SATELLITE TEMPERATURE SOUNDINGS

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1. INTRODUCTION

Since 1969 passive infrared and microwave radiometers have been used to provide vertical temperature and moisture profiles for Numerical Weather Prediction. The greatest impact has been demonstrated in the Southern Hemisphere, for example a study by Kelly et al. (1978) showed a large forecast improvement in the Australian region using satellite derived vertical profiles. Other studies have also demonstrated improved Southern Hemispheric forecasts (e.g. Bengtsson, 1985; Kashiwagi, 1987). The forecast impact in the Northern Hemisphere is less evident and it now appears, with the current ECMWF assimilation system that the current operational methods of satellite retrieval can in fact degrade the analysis in some situations unless strong quality control is applied (Pailleux et al., 1988). It is now even more important that the interface between the satellite radiances measurements and the data assimilation be examined, better retrieval methods be developed and the improvements offered by new satellite instruments be studied.

2. SATELLITE SOUNDINGS (PAST AND PRESENT)

a) Instruments (Table 1)

Infrared instruments have evolved from the medium spectral and low spatial resolution interferometer and grating spectrometer flown on the Nimbus-3 satellite in 1969 to the high spatial and low spectral resolution filter radiometers currently flying on the operational polar orbiting (NOAA) and geostationary (GOES) satellites. The microwave radiometers utilized have been of the conventional Dicke design. The evolution of the infrared sounding instruments has been driven by the need for high spatial resolution to probe the clear air interstices of the earth's broken cloud cover. Microwave soundings, which penetrate clouds, were initially much larger and heavier and consumed more power than infrared radiometers when compared with infrared sounders on a per channel per unit field-of-view basis. Advances in microwave radiometer technology have permitted the number of spectral channels to be increased, the field-of-view reduced, and the signal-to-noise ratio (SNR) to be improved without a corresponding increase in the weight, volume, and power requirements.

The current satellite sounding capability is represented by the 27 spectral channel system of infrared and microwave instruments called the TIROS Operational Vertical Sounder (TOVS) flying aboard NOAA polar orbiting satellites, the seven channel Special Sensor Microwave Temperature (SSM/T) sounder aboard the U.S. Air Force's polar orbiting Defense Meteorological Satellite (DMSP), and the 12 spectral channel infrared VISSR Atmospheric Sounder (VAS) aboard the U.S. Geostationary Operational Environment Satellite (GOES). These three currently operational sounding systems are quite different in their capabilities. The polar orbiting NOAA/TOVS has higher spatial resolution than its SSM/T counterpart aboard the DMSP (22-km in the IR and 110-km in the MW versus 175-km in the MW for SSM/T). The temporal resolution is limited to 12 hours by the polar orbit of each satellite (higher temporal coverage is achieved by assimilating data from the combination of satellites). On the other hand, the VAS possesses a very high spatial (8-km) and temporal (typically one hour) resolution, but its data are geographically limited to that portion of the earth's area (typically 20% of the earth's area) in view of the GOES. The vertical resolution of each system is also different as shown by the temperature profile weighting functions (discussed in the next section) for each spectral channel (Fig. 1).

b) Radiance processing

The first problem is to remove the effect of cloud on the satellite measurements, principally on the infrared channels. However, liquid water and rain affect certain microwave channels. The current NESDIS operational method produces so-called "clear" and "cloud-cleared" radiances (McMillin and Dean, 1982), however, cloud detection and cloud-clearing processes still are a major source of error. Some retrieval methods limit themselves to the detection of cloud and only use cloud-free channels (Smith et al., 1985; Chedin, 1989; McMillin 1989). Other methods attempt to retrieve temperature and humidity profiles simultaneously (e.g. Susskind et al., 1984; Smith et al., 1987; Eyre, 1989).

Table 1 Passive Radiometers for Sounding the Lower Atmosphere from U.S. Satellites

Year	Spacecraft	Sensor Name	Sensor Type	Number of Spectral Channels	Spectral Intervals (Nominal Resolution)	Angular (Ground) Resolution	Scanning Limits
1969	NIMBUS-3	SIRS-A	Grating Spectrometer	8	11-15 μm (5 cm^{-1})	12° (250 km)	nadir only
		IRIS-A	Michelson Interferometer	240	6.2-25 μm (5 cm^{-1})	8° (170 km)	nadir only
1970	NIMBUS-4	SIRS-B	Grating Spectrometer	14	11-35 μm (5 cm^{-1})	12° (250 km)	±35
		IRIS-D	Michelson Interferometer	393	6.25-25 μm (2.8 cm^{-1})	5° (100 km)	nadir only
1972 to 1979	ITOS-D Series	VTPR	Filter Wheel Radiometer	8	12-19 μm (15 cm^{-1})	2.3° (55 km)	±30.3°
1972	NIMBUS-5	ITPR	Multi-Detector Telescope Radiometer	7	3.8-20 μm (15 cm^{-1})	1.5° (30 km)	±38°
		NEMS	Dicke Type Radiometer	5	0.5-1.350 cm (220 MHz)	10° (200 km)	nadir only
1975	NIMBUS-6	HIRS	Filter Wheel Radiometer	17	0.6-15 μm (15 cm^{-1})	1.5° (30 km)	±36°
		SCAMS	Scanning Dicke Type Radiometer	5	0.5-1.35 cm (220 MHz)	7.5° (150 km)	±43°
1978 to Present	TIROS-N Series	HIRS-2	Filter Wheel	20	0.6-15 μm (15 cm^{-1})	1.3° (20 km)	±49.5°
		MSU	Scanning Multi-Receiver Radiometer	4	0.5-0.6 cm (200 MHz)	7.5° (110 km)	±48°
	DMSP	SSM/T-1	Single Reflector Scanner	7	0.5-0.6 cm (250 MHz)	14° (210 km)	±36°
1980 to Present	GOES Series	VAS	Filter Wheel Radiometer	12	0.6-15 μm (20 cm^{-1})	0.2-0.4 mr (7-14 km)	360°
1990	DMSP Series	SSM/T-2	Single Reflector Scanner	5	0.16-0.33 cm (1000 MHz)	3° (46 km)	±40.5°
1991	GOES-NEXT	GVS	Filter Wheel	19	0.6-15 μm (15 cm^{-1})	0.3 mr (10 km)	±8°
Planned (1991)	Advanced TIROS	AMSU	Multiplexed Tri-reflector Radiometer	20	0.15-1.60 cm (300 MHz)	3.3° (45 km)	360°
Proposed	Advanced GOES-NEXT	HIS	Optimally Scanned Interferometer	2500	3.7-17 μm (0.4-2.0 cm^{-1})	0.3 mr (10 km)	Programmable
Proposed	Polar Platform	AIRS*	Interferometer or Grating Array Spectrometer	4000	3.4-17 μm (0.4-2.0 cm-1)	0.6° (10 km)	±49°

*Two instrumental approaches are currently being completed for the Polar Platform

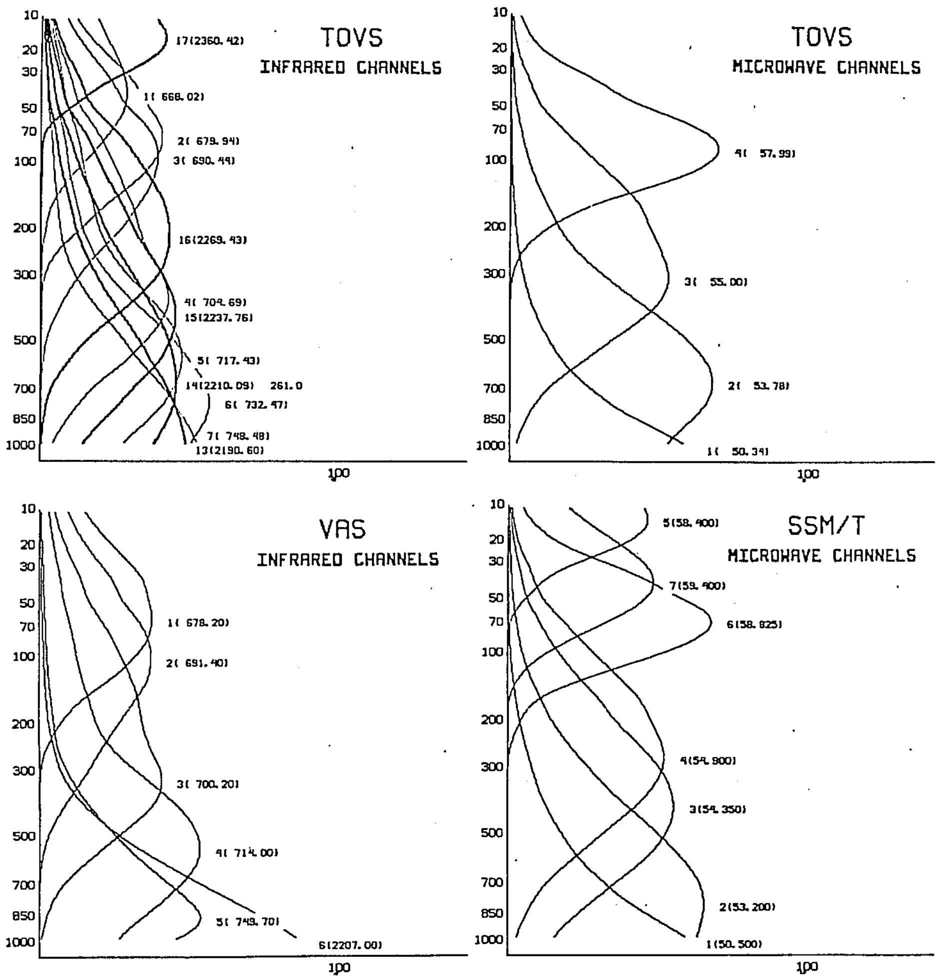

Fig. 1 Standard atmosphere dry component Planck radiance weighting functions ($d\tau/d\ln p$) for infrared and microwave channels of TOVS, VAS, and the SSM/T. The channel central frequencies (cm^{-1} for infrared and GHz for microwave) are given in parentheses.

3. THEORY

(a) Radiative transfer equation

The physical principal governing the temperature profile measurements is the same for all of these sensors. The temperature structure of the atmosphere is inferred from measurements of the earth's radiance in an absorption band due to gaseous constituents whose concentration is uniform. (The 4.3 μm CO_2, 15 μm CO_2, and 5 mm O_2 bands are used for the temperature profile sensing. Table 2 shows the TOVS sounding channels characteristics). The instruments are designed to measure the radiance of different frequencies or wavelengths within one or more of these bands. By varying the frequency, one varies the level of the atmosphere from which the measured radiation originates. For example, absorption is most intense at the centre of the band; consequently, this radiation emanates from only the very top of the atmosphere because of the strong attenuation at lower levels. On the other hand, radiation arising from the lowest regions of the atmosphere can be measured at those frequencies far from the band centre which are characterized by little absorption. Radiation received from intermediate levels is measured at frequencies associated with moderate absorption.

The outgoing radiance from earth measured by any channel of TOVS is related to the atmosphere's temperature and absorbing gas structure by the radiative transfer equation.

$$R(\nu) = B_\nu[T(p_o)]\ \tau_\nu\ (p_o) - \int_o^{p_o} B_\nu[T(p)]\ \frac{d\tau_\nu(p)}{dx(p)}\ dx(p), \qquad (1)$$

where $R(\nu)$ is the outgoing spectral radiance within a spectral channel centred at frequency ν, B_ν, the Planck radiance for temperature $T(p)$ at pressure p, $\tau_\nu(p)$ the transmittance of the atmosphere above pressure p, and $x(p)$ is an arbitrary function of pressure.

In particular, the radiation received at frequency ν is the sum of all the radiance contributions from the earth's surface and from all individual levels in the atmosphere.

$$R(\nu_j) = \sum_{i=1}^{N} B[\nu_j, T(p_i)]\, w(\nu_j, p_i) \qquad (2)$$

with

$$w(\nu_j, p_i) = \varepsilon(\nu_j, p_i)\ \tau(\nu_j, \sigma_{p_i})$$

In (2) $B[\nu_j, T(p_i)]$ is the Planck radiance source for the i^{th} pressure level (p_i), having a temperature T, $\varepsilon(\nu_j, p_i)$ is the emissivity of the emitting medium at the pressure p_j for the radiation of frequency ν_j, $\tau(\sigma_{p_i})$ is the transmissivity of the atmosphere above the i^{th} level.

$B(\nu,T)$ is explicitly

$$B(\nu,T) = C_1\nu^3/[\exp\ (C_2\nu/T)-1] \qquad (3)$$

where C_1 and C_2 are the constants of the Planck function.

The term on the right of (2) is the sum of the component of radiance arising from the surface and all the radiation components originating in the atmosphere itself. These radiance contributions are weighted by the function $w(\nu_j, P_i)$ reference (Fig. 1) and Table 2.

The problem is to determine the temperature of the N levels from radiance observations at say M discrete frequencies. However, because of the vertical width of the weighting functions, there is no unique solution; that is, many different temperature profiles will give rise to the same radiance measurements. Furthermore, the temperature profile solution tends to be unstable in the sense that small radiance measurement errors tend to produce disproportionately large errors of temperature.

In view of these difficulties many methods for solving the numerical problem have been proposed. In most of these, the solution is approximated in a linear form. The coefficients of the solution can be defined in several ways.

Table 2 Characteristics of TOVS sounding channels

HIRS Channel number	Channel central wavenumber	Central wavelength (μm)	Principal absorbing constituents	Level of peak energy contribution	Purpose of the radiance observation
1	668	15.00	CO_2	30 mb	Temperature sounding. The 15 μm band channels better sensitivity to the temperature of relatively cold regions of the atmosphere than can be achieved with the 4.3 μm band channels. Radiances in Channels 5, 6 and 7 are also used to calculate the heights and amounts of cloud within the HIRS field of view.
2	679	14.70	CO_2	60 mb	
3	691	14.50	CO_2	100 mb	
4	704	14.20	CO_2	400 mb	
5	716	14.00	CO_2	600 mb	
6	732	13.70	CO_2/H_2O	800 mb	
7	748	13.40	CO_2/H_2O	900 mb	
8	898	11.10	Window	Surface	Surface temperature and cloud detection
9	1028	9.70	O_2	25 mb	Total ozone concentration
10	1217	8.30	H_2O	900 mb	Water vapour sounding. Provides vapour corrections for CO_2 and window channels.
11	1364	7.30	H_2O	700 mb	
12	1484	6.70	H_2O	500 mb	
13	2190	4.57	N_2O	1000 mb	Temperature sounding. The 4.3 μm band channels provide better sensitivity to the temperature of relatively warm regions of the atmosphere than can be achieved with the 15 μm band channels. Also, the short-wavelength radiances are less sensitive to clouds than those for the 15 μm region.
14	2213	4.52	N_2O	950 mb	
15	2240	4.46	CO_2/N_2O	700 mb	
16	2276	4.40	CO_2/N_2O	400 mb	
17	2361	4.24	CO_2	5 mb	
18	2512	4.00	Window	Surface	Surface temperature. Much less sensitive to clouds and H_2O cloud contamination and derive surface temperature under partly cloudy sky conditions. Simultaneous 3.7 and 4.0 μm data enable reflected solar contribution to be eliminated from observations.
19	2671	3.70	Window	Surface	
20	14367	0.70	Window	Surface	Cloud detection. Used during the day with 4.0 and 11 μm window channels to define clear fields of view.

MSU	Frequency (GHz)	Principal absorbing constituents	Level of peak energy contribution	Purpose of the radiance observation
1	50.31	Window	Surface	Surface emissivity and cloud attenuation determination.
2 3 4	53.73 54.96 57.95	O_2 O_2 O_2	700 mb 300 mb 90 mb	Temperature sounding. The microwave channels probe through clouds and can be used to alleviate the influence of clouds on the 4.3 and 15 μm sounding channels.

SSU	Wavelength (μm)	Principal absorbing constituents	Level of peak energy contribution	Purpose of the radiance observation
1 2 3	15.0 15.0 15.0	CO_2 CO_2 CO_2	15.0 mb 4.0 mb 1.5 mb	Temperature sounding. Using CO_2 gas cells and pressure modulation, the SSU observes thermal emissions from the stratosphere.

(b) The numerical solution

Because of the known nature of the atmosphere, there is no need to determine the entire magnitude of T. One always has available a reasonable guess of the solution, for example, a climatology mean for a forecast profile. Hence, it is convenient to write equation (2) in terms of a deviation from an initial state, denoted by the zero subscript.

$$R(\nu_j)-R_o(\nu_j) = \sum_{i=1}^{N} B[\nu_j,T(P_i)]-B[\nu_j,T_o(P_i)] \; W(\nu_j,P_i)+\varepsilon(\nu_j) \tag{4a}$$

where $\varepsilon(\nu_j)$ is the measurement error. In matrix form

$$\underline{r} = \underline{b}\underline{\underline{W}} + \underline{\varepsilon} \tag{4b}$$

In order to solve (4) for the temperature profile it is necessary to linearize the Planck function dependence upon frequency. This can be achieved since in the infrared region the Planck function is much more dependent upon temperature than frequency.

The general inverse solution (Fleming and Smith, 1971) of (4) for the temperature profile takes the form

$$B[\nu_r,T(P_i)] - B[\nu_r,T_o(P_i) = \sum_{i=1}^{M} a(\nu_j,P_i)[R(\nu_j)-R_o(\nu_j)] \tag{5a}$$

where ν_r is the fixed central reference frequency used for the Planck function linearization and the temperature is obtained from the inverse of (3).

$$T = C_2 \, \nu_r/\ln[(C_1\nu_r^3/B) + 1] \tag{5b}$$

The matrix form of (5) is

$$\underline{b} = \underline{r}\underline{\underline{A}} \tag{5c}$$

Assuming negligible measurement error,

$$\underline{\underline{A}} = \underline{\underline{W}}^{-1} \tag{6}$$

where "$^{-1}$" denotes the inverse matrix. In practice, however "A" cannot be defined by (6) because of the near singularity of the matrix W. This is due to the lack of vertical independence of the weighting functions as can be seen in Fig. 1. This direct solution is highly unstable in the sense that small errors of radiance measurement cause disproportionately large errors of temperature.

Various retrieval methods have been used to equation (5c) and a comprehensive review is given by Rodgers (1976). In the past NESDIS used a real time regression method as described by Smith (1976) and (1979). Currently NESDIS have changed to a library search method to obtain the background profile and follow this with a minimum variance solution (Golberg et al., 1986, 1988; Fleming et al., 1988). These methods are described in this volume by McMillin. Two alternate retrieval methods: 3I (Chedin) and Nonlinear Optimal Estimation (Eyre) are also described in this volume.

4. PRESENT OPERATIONAL PERFORMANCE

Typical operational coverage received at ECMWF for NOAA10 and DSMP are shown in Figs. 2a and b. The horizontal resolution of NOAA10 is approximately 250 km which is reduced from an initial resolution of 80 km. DMSP is received at its full resolution of about 200 km.

A guide to the accuracy of sounding products can be found by collocating satellite sounding and radiosondes (±3 HR and 200 km). There is at least 1° RMS in the collocation due to the time and space window. Figs. 3 a, b, c, and d show statistics for a 6 day period just after the introduction of the NESDIS physical method. The TOVS clear soundings are the most accurate and have least bias, the "NSTAR" (partly cloudy) and the "CLOUDY" soundings are of similar quality.

5. FUTURE PROSPECTS

In the near term, satellite sounding capabilities will be enhanced through the addition of more microwave channels on the NOAA and DMSP satellite systems. The NOAA satellite will possess an Advanced Microwave Sounding Unit (AMSU) which possesses much higher spatial resolution (15-50 km) and many more spectral channels than the current MSU (twenty channels for the AMSU rather than four channels for the MSU). The DMSP will add an SSM/T2 package which,

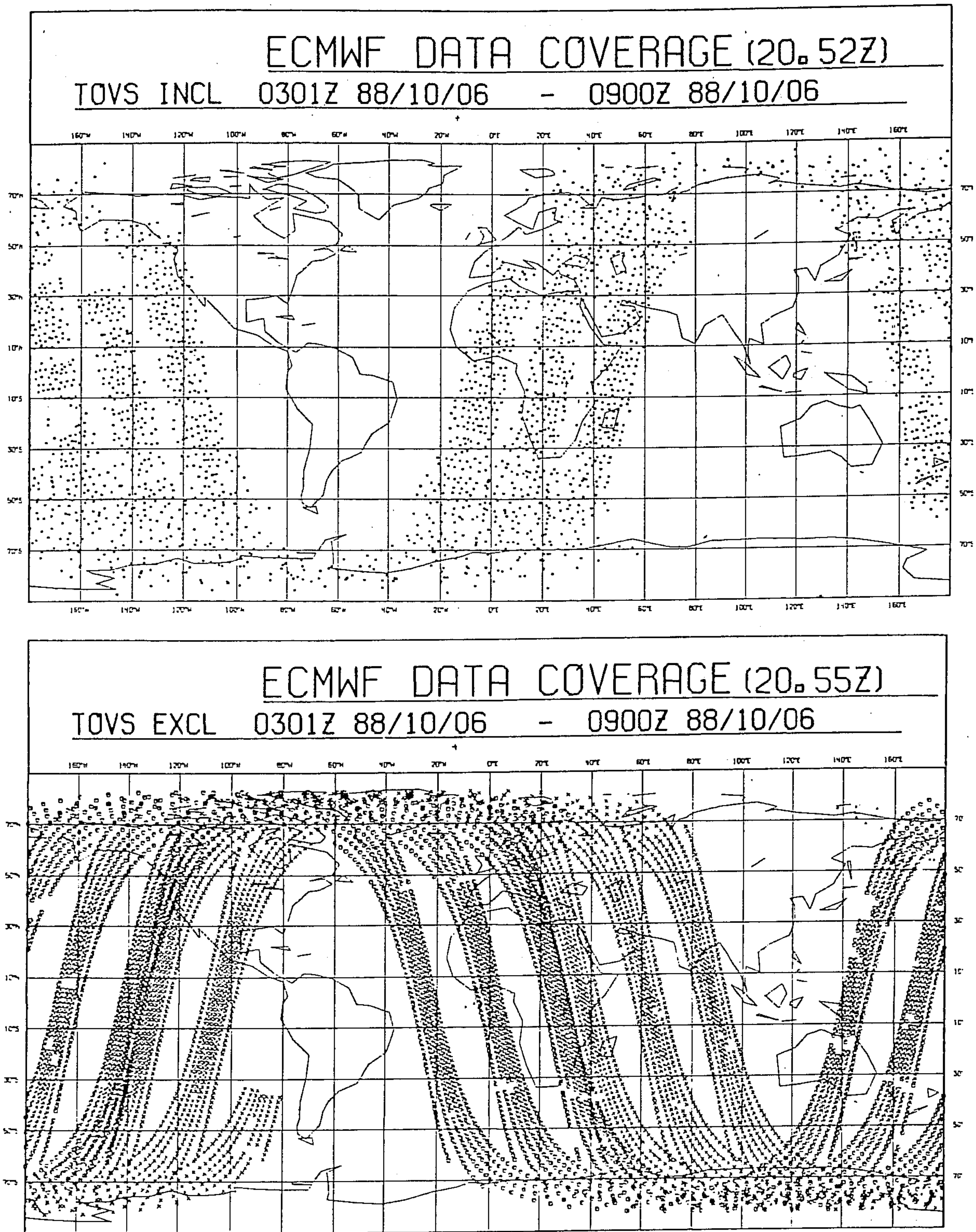

Fig. 2 Data coverage received at ECMWF for a typical six hour period.
(a) NOAA-10 data used in an active mode in the ECMWF assimilation.
(b) DMSP-8 and 9 data used in a passive mode in the ECMWF assimilation.

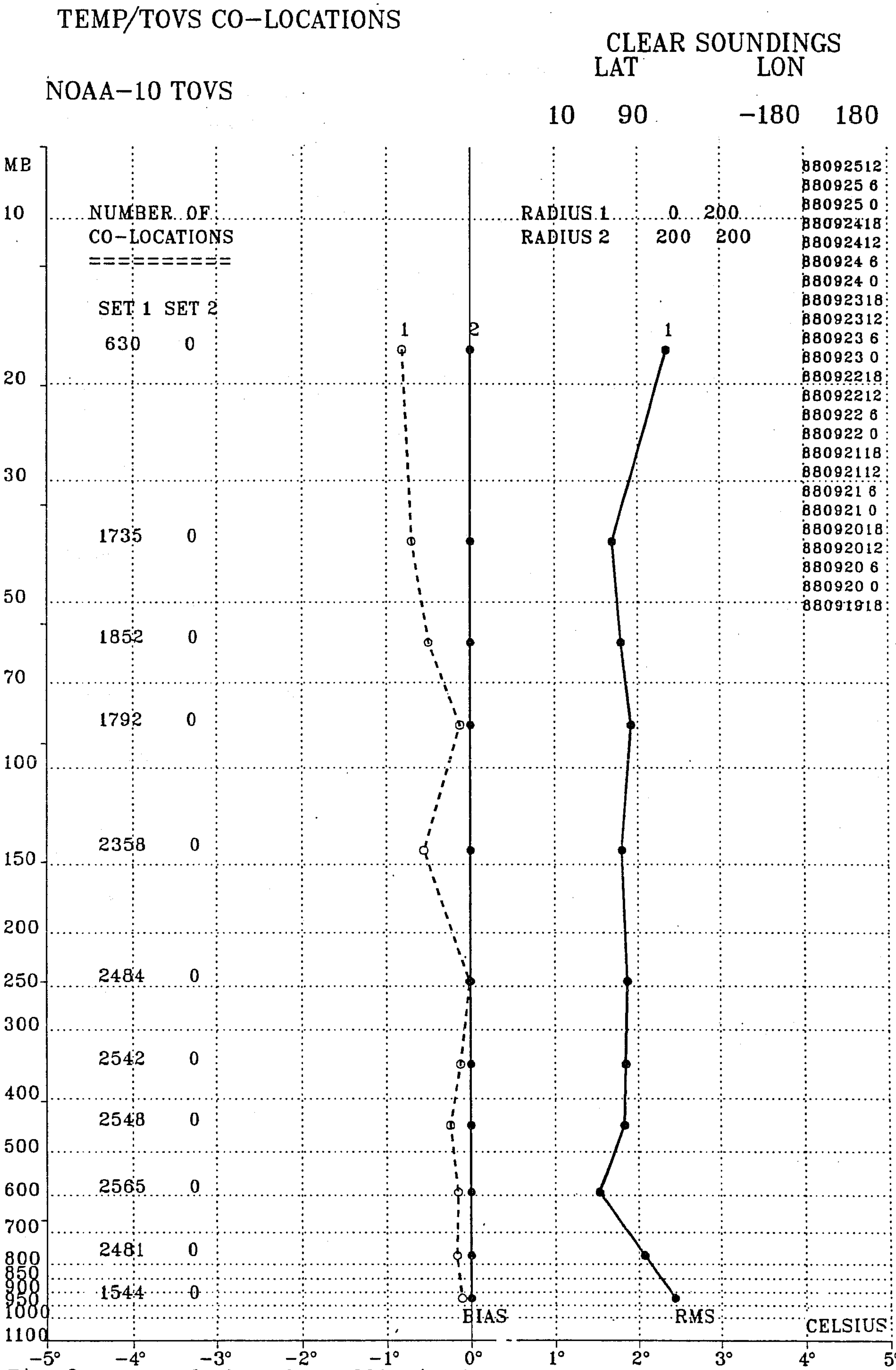

Fig. 3 RMS and Bias of satellite/radiosonde collocations ±3 HR and within 200 km distance the period is from 18Z 19/9/88 to 12Z 25/9/88.
(a) NOAA-10 clear soundings.

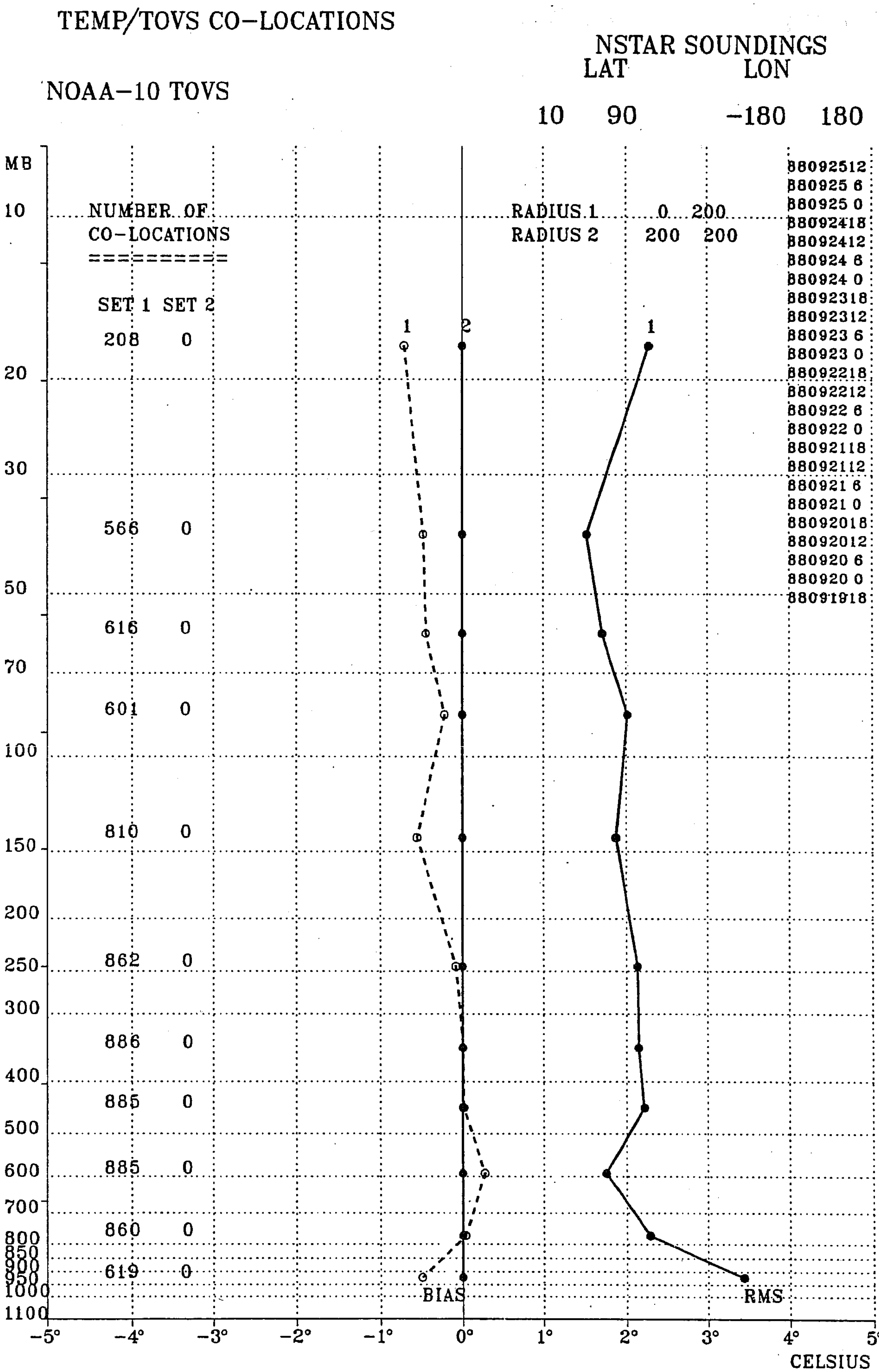

Fig. 3 (b) NOAA-10 "NSTAR" or partly cloudy soundings.

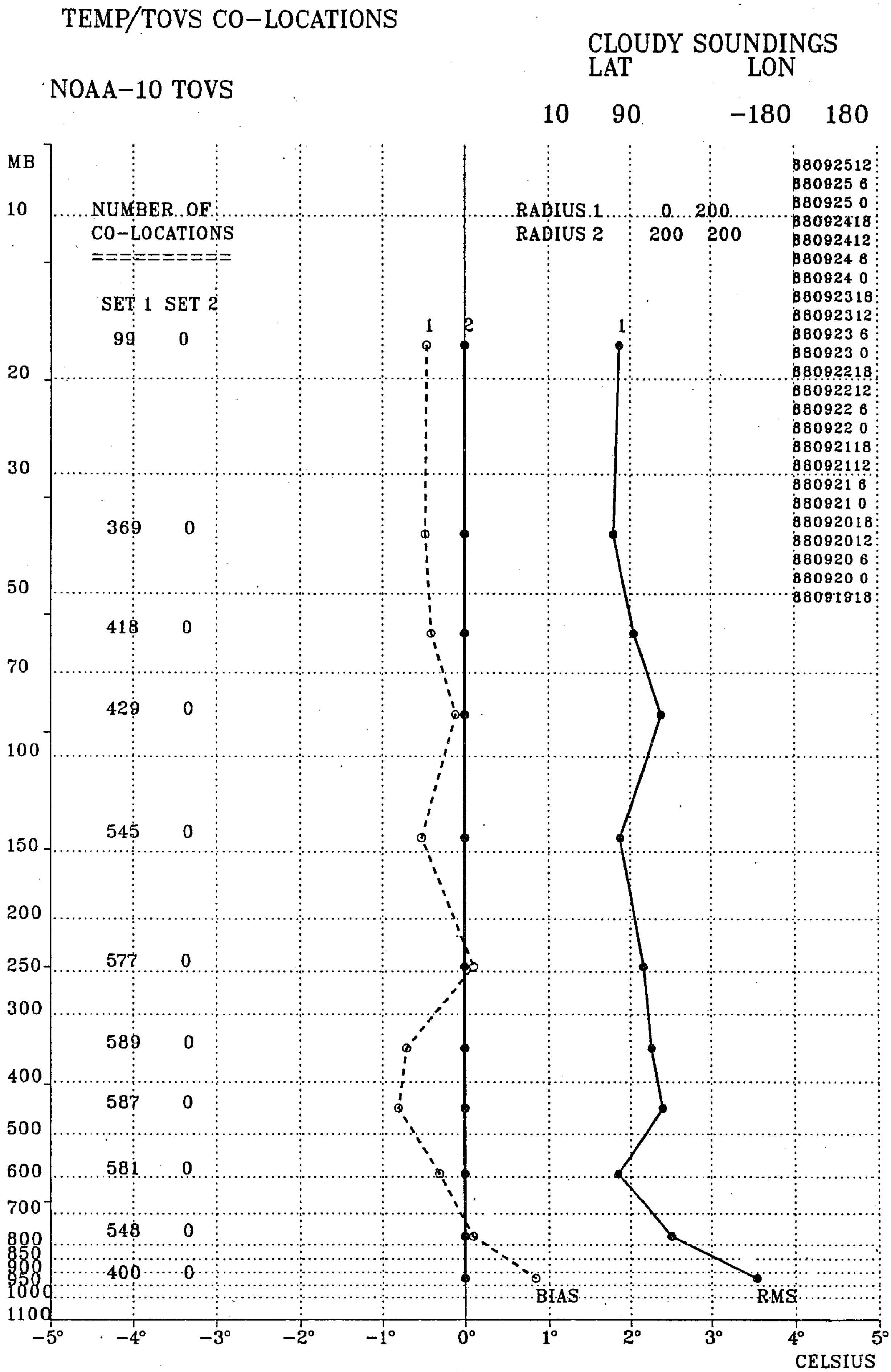

Fig. 3(c) NOAA-10 cloudy soundings

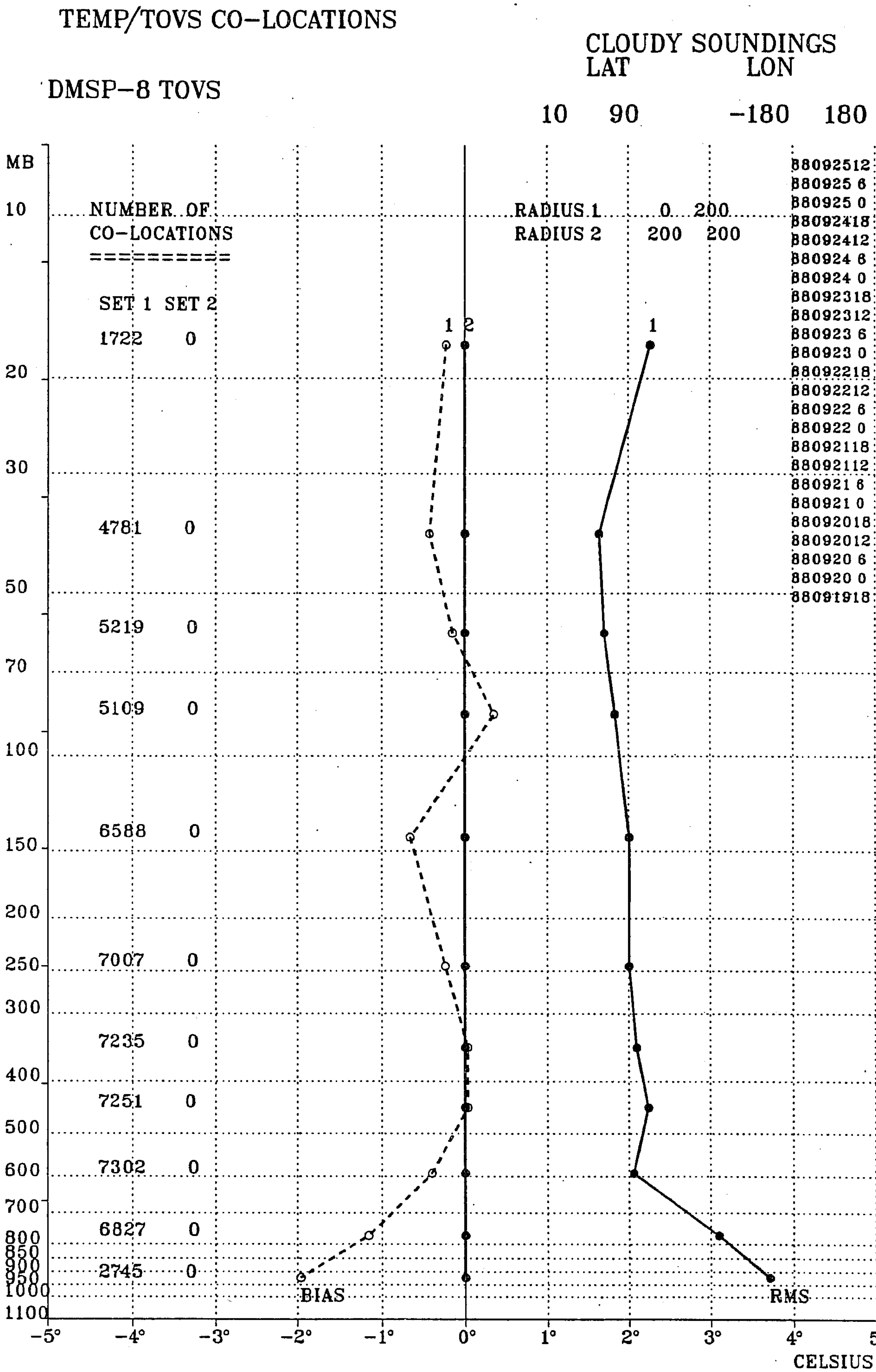

Fig. 3(d) DMSP-8 soundings

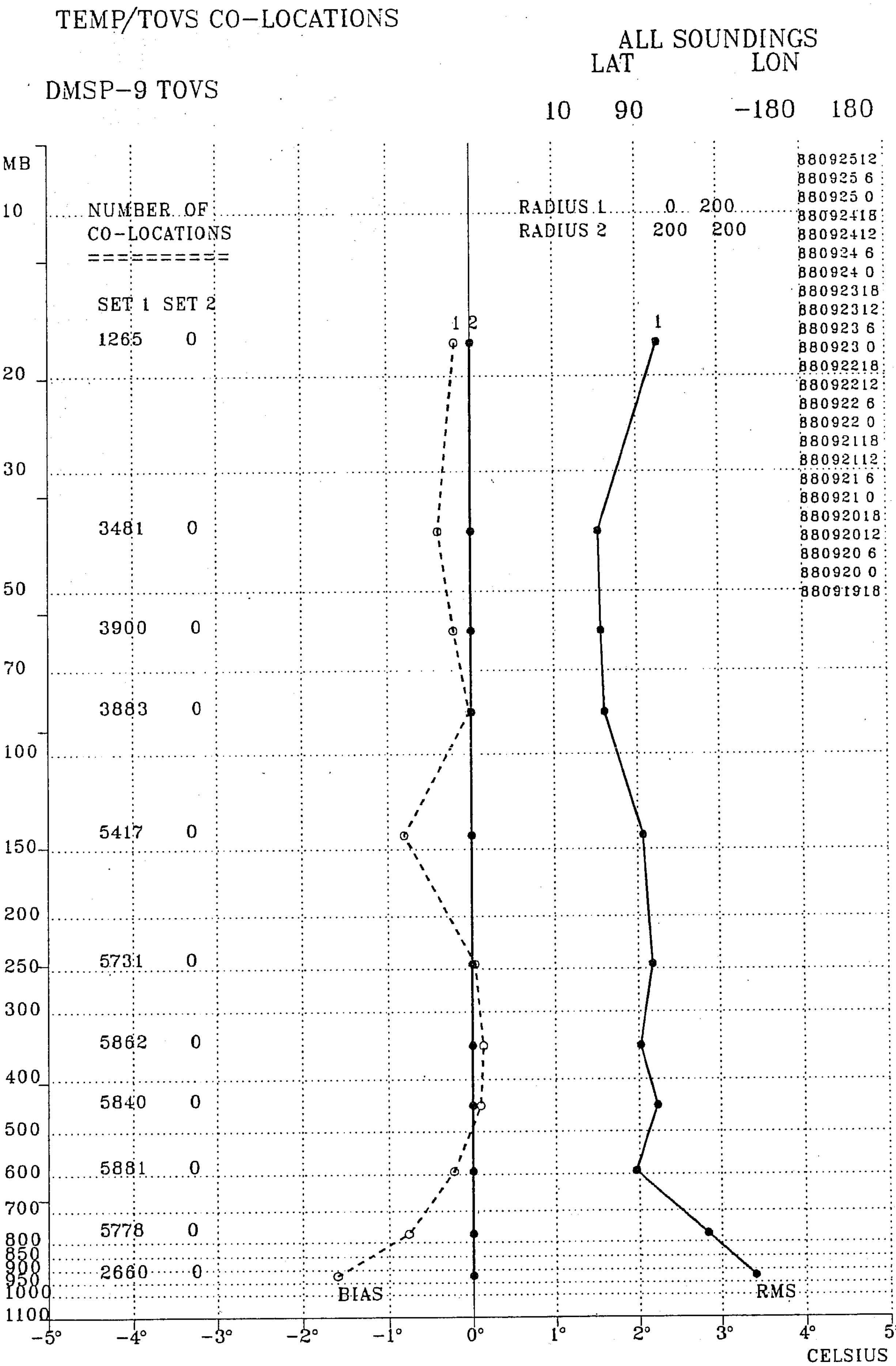

Fig. 3(e) DMSP-9 soundings

like the AMSU, will add a water vapour profiling capability in the microwave region. Figure 4 shows the profile weighting functions for the AMSU; the combined SSM/T and SSM/T2 weighting functions (not shown) are similar.

The greatest advance in satellite sounding capability will take place in the mid to late 1990's when high spectral resolution, broad spectral coverage interferometers (and/or grading spectrometers) are implemented on geostationary and polar orbiting satellites.

This advance results in much higher vertical sounding resolution which is achieved by having a spectral resolution high enough to avoid smearing the upper atmosphere contributions from absorption line centres with lower atmospheric contributions from in between the absorption lines. In addition, broad spectral coverage enables more independent information to be achieved because of the spectrally varying: (1) absorption by various absorbing constituents, (2) line strength dependence upon temperature, and (3) Planck function temperature dependence. Also, redundant information gathered from sampling the quasi-complete spectrum helps to improve the signal-to-noise ratio of the sounding system. The systems proposed possess as many as 4000 spectral channels at 0.5 to 1.0 cm^{-1} resolution as opposed to the 10 to 20 channel instruments with 20 cm^{-1} resolution. This two order of magnitude increase in spectral data density and spectral resolution enables a factor of two to three improvement in vertical sounding resolution (Smith et al. (1988)). This vertical resolution improvement is crucial for improving both short range and extended range numerical weather forecasts.

Fig. 5 shows temperature and water vapour profile weighting functions for a selection of channels from an Advanced Interferometer Radiometer Sounder (AIRS) proposed for the Polar Platform and a next generation GOES (Smith et al. 1987). Note that the ordinate and abcissa for the water vapour functions is different than that for the temperature functions. (The water vapour component weighting functions are two to three times sharper than the dry component). Each individual weighting function is at least 50% sharper than its low resolution counterpart (see Fig. 1). This weighting function resolution coupled with the quasi-complete spectral coverage provides higher sounding performance. To quantify this improvement, Fig. 6 shows the RMS errors of atmospheric temperature and water vapour expected for the AIRS with

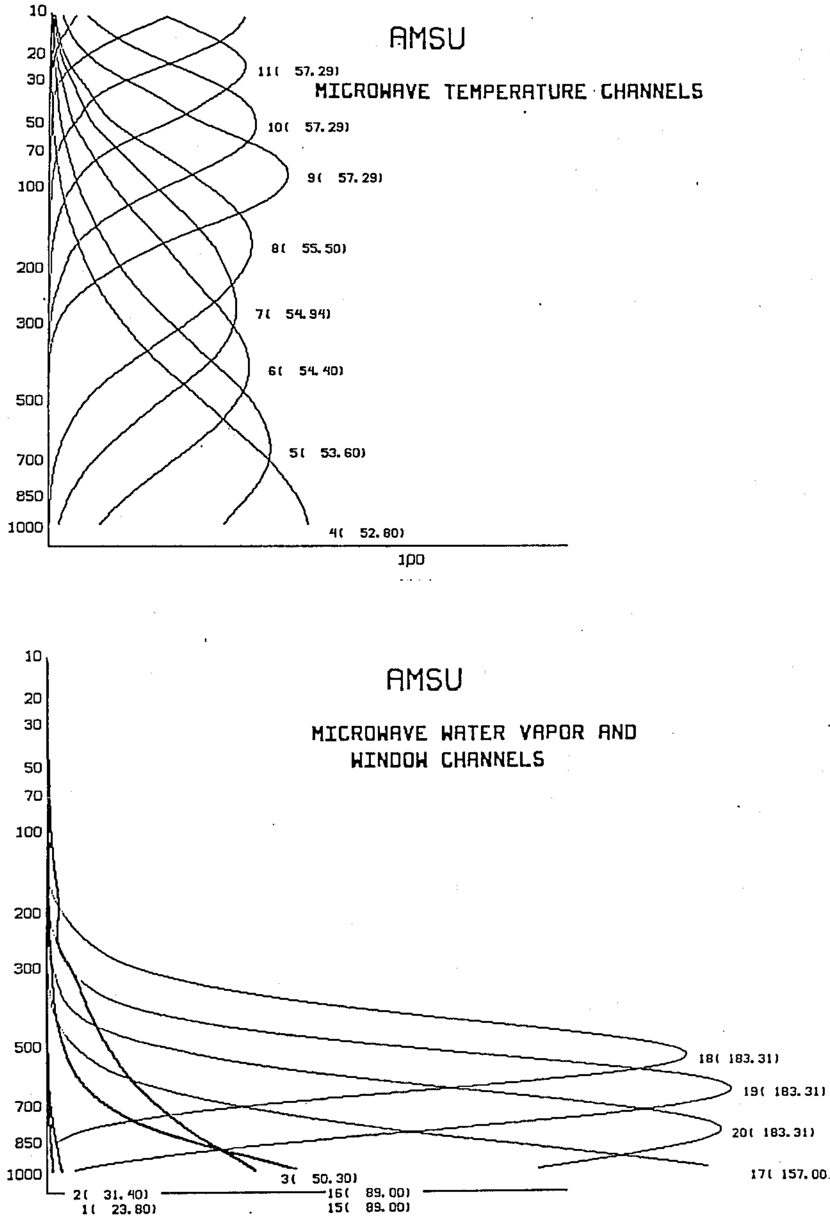

Fig. 4 Standard atmosphere radiance weighting functions for AMSU (a) temperature, and (b) sounding channels.

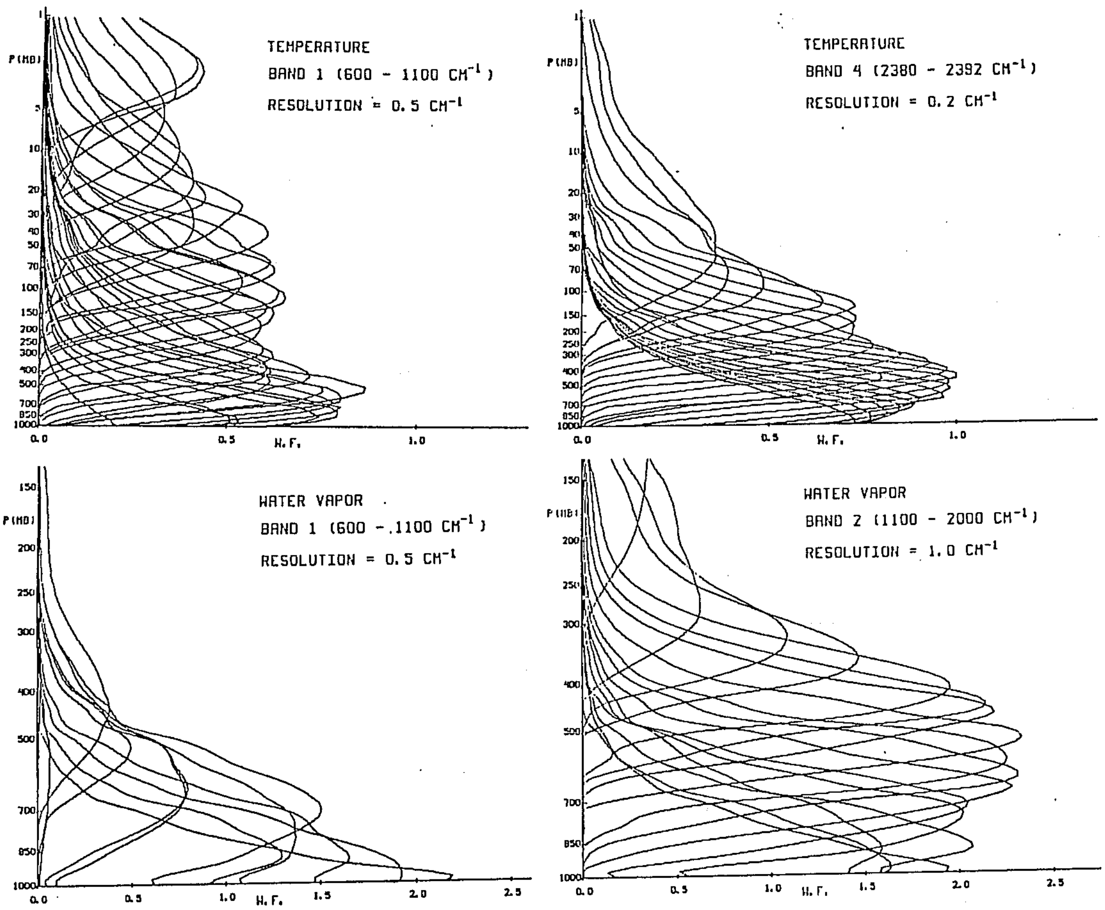

Fig. 5 A selection of temperature (dry) and water vapor (wet) components of the Planck radiance weighting functions ($\tau_{H2O} \cdot d\tau_{dry}/d\ln p$, and $\tau_{dry} \cdot d\tau_{H2O}/d\ln p$, respectively) for several spectral bands of the AIRS interferometer. Note the scale differences for the temperature (dry) and water vapour (wet) components.

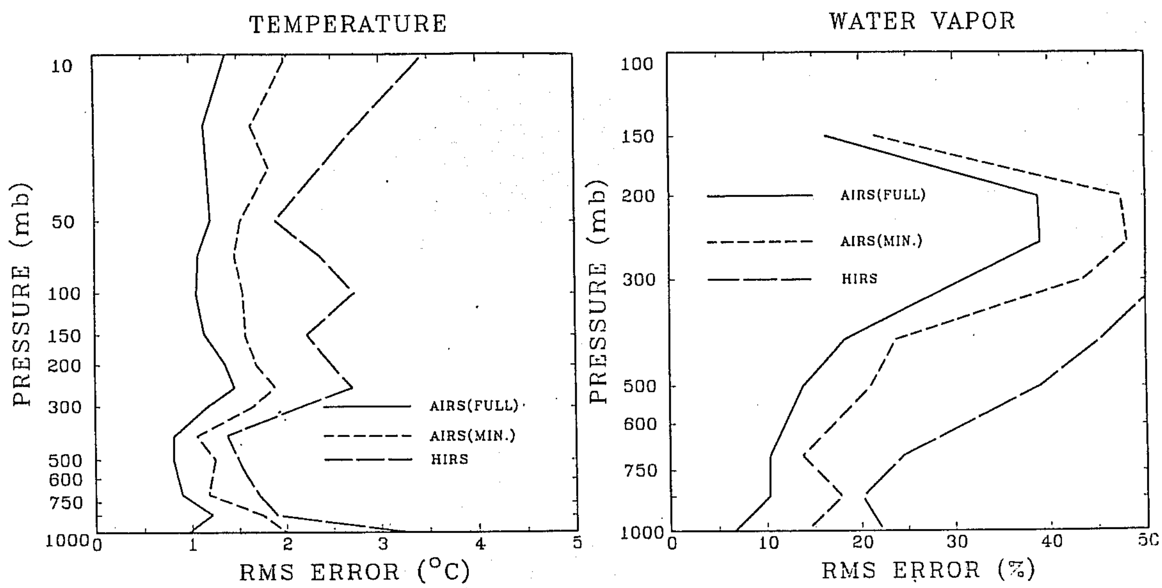

Fig. 6 Profile retrieval errors expected for the AIRS interferometer assuming a brightness temperature noise level of 0.25°C. AIRS (full) denotes all spectral channels used, AIRS (MIN) denotes 115 carefully selected spectral channels used, and HIRS denotes the 19 infrared spectral channels of the TOVS used.

full spectral coverage (3.14-18 µm) versus an "optimal" selection of 115 spectral channels (MIN), both compared to the current HIRS infrared component of TOVS. (These error estimates were obtained from retrievals from radiances simulated from a global sample of 1200 radiosonde observations). As may be seen, the combination of high spectral resolution and quasi-complete spectral coverage enables 1°C temperature and a 10-20% tropospheric precipitable water vapour profile accuracy to be achieved.

Finally, Fig. 7 shows an example experimental result from the High spectral resolution Interferometer Sounder (HIS) which is an airborne prototype of the AIRS (Smith et al., 1988). With the HIS, radiance spectra (3.5-18 µm) are achieved with high spectral resolution ($\lambda/=\Delta\lambda 2000$) and high spatial resolution (2 km) from the NASA ER2 aircraft flight altitude of 20 km. As can be seen from Fig. 7, fine scale vertical and horizontal temperature and water vapour features are resolved by this sytem. In fact, the water vapour profile resolution of the HIS appears good enough to resolve vertically independent features within 50-100 mb layers of the atmosphere. When this sounding capability is implemented from geostationary satellites, the wind profile might be deduced by tracing the motions of water vapour features in narrow layers from a time sequence of the retrieved three-dimensional water vapour structure.

Beyond the high spectral resolution and quasi-complete spectral coverage provided by future passive radiometers, active laser techniques are being considered to achieve an even higher vertical resolution sounding capability. The use of DIAL for vertical water vapour profiling has already been demonstrated from the ground and aircraft (Browell et al., 1987; Korb et al., 1982). Similar techniques can be applied for temperature profiling (Korb et al. 1983). Possibly the ultimate satellite sounding capability will result from a combination of active and passive techniques whereby the active system defines the details of the atmosphere's molecular, aerosol, and cloud structure and the passive system defines the thermal characteristics of these absorbing constituents. A practical example might be the combination of a DIAL water vapour sounder with a high spectral resolution water vapour emission sensor (e.g. the AIRS) for achieving the very high vertical temperature sounding resolution afforded by extremely sharp water vapour channel weighting functions (Fig. 5).

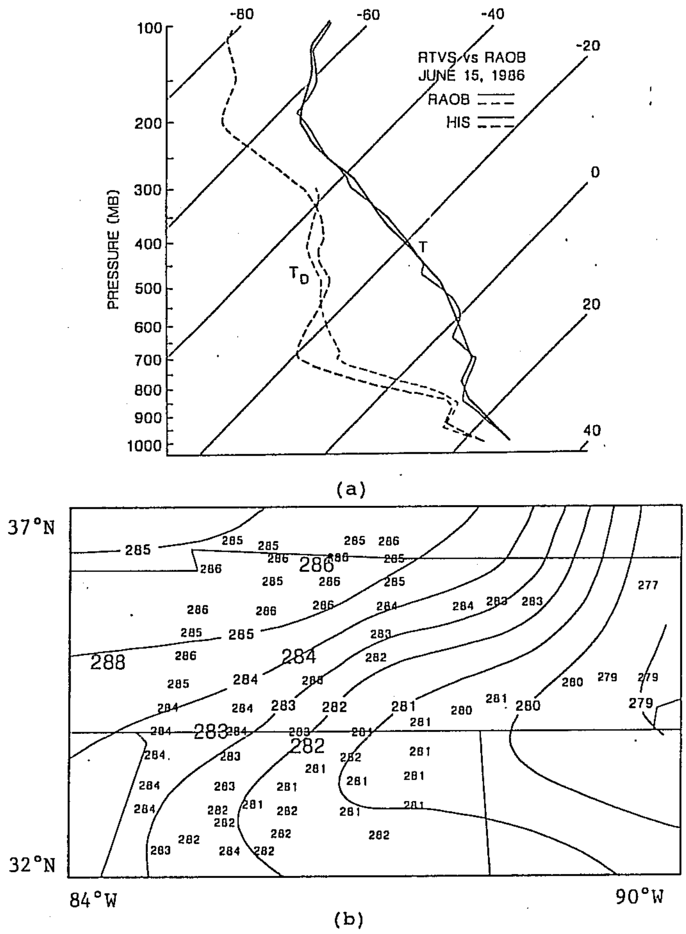

Fig. 7 (a) Comparison of a typical temperature and water vapor sounding retrieved from HIS radiance spectra with a nearly coincident radiosonde observation. (b) Analysis and plot of 850 mb dewpoint temperatures retrieved from HIS spectra with special radiosonde observations (large numerals) superimposed for comparison.

6. CONCLUSIONS

Satellite temperature soundings derived from current instruments increase the accuracy of forecasts in the Southern Hemisphere. However, in the Northern Hemisphere more advanced instruments may be required to make substantial improvements to Numerical Forecasts. Improved retrieval methods and the use of Variational Analysis methods should lead to some improvements using the current operational instruments, however the new satellite instrument programs must be strongly supported by the NWP centres.

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