.4	2.6	11	0.0	1.6				678	0.6	3.0
20-10	11	0.0	2.1	11	0.1	1.7				663	0.1	2.3

(1) From Phillips et al (1979). Ocean stations only: seven in Northern Hemisphere extratropics, from 39 to 66°N, four in the tropics, from 29°S to 32°N, and three in Southern Hemisphere extratropics, from 40 to 54°S.

(2) From Gruber and Watkins (1982). All operational radiosonde data which passed NMC-Washington quality checks were used for comparisons, thus they are weighted toward continental conditions.

during two periods early in the FGGE observing year: 30 January-28 February, and 29 March-27 April 1979. Comparisons with seven oceanic radiosonde stations from 39° to 66°N are included in the table under latitude zone 30-60°N. In the same manner, four stations located from 32°N to 29°S are included in the zone 30°N-30°S, and three stations from 40° to 54°S are included in the belt 30°-60°S. Gruber and Watkins used all radiosonde observations in each of the three latitude zones which passed the most stringent quality control of the National Meteorological Center-Washington (A-type soundings). Thus the population of soundings used in their comparisons was much larger than Phillips et al, but it is heavily weighted to continental areas, a detriment especially for the cloudy microwave retrievals.

Both groups linearly interpolated between 12h radiosonde observations to the time of the satellite sounding, or accepted a time difference of up to 6h, if there was only one sounding in a 24h period. Gruber and Watkins accepted a spatial separation of from 1° to 3° of latitude between the nearest satellite sounding and the radiosonde with which it was being compared. The separation accepted is a function of latitude, depending on the number of radiosondes available for comparison in each latitude zone. For example, 1° separation was used in the zone 40-60°N while 3° was accepted in the zone 10-90°S. On the other hand, Phillips et al used all of the satellite sounding retrievals located within 600 km of a radiosonde station to interpolate to the station location by means of an analysis method using a standard univariate optimal interpolation process. This approach mixes up clear, partly cloudy and cloudy retrievals. Therefore, they gave clear soundings a weight of 300, partly cloudy 200 and cloudy ones 100. If the ensemble of satellite soundings being interpolated had an average weight greater than 250, it is called a "mostly clear" sounding. If the average weight has less than 150, it is considered "mostly cloudy". Only about 10% of the soundings during the two periods studied in the first half of 1979 had an average wieght between 150 and 250, and are not included in the statistics of Table 5.

Examination of Table 5 indicates a number of points regarding the TIROS-N soundings:

- In the latitude zone 30-60°N, there was a reduction in both the bias and RMS differences from the beginning of 1979 to the end. This probably reflects the many improvements introduced into the processing system during the course of the year.
- The cloudy microwave soundings in the troposphere during 1979 show both a larger (negative) bias and higher RMS difference compared to clear soundings, perhaps partially due to the limited vertical resolution of the Microwave Sounding Unit. It also may result from contamination of some microwave radiances by precipitation (Phillips, 1980), and the clear to partly cloudy conditions and continental bias of the radiosondes used to generate the retrieval coefficients (Phillips, 1981).
- The RMS differences in the tropics are small (about 1.5K is typical for clear soundings which predominate there). This is expected because of the weak temperature gradients in the tropics. This also can be taken as an indication that there is significant degradation in the statistics for higher latitudes resulting from the space-time separation between satellite soundings and radiosondes used in the comparison.
- The biases of the cloudy soundings even at the end of 1979 are still too large for comfort. This is critical since the number of cloudy soundings then was about one-third of the number of clear soundings.

Phillips (1981) points out that in winter the cloudy retrievals can form as much as 65% of the oceanic data north of 30°N. (Fortunately, the number of cloudy soundings was substantially reduced in mid-1980 by the introduction of TARM-2).

o Comparison of the means for the cloudy retirevals during the January-February period with those in July-August indicates a seasonal pattern in the mean differences or bias which probably contributes significantly to the RMS error. Phillips (1981) argues that this results from the use of continentally dominated correlation statistics whereas the cloudy retrievals are obtained primarily over the oceans.

Gruber and Watson (1982) also have compared the performance of TIROS-N and NOAA-6 during the last three months of the FGGE observing year when both were producing soundings (see Table 6). There is very close agreement between TIROS-N and NOAA-6 soundings when each are compared to radiosondes. Except in the lowest atmospheric layer (1000-850 mb), the mean and RMS differences seldom differ by more than 0.2K. This demonstrates the high precision of the TOVS radiance measurements themselves. The large differences in the means of the cloudy tropical soundings derived by TIROS-N and NOAA-6 are unexplained.

Three major changes in the processing of satellite soundings have been introduced since the end of the FGGE observational year:

o 13 February 1980 - procedure after Phillips (1980) to eliminate rain-contaminated microwave (cloudy) soundings over the oceans. Phillips also presents a method devised by Robert Green for using the radiance data on the FGGE Level IIb archive tape to eliminate the contaminated soundings retrospectively.

Table 6

Comparison of TIROS-N and NOAA-6 Soundings with Radiosondes September-November 1979

(from Gruber and Watkins, 1982)

Layer	CLEAR				CLOUDY			
	Mean		RMS		Mean		RMS	
cb)	T-N	N-6	T-N	N-6	T-N	N-6	T-N	N-6
100-85	0.7	0.4	2.7	2.3	-0.5	0.3	3.6	3.5
85-70	0.2	-0.1	1.9	1.8	-0.1	0.2	2.7	2.7
70-50	0.1	0.1	1.5	1.4	0.1	0.1	2.0	2.0
50-40	0.1	0.1	1.9	1.7	-0.2	-0.4	2.5	2.3
40-30	0.1	0.1	1.9	1.8	-0.3	-0.5	2.6	2.6
30-25	-0.1	-0.1	2.1	2.2	-0.2	-0.3	2.8	2.9
25-20	0.1	0.1	2.2	2.1	0.2	0.3	2.5	2.4
20-15	0.0	-0.1	2.2	2.1	0.4	-0.4	2.3	2.2
15-10	-0.2	-0.4	1.9	1.9	0.1	-0.1	1.9	2.0
				30^oN - 30^oS				
100-85	0.2	0.2	1.9	1.8	-1.1	-1.5	3.0	3.6
85-70	0.2	0.2	1.8	1.7	-0.8	-1.0	2.8	2.9
70-50	-0.1	0.0	1.3	1.3	-0.6	-0.2	1.5	1.6
50-40	-0.1	-0.1	1.6	1.5	-0.9	-0.1	2.0	2.1
40-30	-0.1	0.1	1.6	1.6	-1.3	-0.3	2.2	2.0
30-25	-0.1	0.1	1.7	1.8	-1.4	-0.2	2.5	2.1
25-20	0.0	0.1	1.7	1.7	-0.9	0.1	2.2	2.0
20-15	0.0	0.1	1.9	1.9	-0.3	0.3	2.1	2.0
15-10	0.0	-0.1	2.2	2.2	0.5	0.4	2.3	2.4
				30^oN - 60^oS				
100-85	-0.5	0.2	2.8	2.5	0.4	0.5	3.3	3.8
85-70	0.0	0.2	2.4	2.3	-0.6	-0.4	2.7	2.8
70-50	0.1	0.0	1.9	1.9	-0.8	-0.7	2.4	2.3
50-40	0.1	-0.1	2.1	2.2	-1.1	-1.0	2.7	2.6
40-30	0.3	0.0	2.2	2.1	-0.8	-0.6	2.5	2.5
30-25	0.6	0.6	2.4	2.4	0.0	0.2	2.7	2.5
25-20	0.8	0.7	2.7	2.4	1.2	1.1	3.2	2.8
20-15	-0.1	-0.1	2.4	2.3	0.3	0.1	2.4	2.4
15-10	-0.3	-0.2	2.1	2.1	-0.1	-0.5	2.2	2.2

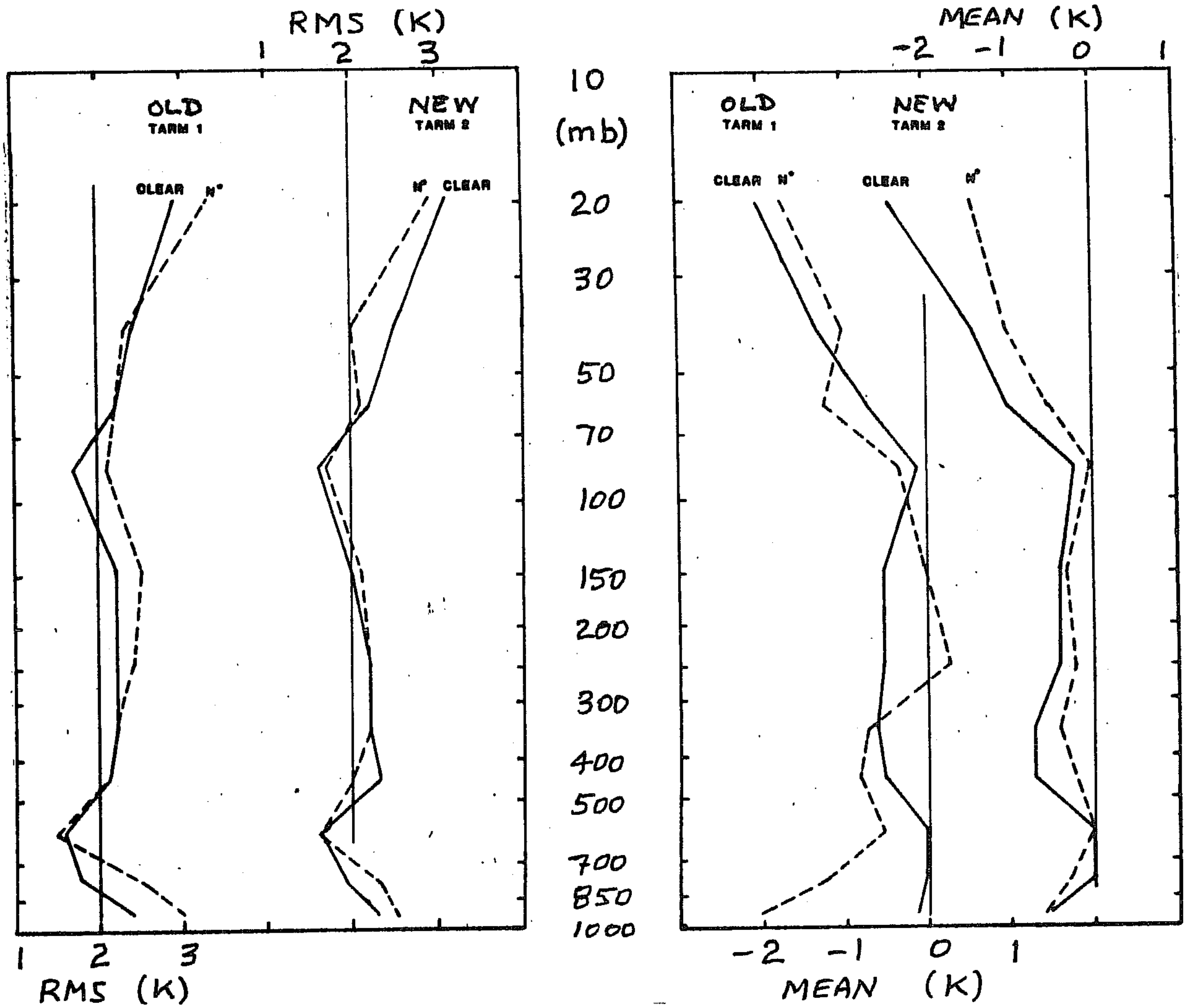

Fig. 7. Comparison of the old and new (TARM-1 and TARM-2) methods of deriving "clear" radiances from observed radiances in partly cloudy regions. Solid lines are for soundings based on radiance sets determined to be cloud-free. Dashed lines are based on the partly cloudy cases which have been corrected to derive equivalent clear radiances (from McMillin and Dean, 1982).

Table 7

RMS Differences between Old and New Method for Cloudy Retrievals and Eleven Maritime Radiosonde Stations

(After Phillips, 1981)

Time period of comparison: 8 December 1979-20 January 1980

Layer (mb)	Sample Size	Old Method	New Method	Improvement
1000-850	153	3.69	2.86	.83
850-700	283	2.70	2.39	.31
700-500	280	2.27	1.60	.67
500-400	272	2.66	2.25	.41
400-300	266	2.38	2.31	.07
300-200	267	2.24	2.15	.09
200-100	238	1.49	1.64	-.15

(Radiosonde data have been interpolated to the satellite times, and the satellite soundings within 600 km of the radiosonde interpolated to the radiosonde location.)

Table 8

Yearly* Average RMS Differences between Satellite Soundings and Radiosondes

(Based on McMillin et al., 1983)

* 1 November-31 October

Layer (mb)	Clear		Partly Cloudy		Cloudy	
	1979-80	1981-82	1979-80	1981-82	1979-80	1981-82
1000-850	2.81	2.88	3.10	3.03	3.78	3.62
850-700	2.35	2.32	2.73	2.63	3.36	3.20
700-500	2.02	1.95	2.14	2.03	2.74	2.54
500-400	2.31	2.21	2.41	2.32	2.96	2.78
400-300	2.28	2.16	2.37	2.31	2.97	2.65
300-200	2.29	2.14	2.47	2.15	2.83	2.46
200-100	2.07	1.97	2.19	1.99	2.33	2.22
100- 70	2.16	2.02	2.16	2.08	2.24	2.14

Comparisons calculated from radiosondes within ±3 hours and 3 degrees of latitude from the satellite observation.

- 10 June 1980 - the new TARM-2 procedure for deriving "clear" radiances from observed radiances in partly cloudy regions was introduced (McMillin and Dean 1982). Figure 7 shows a significant improvement in both the mean and RMS differences compared to radiosondes for the partly cloudy cases (N*), particularly in the lower layers of the atmosphere. As mentioned earlier, perhaps an even more important result was a 50% reduction in the number of soundings classified as cloudy and requiring the use of only the microwave channels in the troposphere.
- July-August 1980 - A new microwave (cloudy) retrieval scheme proposed by Phillips (1981) was introduced. Only oceanic radionsondes under primarily cloudy conditions now are used to generate the correlation coefficients, thus removing the continental and cloud cover biases which existed earlier. It also uses sea surface temperature as an additional predictor and a more direct statistical regression than the empirical orthogonal functions used previously. Table 7 compares the new method with the old for TIROS-N data during the period 8 December 1979 - 20 January 1980. There is significant improvement in all layers except the highest. The RMS difference here should be nearly the same since it is above cloud level and the infrared data should dominate.

Table 8, based on McMillin et al (1983) compares the satellite performance during the period 1 November 1979 - 31 October 1980, during which these changes were introduced, to the period November 1981 through October 1982. It is unfortunate that McMillin et al did not include data for the first year of operation, 1979, so a "before-and-after" comparison could easily be made. It is difficult to compare the data in this table with those in Table 5 from Phillips et al (1979), and Gruber and Watkins (1982) because of the differences in geographical and seasonal coverage, and in comparison procedures. However, even though the major changes were introduced during the 1979-80 year, comparison with 1981-82 shows definite improvement in all three classes of soundings and in all layers except for 1000-850 mb clear soundings. The largest improvement is for cloudy soundings, averaging 0.2 K over all layers.

Phillips (private communication) has calculated the RMS differences for oceanic soundings in the latitude belt 30-60°N for the period 17-30 November 1981 after all of the changes were incorporated. Table 9 presents his data (from Johnson, 1983). These data were handled in the same manner as those of Phillips et al (1979) used in Table 5 so that a direct comparison is more appropriate. For convenience, the relevant data from Table 5 are repeated in Table 9. The improvement is quite clear, particularly in the cloudy retrievals. They show an improvement of 1 K averaged over all layers from January-February 1979 to November 1981. In the latter period, the cloudy soundings are comparable to the partly cloudy soundings.

It is interesting to compare Phillips' data for November 1981 with the ECMWF data in Table 2. They are closely comparable and yet Phillips' data are not corrected for radiosonde errors, colocation errors or the differences in sampling between satellite soundings and radiosonde observations. Clearly, while Table 2 may be applicable during the FGGE period, it should be revised for satellite soundings produced after 1980.

5.3 Representativeness

Here we will consider briefly the questions of radiosonde accuracy, colocation errors and the sampling differences between radiosondes and satellite soundings as they relate to efforts to estimate the accuracy of the satellite

Table 9

RMS Differences Between Satellite Soundings and Radiosondes

30 - 60°N

(Based on Phillips et al., 1979 and Phillips, private communication)

	30 JAN-28 FEB 79		29 MAR-27 APR 79		17-30 NOV 1981	
Layer (mb)	Mostly Clear	Mostly Cloudy	Mostly Clear	Mostly Cloudy	Partly Cloudy	Cloudy
1000-850	2.9	4.0	2.3	3.1	2.7	2.4
850-700	2.1	3.1	1.4	2.4	2.2	2.3
700-500	2.6	3.3	1.7	2.4	1.6	1.5
500-400	2.2	3.3	1.8	2.5	2.0	2.2
400-300	2.2	3.1	2.2	2.4	2.2	2.4
300-200	2.2	2.8	2.0	1.9	2.0	1.9
200-100	1.8	1.6	1.8	1.6	1.5	1.5

- Only ocean colocations are used.
- Radiosondes are interpolated in time to that of the satellite soundings and the satellite soundings are interpolated to the radiosonde locations.
- TIROS-N only in 1979, both TIROS-N and NOAA-6 included in 1981.

Table 10

Comparison of Interpolation and Non-interpolation Techniques for Calculating RMS Differences Between Satellite Soundings and Radiosondes

(Based on McMillin et al., 1983)

Layer (mb)	Interpolated(1)	Non-interpolated(2)
1000-850	2.1	2.7
850-700	1.7	2.2
700-500	1.2	1.8
500-300	1.3	2.1
300-200	2.0	2.0
200-100	2.0	1.9
100- 70	1.4	1.7
70- 50	1.3	1.9
50- 30	1.3	1.8
30- 10	1.9	2.4

(1) The method of Phillips et al. (1979) in which 12h radiosondes are interpolated in time to that of the satellite soundings, and the satellite soundings within 600km of the radiosonde location are interpolated to that location.

(2) Colocations within ±3h and 3 degrees of latitude taken as an exact colocation in space and time.

soundings and their representativeness. McMillin et al (1983) have addressed these questions in a comprehensive way. Broderick and Thomasell (1984) have attempted to assess the relative errors of satellite soundings and radiosondes by comparing two independent objective analyses of radiosondes and satellite soundings with the same subset of radiosonde reports. These two comparisons are then used to arrive at an estimate of the "true" satellite sounding error of about 1-1.5 K for layer means, 1000-500mb and 700-300mb.

There have been many comparisons of radiosondes over the years. However, in most cases they are performed under carefully controlled conditions and do not reflect the normal operational results which also include observing, processing and communication errors. Bruce et al (1977) have used a large number of serial ascents at 90 min intervals from six stations at White Sands Missile Range, New Mexico to study atmospheric time and space variability and average radiosonde error. Their computed average radiosonde error ranged from about 0.5 K near the ground to near 1.0 K at 130 mb. McMillin et al (1983) compared averages of satellite to radiosonde differences as a function of radiosonde type. When the two most numerous radiosondes (USA and USSR) were compared, it was found that the bias of the two instruments differed by 2.0K in the upper atmosphere. This is a substantial difference when compared to the total satellite-to-radiosonde difference. It also explains some of the differences between comparison statistics for the entire globe and those produced on a regional basis where only one type of radiosonde predominates. McMillin et al (1983) have calculated the RMS differences between satellite retrievals and radiosondes for the same data set but using two different colocation processes. First, as in the normal operational approach, pairs of soundings within ± 3 hours and within 3 degrees of latitude are compared without space or time interpolation. The second method was that used by Phillips et al (1979) in which the radiosondes 12 hours apart are interpolated to the time of the satellite observation, and the satellite soundings for an area around the radiosonde location are interpolated to that location. The comparison, shown in Table 10, indicates that with one exception the interpolation method gives a lower RMS difference. The average of the interpolated differences is 1.6 K RMS compared to 2.0 K with no interpolation.

Bengtsson and Morel (1974) also compared radiosonde reports from closely spaced stations in Europe and found variations averaging about 1.5 K, reflecting both the errors of the radiosondes in the group and the atmospheric variability over distances typical for satellite-radiosonde comparisons.

Bruce et al (1977) used the White Sands data to calculate the atmospheric variability up to 15 km altitude as a function of sounding separation between the six stations used (15 combinations with different separations ranging from 10 to 157 km). Soundings were available every 90 min between 0800 and 1500 local time on 80 days between January 1969 and June 1970. They calculated the average temperature as a function of altitude for a hypothetical 100x100 km satellite sounding area and compared this with individual radiosondes located at the center of the area, at one corner of the area, and 200 km from the center. The calculated variances have been converted to the expected temperature errors due to satellite-to-radiosonde comparisons shown in Figure 8. An individual radiosonde profile anywhere within a 100x100 km area should be expected to differ from the average temperature profile for the area by about 1-1.5 K. Further, this difference increases rapidly with separation distance, approaching 2 K at only 200 km (less than 2° latitude).

Taking all of this evidence into account, it would appear that one should not expect agreement between radiosonde observations and satellite soundings as they are normally compared to closer than about 1.5-2 K RMS and that the true

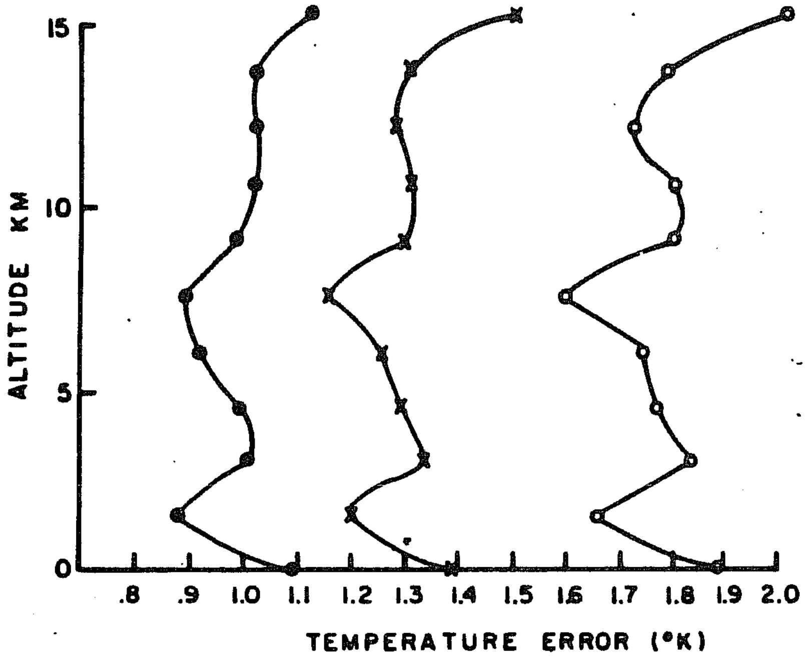

Fig. 8. Expected differences ("errors") between satellite soundings integrated over an area of 100x100 km and radiosonde observations taken (1) at the center of the area, (2) at a corner of the area, and (3) 200 km from the center (from Bruce et al., 1977).

errors of the satellite soundings in measuring volumetric average temperatures are now in the range of 1-1.5 K except for the 1000-850 mb layer. It also reinforces the conclusion that great care must be exercised in comparing performance statistics from different sources.

In global macroscale analysis and prediction models where the higher vertical resolution of the radiosonde is not important, it also appears that the satellite soundings give much more representative observations than radiosondes in terms of both volume mean temperatures and uniformity of coverage.

5.4 Outlook

It certainly would be desirable to have a global set of radiosonde stations launching specially calibrated "standard" sondes at the time of satellite observation for comparisons as well as for the development of the regression coefficients, as long as that method is used in the production of operational satellite soundings. The possibility of such a "baseline" network is being discussed within WMO circles.

There have been promising developments in physical methods of sounding retrieval which do not rely on the use of correlation coefficients with radiosondes. If this approach can be developed to a level of performance at least equal to the present operational method, it can be expected to be introduced into the operational system. This would make the satellite output completely independent of the radiosonde observations with the latter only being used for monitoring the satellite output.

Finally, the UK and USA are considering the development of a 20-channel, high resolution Advanced Microwave Sounding Unit for use on the next series of NOAA polar orbiting satellites. This instrument is expected to eliminate the cloud problem, provide at least as good vertical resolution as the present infrared channels on TOVS, reduce the aliasing which exists in the distribution of soundings within the global data sets produced today, and increase the horizontal resolution of the sounding output, if needed, to 60-120 km.

6. SATELLITE MOISTURE SOUNDINGS

6.1 The Method

The principle for deriving atmospheric moisture soundings from satellite multispectral radiance measurements is very similar to that used for temperature retrievals (Hayden, 1979, pp 20-22, Smith et al, 1979, p. 1182). The TOVS operational processing system uses the output of the temperature retrieval to establish the temperature of the water vapour in the atmospheric column. The same eigenvector regression technique then is used to obtain the vertical profile of water vapour mixing ratio, using the radiances measured by those channels particularly sensitive to water vapour.

As can be seen in the lower right portion of Figure 6, the three channels most sensitive to water vapour, (10), (11) and (12), provide only very broad vertical discrimination. Further, in the case of a moderately moist atmosphere, even the most transparent of these channels (10 and 11) receive their major contribution of radiant energy from water vapour around 800 mb, the bulk of the water vapour in the moist atmospheric column is below this level and is barely sensed by the radiometer. The dominant contribution to the radiance measured by channel 10 comes from the earth's surface, rather than atmospheric water vapour. In addition, cloud contamination, even in partly cloudy conditions, is very severe for moisture retrievals using infrared radiances. Unfortunately there are no moisture channels in the Microwave Sounding Unit.

Total precipitable water above the pressure level at which each radiance measurement becomes reasonably sensitive to water vapour is the more natural product of the measurement technique than is mixing ratio. Both the precipitable water and the radiance are vertically integrated quantities. Thus, the mixing ratio profile is a derivative quantity and not much information on its vertical structure can be provided.

Because of these limitations, little has been published on the evaluation of the TOVS moisture data or their use in analysis.

6.2 Accuracy

In evaluating TIROS-N atmospheric moisture profiles, Gruber and Watkins (1981) conclude that the technique produces highly smoothed vertical profiles and doesn't work in cloudy or partly cloudy areas. In comparisons with radiosonde data during the periods 16-18 April and 8-11 September 1979, they did find that reasonable values of total precipitable water content were given in areas on the order of 20-70 km which were cloud-free.

In the two periods selected, generally cloud-free conditions prevailed over the eastern United States so that there was good coverage of satellite moisture data for comparison with radiosondes. The area east of 110°W longitude was used to reduce the influence of mountainous terrain. Radiosonde data within 3 h of the satellite data were used, but also they interpolated between 12 h data to the times of the satellite observations. There was no correction for spatial separation; location differences of 1° latitude were acceptable in the latitude zone 40-60°N and 1.5° from 30 to 40°N.

Figure 9 shows a comparison between TOVS data and radiosondes of water vapour mixing ratio profiles in the latitude zone 30-60°N during the period

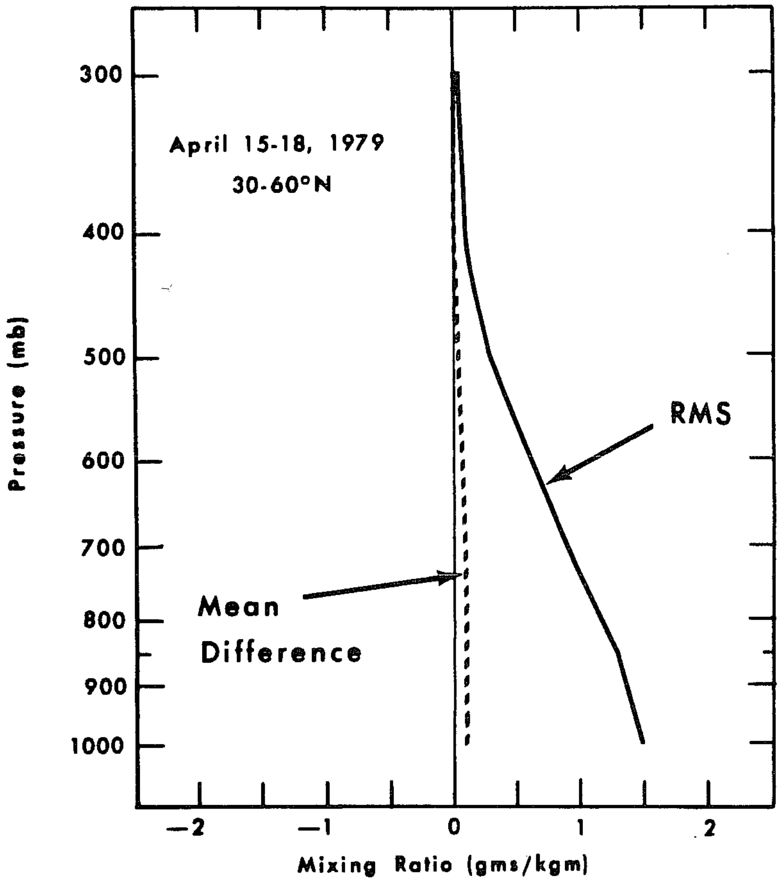

Fig. 9. Water vapour comparisons between TIROS-N TOVS retrievals and radiosondes over the eastern United States from 30 to 60° N during the period 15-18 April 1979 (from Gruber and Watkins, 1981).

Table 11

Comparisons of Precipitable Water Measured by TIROS-N and Radiosondes, Eastern United States

16-18 April 1979 (58 samples)

Precipitable water (cm)

Layer	TIROS-N Mean	 Std Dev	Radiosonde Mean	 Std Dev	Difference* Mean	 Std Dev
Sfc-700	1.2	0.3	0.9	0.4	0.3	0.5
700-500	0.3	0.1	0.2	0.1	0.1	0.1
Total	1.6	0.4	1.2	0.5	0.4	0.6

8-11 September 1979 (106 samples)

Layer	TIROS-N Mean	 Std Dev	Radiosonde Mean	 Std Dev	Difference* Mean	 Std Dev
Sfc-700	2.1	0.6	2.0	0.9	0.1	0.5
700-500	0.6	0.2	0.5	0.3	0.1	0.2
Total	2.9	0.8	2.6	1.1	0.3	0.6

* The means and standard deviations of the individual comparisons, TIROS-N minus radiosonde.

15-18 April 1979. There were 200 observation pairs at 1000 mb and 388 at each level above. The climatological average mixing ratio at 1000 mb for this latitude in April is about 6 g/kg and the standard deviation is 1.9 g/kg. Comparisons of total precipitable water, and the precipitable water in the two layers surface-700 mb and 700-500 mb for the April and September periods are given in Table 11.

Gruber and Watkins point out the overestimation by the satellite of the surface to 700 mb moisture in April when a warm, dry high pressure system dominated the region. They attribute the over estimation to the correlation coefficients being dominated by predominantly moist data. They also find that the satellite is not good at estimating extreme conditions in the surface-700 mb layer.

Note that the mean precipitable water content derived from the satellite radiances always is greater than the radiosonde means during both periods. In the April period, the standard deviations of the individual TIROS-N minus radiosonde observations equal or exceed the standard deviations of either the TIROS-N or radiosonde observations. That is, the variations between satellite and radiosonde is larger than the variations in water content measured by either technique.

From these results it is easy to see how the satellite determinations of water vapour, except for total content, have received little attention. Hayden et al (1981) have taken a different approach to the derivation of layer average estimates by a rather complex process using surface observations and requiring careful subjective editing with an interactive processor. The technique involves three major changes to the current operational methods. First, the surface contribution to the outgoing radiance is estimated in a rather complex process and subtracted from the measured radiances before making temperature and moisture retrievals. Second, the temperature-moisture solution is iterated to ensure that the radiative transfer equation is satisfied for low-level moisture. Third, in areas of extensive cloud cover, a cloud-moisture model is used to define the atmospheric moisture below the cloud.

The results for only one case study are given. This case gave good agreement with radiosondes in respect of the patterns and gradients of moisture in the surface-700 mb and 850-500 mb layers. However, point comparisons with radionsondes show large discrepancies which are attributed to the different methods of sampling the moisture which is too variable in space and time.

Additional tests of this approach may establish its value in space and time interpolation of moisture fields in areas already blessed with a reasonable network of surface and radiosonde observations. However, the processing scheme does not appear suitable for routine operational retrievals of moisture from satellite data.

6.3 Representativeness and Outlook

Since moisture is not a very conservative atmospheric parameter, but is highly variable in space and time, it always will be difficult to provide a reasonable means of verifying satellite retrievals. Certainly the instantaneous spot profiles obtained from radiosondes once or twice a day will not be adequate. A ground-based network of instruments continuously measuring total precipitable water, combined with a dense network of radiosondes may prove useful.

The water vapour portion of the Advanced Microwave Sounding Unit (AMSU) being developed by the United Kingdom offers promise of providing useful profiles of moisture under both cloudy and clear conditions. It will have four moisture channels whose weighting functions will peak at the surface, 800, 600 and 400 mb and whose vertical resolution is better than the moisture channels of TOVS (Figure 10). The field of view will be 20 km compared to the 110 km of the TOVS MSU. We look forward to the evaluation of the AMSU data when they become available in the early 1990's.

7. SEA SURFACE TEMPERATURE

Sea surface temperature can be and are derived as an internal part of the TOVS sounder processing. However, the routine sea surface temperature determinations disseminated during and subsequent to FGGE have been produced from the radiances measured by the Advanced Very High Resolution Radiometer (AVHRR) flown on the TIROS-N series (Schwalb, 1978). The AVHRR instruments flown on TIROS-N, NOAA-6 and NOAA-8 included four channels: 0.55-0.90 (visible), 0.725-1.10 (near infrared), and 3.55-3.93 and 10.3-11.3μm (atmospheric infrared windows). The visible channel was narrowed to 0.58-0.68um and a fifth window channel, 11.5-12.5μm was added to the AVHRR flown on NOAA-7 and to be flown on NOAA-9 et seq. The resolution of AVHRR in all channels is about 1 km at the subsatellite point. The global coverage digital data stored on the satellite are averaged to a resolution of 4 km. The noise level of the system is very low: equivalent to 0.1% in albedo for the visible and near infrared channels, about 0.2 K for the 3.7 um channel, and less than 0.1 K for the 11 and 12 um channels.

7.1 The Method

The initial operational production of sea surface temperatures was based on the use of linear regression coefficients based on approximately colocated ship and satellite observations. Because of the major effect of clouds, the HIRS sounder data were used with the AVHRR in a cloud classifier - filtering

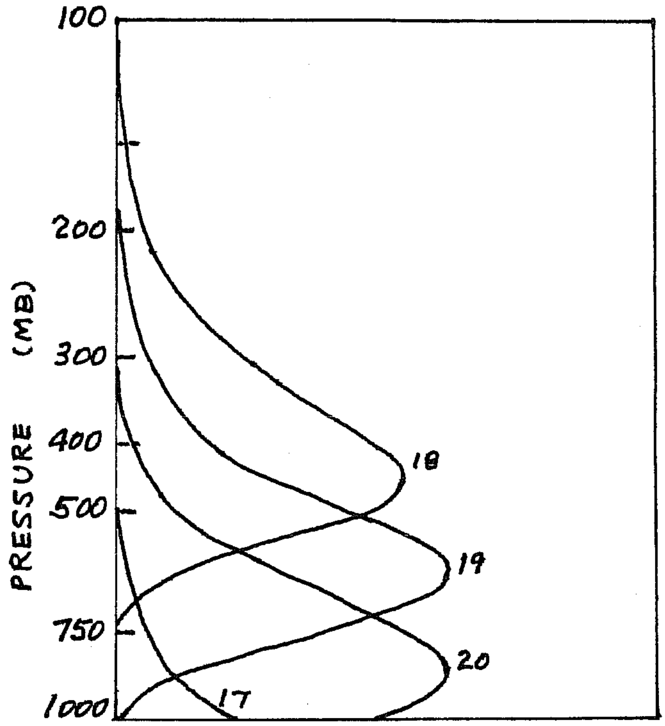

Fig. 10. Weighting functions for the water vapour channels of the Advanced Microwave Sounding Unit, indicative of the sensitivity of each channel to water vapour as a function of pressure height (U.S. Standard Atmosphere).

technique and for atmospheric corrections of the AVHRR radiances (Walton, 1980). This initial data processing system, used until November 1981, did not take full advantage of the multi-spectral channels of the AVHRR and was handicapped by using merchant ship data to establish the correlation coefficients. As a result, comparisons of the operational satellite sea surface temperatures with ship data for April 1979 showed RMS differences of 1-2 K and mean differences of -0.2 K (satellite colder), the bias in the tropical zone 10^{o}N-10^{o}S was -1.2 K (Johnson, 1979).

This performance was poorer than the requirements and expectations for such data (Table 1). This led to a change in the operational processing scheme in November 1981 to one which takes full advantage of the multispectral capability of the AVHRR (McClain et al, 1983). Bernstein (1982) has shown the importance of eliminating all cloud contamination from the satellite radiance observations. In particular, radiance observations containing contamination by spatially unresolved clouds, smaller than the 1 km field of view of the sensor, must be eliminated. By careful processing and editing of full resolution TIROS-6 daytime observations (so the visible channel could be used to minimize cloud contamination), Bernstein achieved a significant improvement in the quality of satellite determinations.

Several workers also have stressed the importance of accurately determining atmospheric corrections, primarily for water vapour. McMillin and Crosby (1984) present the theory for the use of multiple infrared window channels to achieve a significant improvement in the accuracy of sea surface temperatures derived from satellite radiances. McClain et al (1983) summarize the practical application of both cloud filtering and multiple channels to the operational processing. While perhaps not as effective as Bernstein's technique for minimizing contamination by clouds, it is more suitable for routine, global data processing and produces temperatures of comparable quality.

Cloud contaminated radiances are filtered out by a series of tests which compare the visible channel responses (in daylight only) with the values expected in the absence of clouds; by comparing responses in a 2x2 array of adjacent field-of-view measurements and requiring that they agree to within the very low variation of the instrument system noise; and at night by comparing the coincident radiances in the 3.7 um and the 11 or 12 um windows to detect the presence of continuous low cloud cover, thin cloud layers or sub-resolution cloud elements.

Before this cloud filtering, the 4 km resolution global AVHRR data are processed in 11x11 scan-spot arrays with the centers of adjacent arrays spaced approximately 25 km apart, thus providing large overlap between adjacent arrays. Various quality tests are performed on these arrays. Out of 840,000 arrays processed daily, about 320,000 pass all of the preprocessing quality tests. The remaining arrays are split between day and night data, generally about 140,000 and 180,000, respectively.

After the arrays have been processed through the day or night cloud filters, the sea surface temperatures are calculated using the multi-channel, linear regression equations. The regression coefficients, with temperature dependent bias corrections, were established by comparison of satellite data with buoy temperatures matched within 25 km and 24 hours. The resulting equations for day and night are:

$$T = 1.035T_{11} + 3.046\ (T_{11} - T_{12}) - 283.93 \quad \text{(day)} \qquad (1)$$

and

$$T = 1.060T_{11} + 1.038\ (T_{3.7} - T_{12}) - 289.55 \quad \text{(night)} \qquad (2)$$

where $T_{3.7}$, T_{11} and T_{12} are the brightness temperatures in degrees K as measured in the three infrared channels of the AVHRR. The coefficients are not revised regularly as is done in the processing of TOVS atmospheric sounding data. Typically about 15-20,000 daytime temperatures are produced each day over the globe and about 20,000 at night for a daily total of 35-40,000.

7.2 Accuracy

The rather poor accuracy of operational sea surface temperature determinations from AVHRR prior to November 1981 already has been mentioned. Bernstein (1982) did use NOAA-6 AVHRR data from the northeast Pacific Ocean during the period August 1979 through November 1980 to obtain temperatures which agree with expendable bathythermograph (XBT) and buoy data within about 0.6 K RMS. But the procedure used to process the satellite data limit its application to projects of limited scope in time and space and where full resolution (1 km) data are available, rather than the 4 km global data.

McClain et al (1983) have compared the temperatures from the new operational technique with those obtained from buoys and merchant ships. The results in Table 12(a) were obtained in comparison with buoy observations coincident within 25 km and 24 h with the satellite observations. The buoys were located in the western Atlantic, eastern Pacific, Gulf of Mexico and the Great Lakes; their temperatures ranged from 278 to 303 K. We find the agreement now is much better than 1 K and the bias is very small. They also used the same data set with the previous operational TIROS-N retrieval algorithms; 73 comparisons with buoys gave a bias of -0.40 K and RMS difference of 1.46 K.

McClain et al also compared the satellite data with merchant ship reports coincident within 100 km and 48 hours in November 1981 and determined the mean and RMS differences for each 20° latitude band from 60°S to 80°N. They found an overall RMS difference of 1.56 K for the new method compared to

Table 12

Comparisons of Current Operational AVHRR Sea Surface Temperature Retrievals with the In situ Observations

(a) McClain, et al . (1983)

November 1981 operational regression coefficients

	Sample	Bias	RMS
Buoys, daytime	76	+0.02	0.78
nighttime	74	+0.02	0.58

(b) Strong and McClain (1984)

November 1981 - August 1982 (except latitude bands beneath the El Chichon aerosol cloud), operational retrievals with November 1981 regression coefficients

	Sample	Bias	RMS
Merchant ships	24,792	-0.43	1.81
Moored buoys	240	-0.47	1.05
Drifting buoys	472	-0.22	0.68

(c) Strong and McClain (1984)

Revised regression coefficients with November 1981-August 1982 data base

	Sample	Bias	RMS
Drifting buoys only, daytime	68	-0.02	0.49
nighttime	84	-0.01	0.57

2.19 K for the old method. The ten-day average RMS and bias values for all of the 20° latitude bands also showed global uniformity in the performance using the new method.

Strong and McClain (1984) compared the operational satellite retrievals during the period November 1981 - August 1982 with merchant ships, moored buoys and drifting buoys with the results shown in Table 12(b).

Excellent agreement is found with the drifting buoys except for the small bias of -0.22 K. The larger difference in the comparisons with the moored buoys probably results from their location in coastal areas where higher horizontal temperature gradients prevail and reflect the added errors resulting from the 50 km and 24 h maximum separation between satellite and in situ measurement which was allowed. The poor quality of the merchant ship data is indicated by the large RMS difference compared to either class of buoy data.

A persistent negative bias of about 0.4 K characterized the nighttime satellite retrievals from early 1982 until mid-September 1982. The bias was removed at that time by revising the coefficients in the regression equations on the basis of 164 comparisons with drifting buoys only. The new coefficients are:

$$T = 1.0346\ T_{11} + 2.58\ (T_{11} - T_{12}) - 283.21 \quad \text{(day)} \qquad (3)$$

and

$$T = 1.0170\ T_{11} + 0.97\ (T_{3.7} - T_{12}) - 276.58 \quad \text{(night)} \qquad (4)$$

These revised equations were then tested with 152 independent comparisons with drifting buoys from the period November 1981 - August 1982 with the results shown in Table 12(c). For both day and night data combined, the revised RMS difference now is 0.54 K and the bias -0.01 K.

Problems with the sea surface temperature retrievals developed after the eruption of the El Chichon volcano in April 1982. The number of daytime retrievals was drastically reduced beneath the expanding volcanic aerosol cloud due to the daytime cloud tests in the processing system. According to Strong et al (1983), pronounced negative biases developed in the nighttime retrievals that passed the tropospheric cloud screening tests. Biases as large as -2 K in the region of the volcanic cloud continued through 1982 and only began to decrease in the (N.H.) spring, 1983. They have developed a technique for use in daytime to correct for the aerosol cloud by estimating the optical depth through the volcanic cloud from the AVHRR visible channel data. It appears that for optical depths less than 0.5, a linear relationship exists between optical depth and the negative bias. The correlation coefficient is 0.8 and the standard deviation is 0.9 K.

The optical depth technique cannot be used at night. Strong et al have proposed using the three infrared channels in two pairs, 3.7 and 11, and 11 and 12um to derive two sea surface temperatures. In the absence of a high altitude volcanic cloud the two temperatures should be nearly the same. However, with such a cloud the second temperature will be noticeably less than the first. This temperature difference is then used to correct the standard nighttime retrieval algorithm. Simulation studies indicate that this procedure may produce RMS errors below 0.5 K with or without aerosols being present. However, definitive testing is awaiting the launch late in 1984 of the next 5-channel AVHRR on NOAA-9.

7.3 Representativeness

Bernstein (1982) indicates that the temperature of the surface "skin" of the ocean, which the satellite is measuring, can differ by 0.1-0.5 K from the bulk temperature at 1m depth which is normally measured by buoys. He also indicates that the diurnal variation in the surface skin temperature can be as large as 0.5 K, and horizontal gradients can be a few tenths of a degree over a few tens of kilometers. Of course the largest differences should be expected in regions of calm seas and winds. Taking these natural variations into account, it is not likely that differences much smaller than 0.5 K can be obtained even between perfect satellite and buoy measurements, considering the space and time colocation windows used in comparisons.

Bernstein quotes an accuracy of about 0.2 K for both expendable bathythermographs (XBTs) and drifting buoys. Strong and McClain (1984) compared XBT observations with satellite temperatures and found that the variation of the differences exceeds that observed month after month in comparisons of satellite determinations with drifting buoys. Strong and McClain point out that the drifting buoys stay in the same water mass so that the temperature changes occur quite slowly, with most observations in one day not varying by more than ±0.1 K. They believe that the RMS accuracy of the drifting buoys is better than 0.5 K. Their comparisons of satellite temperatures with both fixed and drifting buoys (Table 12b) indicate the superiority of drifting buoys for commparisons with satellite data. The larger departures in respect of the fixed buoys most likely result from their use in areas with large time and space gradients of temperature, associated with the time and space acceptance window for the comparisons with satellite determinations.

All evidence points to the relatively poor quality of merchant ship temperatures. Comparisons were made by Saur (1963) between normal "intake" ships' temperatures and special "bucket" temperatures measured by trained meteorological technicians aboard 12 vessels operating for more than a year in the North Pacific Ocean. The bias of the total fleet was 0.7 K and the standard deviation 0.9 K. The bias of individual ships varied from -0.3 to +1.7 K; the 95% confidence limits for the fleet bias were 0.7 ±0.3 K. Bernstein compared individual ship reports with sea surface temperature analyses based on all of the ship observations and found a standard deviation of 1.24 K for 2295 ship observations. Similar analyses of his satellite determinations gave a standard deviation of the scatter of 0.61 K for 2050 observations. Strong and McClain (1983) point out (Table 12b) that the RMS difference between satellite and merchant ship temperatures (1.8 K) is about three times that found in comparisons between satellites and drifting buoys. Part of this difference can be a sampling problem. As Strong and McClain point out, the water sampled by merchant ships is usually at depths of 5m or more; temperatures at these depths can differ by several tenths of a degree from those of the surface, especially during periods of weak vertical mixing.

7.4 Outlook

These data indicate that present AVHRR satellite sea surface temperatures are superior to merchant ship data and exceed the minimum requirement of 1 K. They appear to approach the accuracy of good buoy data when space and time variability of surface temperature is considered. There is a problem underneath volcanic plumes in the stratosphere. More work must be done on this problem before any assurance can be given regarding the utility of the satellite determinations under these conditions.

Drifting buoys have established themselves as the preferred in situ sensing device for monitoring the performance of the satellite retrievals. A moderate number of these buoys distributed globally should be maintained to provide for continued monitoring of the satellite observations. The AMSU may provide competitive data in respect of accuracy, while also eliminating the contamination by both clouds and volcanic eruptions which affect infrared measurements.

8. CONCLUSION

We see that the quantitative data routinely derived from satellite observations have improved since 1979, the FGGE observational year. In 1984 only the operationally produced moisture profiles are not of adequate quality to be useful. Referring back to the minimum requirements for FGGE and the satellite expectations set forth in 1973 (Table 1), the temperature soundings meet the expectations except in the 1000-850 mb layer and may be approaching the requirement of 1 K, when the sampling differences and radiosonde accuracies that affect comparisons of satellite retrievals are considered. The Advanced Microwave Sounder Unit offers promise of further improvement in temperature sounding as well as the likelihood of producing useful moisture profiles.

Cloud-motion winds now seem to have stabilized in their accuracy among the GMS, GOES and METEOSAT products at about 4-6 mps for low level and 12 mps for high-level winds. While this does not achieve the minimum requirement of 2-3 mps, they are improved over those produced during FGGE and have shown utility.

Sea surface temperature observations now are produced from satellite data with a horizontal resolution of 50 km and an accuracy considerably better than the minimum requirement of 1 K. This represents a significant improvement over the retrievals obtained during the FGGE observing year.

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