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INFRA-RED SENSING OF UPPER AIR TEMPERATURE OVER INDIAN SEAS BY NIMBUS III*

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ABSTRACT

Satellite Infra-Red Spectrometer (SIRS) data for a few days has been used to study the temperature distribution in the upper air over the data-sparse region of Indian Seas. The vertical temperature profiles so calculated are compared with the actual temperature soundings of nearby meteorological stations representative of the conditions in the Bay of Bengal and Arabian Sea.

INTRODUCTION

THE prospect of determination of vertical temperature distribution upto a considerable height in the earth's atmosphere on a world-wide scale, by means of radiometric measurements from the satellites, has excited the interest of Meteorologists in recent years. Satellite measurements offer a means to survey the vast areas covering almost two-third of the globe by oceans and other inaccessible areas where establishment of ground-based stations for day to day observations is not possible. With the help of present high speed electronic computer the satellite may provide a quicker means of obtaining day to day sondings, than the present-day radiosonde. Further, while the radiosonde is effective only upto a limited altitude, temperature profiles upto much higher heights can be obtained from satellite measurements.

The Satellite Infra-Red Spectrometer (SIRS) was developed by the United States National Environmental Satellite Centre for indirect measurement of vertical temperature distribution of the atmosphere. The spectrometer was on board NIMBUS III Weather Satellite, which was successfully launched on 14th April, 1969.

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SATELLITE OBSERVATIONS AND THEIR CORRELATION WITH ATMOSPHERIC TEMPERATURE

Several atmospheric gases including molecular O_2 and CO_2 are known to be uniformly mixed up to an altitude of 30 km CO_2 is assumed to have a uniform mixing ratio of about 0.0315 per cent by volume. Gases like O_2, CO_2 etc. and water vapour present in the atmosphere absorb significantly the terrestrial longwave radiation; it follows that they are also significant emitters of radiation in those ranges of long wavelength in which they absorb. The strong absorption and emission by CO_2 in the 15 micron band of the terrestrial infra-red radiation provide the basis for the determination of the vertical temperature distribution in the atmosphere.

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The satellite observations for dertermining the temperature profile is obtained by the Infra-red spectrometer (SIRS) which was designed for use on board Nimbus III satellite. The outputs of the SIRS are transformed to spectral radiances by a suitable calibration procedure (Details are available in *The Nimbus III User's Guide*, a NASA publication), which are then used as a group to deduce the temperature profile within the field of view. +The SIRS measures the differences in Infra-red radiation between the earth and deep space in eight spectral band passes each about 0.1 micron wide been 11 and 15 microns of CO_2 gas, which is known to be uniformly mixed up to altitudes of 30 km. These are centred at 11.12, 13.33, 14.01, 14.16, 14.31, 14.45, 14.76 and 14.95 microns of CO_2 gas. The SIRS measures radiance over a field of view of about 225 km square and therefore the temperature profile represents an average over this area.

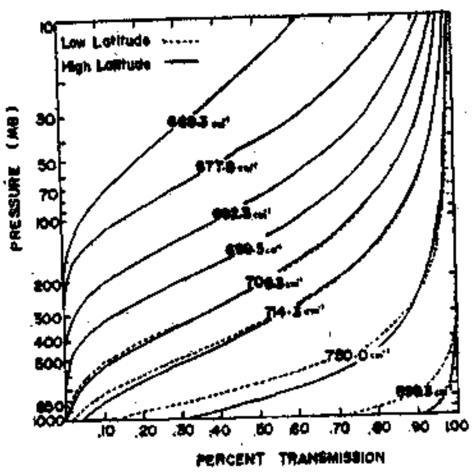

Fig. 1. Atmospheric transmission functions pertaining to the SIRS spectral intervals of observation for two different atmospheres.

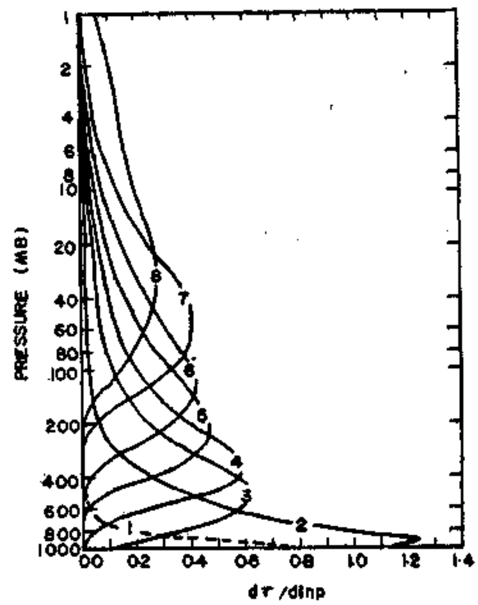

Fig. 2. Derivative transmittance with respect to the logarithm of pressure. These functions approximately describe the relative sensitivity of the eight SIRS radiance observations to temperature variations in various altitude layers of the atmosphere.

Smith *et al.* (1970) illustrated the transmission of the atmosphere above atmospheric levels for radiation in the eight SIRS Channels (i. e. spectral intervals of observation) for a high- and low-latitude atmospheric situation (Fig. 1). The differences in the transmission function in the lowest atmospheric levels result mainly from water vapour differences in the two atmospheric situations while the smaller differences at higher levels result from temperature discrepancies. The derivatives of the transmission functions for a 'standard atmosphere' with respect to the logarithm of pressure are shown in Fig. 2. These derivative functions are the Planck radiance 'weighting' functions for the radiative transfer equation.

METHOD OF CALCULATION OF THE TEMPERATURE PROFILES FROM SIRS RADIATION DATA

In the earlier studies Work (1961), Yamamato (1961), King (1964) and others used numerical methods for deducing vertical temperature profile of the atmosphere. But recent studies on the temperature inversion problem by Wark and Flaming (1966), Rodgers (1966), Westwater and Strand (1968), and others indicate that maximum information about the atmosphere's thermal structure may be derived from satellite radiation observations through the use of statistical relationships. A regression model for deriving the atmosphere's temperature and geopotential height distribution from satellite radiation measurements was developed. Methods of accounting for the influences of clouds high terrain, and hot terrain on the solutions have also been devised by Smith *et al.* (1970).

If the radiances in several spectral intervals are given the integral equations can be written in the form (*Nimbus III User's Guide*)

$$I(v_i) = N \{ B[v_i, T(p_c)]\, T(v_i, p_c) - \int_1^{T_c} B[v_i, T(p)]\, dT(v_i, p) \}$$

$$+ (1-N) \{ B[v_i, T(p_s)]\, T(v_i, p_s) - \int_1^{T_s} B[v_i, T(p)]\, dT(v_i, p) \}$$

$$i = 1 \ldots\ldots M \quad (1)$$

Where,

$I(v_i)$ = Spectral radiance at wave number v_i.

$B[v_i, T(p)]$ = Planck radiance at wave number v_i, and temperature T; in the atmosphere temperature is a function of the pressure level, p and is denoted by T(p).

$T(v_i, p)$ = Fractional transmittance of the atmosphere in the spectral interval centred at wave number v_i, and from pressure level p to the satellite.

N = the product of the fraction of cloud cover within the field of view and the cloud emissivity. If N=O is put, the equation reduces to clear condition of sky.

Subscripts *c* and *s* refer to cloud top and surface.

The function $B[v_i, T(p)]$ can be transformed to T(p), the black body temperature for the radiance value v_i from

$$B[v_i, T(p)] = \frac{2h\, v_i^3 c^2}{\left[\frac{h_c v_i}{KT(p)}\right] - 1}$$

Direct inversion of the radiative transfer equation to obtain temperature profiles from spectral radiances does not yield a practical solution. A more mathematically stable solution is achieved by relating SIRS radiance to atmospheric temperature through statistical equations. These statistical equations are derived by regression methods from large samples of satellite radiance measurements and coincident radiosonde observations. +The statistical samples for the tropics and northern hemisphere contain about 700 sets of observations extending over a two-week period. Techniques have been developed by Smith (1969) and Smith *et al.* (1970) for regression relation between infra-red radiance and atmospheric temperatures and geopotential heights.

Smith *et al.* (1970) found that the eight SIRS radiances are very highly correlated with the temperatures at different pressure levels. The correlation coefficients and multiple correlation coefficients are 0.90 or greater for most pressure levels below 30 mbs. The standard errors are generally less than 2°C. The detailed vertical profile determined from a set of simultaneous equation involving eight spectral radiance is shown in Appendix II.

DATA

Rao and Shivaramakrishnan (1970, MS) has given the vertical temperature profiles for three Indian Stations by SIRS observational methods. In the absence of any other data, the vertical temperature profiles of Bombay and Vishakhapatnam are presented from the above mentioned paper in Figs. 3 and 4.

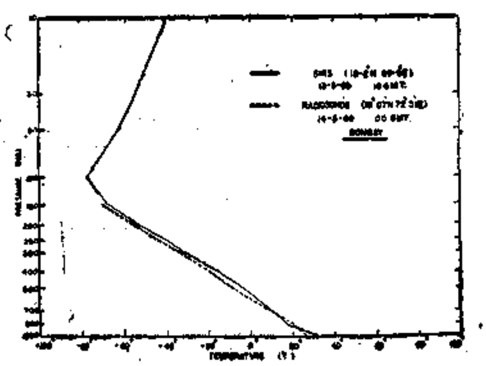

Fig. 3. Comparison of a SIRS—calculated and Bombay Radiosonde observed temperature profile.

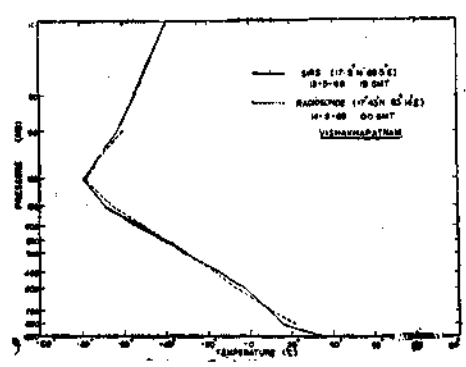

Fig. 4. Comparison of a SIRS—calculated and Vishakhapatnam Radiosonde observed temperature profile.

Table 1 gives the mean values of black body temperature for each wave number and for each isobaric level for use in calculating the regression coefficients applicable. Table 2 gives the regression coefficients for each channel at various isobaric levels for tropical latitudes. Tables 3 and 4 give the measurements of radiances, corrected radiant temperature using Planck's law (Appendix I) and the actual temperatures calculated (Appendix II) at Bombay and Vishakhpatnam on 13-5-69 for clear sky conditions.

TABLE 1. *Mean Values for Regression Coefficients*

			P(mb)	$\bar{T}(P)$
$\bar{T}_B(\nu_1)$	=	295.9	1000	297.9
$\bar{T}_B(\nu_2)$	=	231.5	850	291.9
$\bar{T}_B(\nu_3)$	=	222.8	700	282.3
$\bar{T}_B(\nu_4)$	=	221.1	500	265.6
$\bar{T}_B(\nu_5)$	=	225.5	400	254.2
$\bar{T}_B(\nu_6)$	=	237.1	300	238.6
$\bar{T}_B(\nu_7)$	=	250.7	250	229.6
$\bar{T}_B(\nu_8)$	=	276.9	200	220.1
			150	210.5
			100	205.1
			50	214.5
			30	220.4
			10	234.5
			1	255.8
			0.1	230.0

TABLE 2. *Regression Coefficients*

Pj (mb)	a_{1j}	a'_{1j}	a_{2j}	a'_{2j} (V_i)	a_{3j}	a'_{3j}	a_{4j}	a'_{4j}
1000	.422	-.024	-.022	-.105	1.413	.191	-3.787	-.015
850	.174	.048	.760	.548	-1.279	.014	.526	-.507
700	.047	.025	.932	.210	-.422	-.011	-.365	-.245
500	-.021	-.004	.395	-.010	.507	.045	-1.638	-.074
400	.049	-.003	-.405	.306	.617	.131	-2.853	-.206
300	.081	.004	.318	.177	.224	-.019	-2.875	-.197
250	.046	.001	.191	.018	-.658	-.268	-2.067	.157
200	.022	-.001	-.756	-.191	-1.237	-.223	.722	.295
150	.020	-.001	-.790	-.077	-1.193	.066	3.445	-.043
100	-.040	-.003	-1.160	.224	.793	.167	2.771	-.223
50	-.006	.001	-.351	.023	1.075	.015	.235	.047
30	-.011	.003	-.013	-.125	.381	.072	.348	-.061
10	-.035	.024	.057	.085	-.432	.029	.515	.107

Pj (mb)	a_{5j}	a'_{5j}	a_{6j}	a'_{6j}	a_{7j}	a'_{7j}	a_{8j}	a'_{8j}
1000	2.842	-.082	-1.022	.121	-.762	-.070	.555	.005
850	1.138	-.000	-1.423	.067	1.267	-.007	.345	-.040
700	-.007	.061	-.172	.013	1.074	.023	.172	-.030
500	-.088	.071	.814	.037	.063	.020	-.022	-.009
400	1.976	.201	.114	.109	.714	-.002	-.264	-.015
300	2.880	.340	.015	.161	.317	-.038	-.215	-.008
250	3.792	.367	-.608	.028	.392	.017	-.145	-.005
200	2.821	.097	-1.011	.047	.619	-.051	-.129	.006
150	.472	-.024	-.994	.009	.211	-.007	-.016	.003
100	-.977	.252	-.471	-.199	-.357	.073	.255	-.011
50	-.128	-.163	.082	.020	.222	-.019	-.096	-.010
30	-.172	-.035	.054	.003	.226	-.017	-.057	.004
10	-.288	-.007	.119	-.157	-.049	.005	.075	-.014

Note: $a(\nu_i p_j) = a_{ij}$ $\quad i = 1,2,\ldots\ldots\ldots\ldots8$

$a'(\nu_i p_j) = a'_{ij}$ $\quad j = 1,2,\ldots\ldots\ldots\ldots13$

TABLE 3

Date 13-5-69 TIME 1900 GMT LAT. 19.2°N LONG. 69.9°E (Near Bombay 19.1°N 72.5°E)

Channel	899.3 cm^{-1}	669.3 cm^{-1}	677.3 cm^{-1}	692.3 cm^{-1}	699.3 cm^{-1}	706.3 cm^{-1}	714.3 cm^{-1}	750.0 cm^{-1}
Radiances	115.45	55.59	43.74	41.33	46.71	59.72	75.66	109.09
Corrected Radiant Temperatures	298.75	230.49	219.06	217.92	224.61	238.19	252.71	280.77

Calculated Cloud Pressure: CLEAR

Pressure (mb)	1000	850	700	500	400	300	250	200	150	100	50	30	10
Temps. (°K)	304.6	290.5	283.3	269.9	258.7	241.7	232.9	220.1	205.2	195.2	210.5	218.6	233.9

TABLE 4

Date 13-5-69 TIME 1900 GMT LAT. 17.5°N LONG. 69.5°E (Near Vishakhapatnam 17.4°N 83.1°E)

Channel	899.3 cm^{-1}	669.3 cm^{-1}	677.3 cm^{-1}	692.3 cm^{-1}	699.3 cm^{-1}	706.3 cm^{-1}	714.3 cm^{-1}	750.0 cm^{-1}
Radiances	115.67	55.18	43.51	40.95	46.50	59.72	75.67	108.75
Corrected Radiant Temperature	298.8	230.09	218.80	217.49	224.38	238.19	252.71	279.96

Calculated Cloud Pressure (me): CLEAR

Pressure (mb)	1000	850	700	500	400	300	250	200	150	100	50	30	10
Temps. (°K)	304.8	288.6	282.5	270.3	259.1	242.1	233.3	220.4	204.3	194.3	210.5	218.2	233.7

Appendix I

If R is the radiance measured from the SIRS observation then the Planck's law can be written in the form (after Wark and Flaming, 1966) in terms of wave number ν as,

$$R d\nu = \frac{2hc^2\nu^3}{e^{\frac{hc\nu}{KT}} - 1} d\nu$$

$$\text{Putting} \quad c_1 = 2hc^2 = 1.191 \times 10^{-5}$$

$$\text{and} \quad c_2 = \frac{hc}{K} = 1.439$$

$$T = \frac{c_2\nu}{\log_e\left(1 + \frac{c_1\nu^3}{R}\right)} \qquad (2)$$

R = intensity of radiation ergs/cm² Sec. Strdn. cm^{-1}
h = Planck's constant = 6.625×10^{-27} erg second
c = Velocity of light = 2.998×10^{10} cm/sec.
k = Boltzman's constant = 1.38×10^{-16} erg/degree
ν = Wave number in cm^{-1}
T = Absolute temperature (°K)

Appendix II

For clear sky conditions, the temperature at any level is given by after Smith, Woolf and Jacob (1970).

$$T'(P_j) = \sum_{i=1}^{8} a(\nu_i, P_j)\,[T_B(\nu_i) - \bar{T}_B(\nu_i)] + \sum_{i=1}^{8} a'(\nu_i\, P_j)\,[T_B(\nu_i) - \bar{T}_B(\nu_i)]^2$$

$$T(P_j) = \bar{T}(P_j) + T'(P_j)$$

Where $a(\nu_i, P_j)$ and $a'(\nu_i, P_j)$ are the lenear and non-lenear regression coefficients given in Table II for the eight spectral radiances $\nu_1 = 899.3\ cm^{-1}$, $\nu_2 = 669.3\ cm^{-1}$, $\nu_3 = 677.3\ cm^{-1}$, $\nu_4 = 692.3\ cm^{-1}$, $\nu_5 = 699.3\ cm^{-1}$
$\nu_6 = 706.3\ cm^{-1}$, $\nu_7 = 714.3\ cm^{-1}$, $\nu_8 = 750.0\ cm^{-1}$

$T(P_j)$ is the temperature at level P_j.

$\bar{T}(P_j)$ is the mean temperature at level P_j given in Table 1.

$T'(P_j)$ is the temperature correction for each milibaric level P_j.

$T_B(\nu_i)$ is the equivalent black body temperature for eight different radiance values determined with the help of equation (2).

$\bar{T}_B(\nu_i)$ is the mean black body temperature for eight different radiance values given in Table 1.

Equations (2) and (3) were evaluated by computor methods and the actual temperatures were calculated with the help of the equation (4).

Discussion

Figures 3 and 4 show in general a good agreement between the computed and observed temperatures. A more detailed comparison between calculated and observed temperatures show that about 60 per cent of the differences are less than 3°C. It may be further mentioned that the satellite observations were not at the exact time of observation, secondly the satellite pass is also not exactly through the stations, and the approximate variation of 2 to 3 degrees either longitudinally or latitudinally is difficult to avoid. These discrepancies also introduce some inaccuracy.

Recent papers by Smith (1969), and Fritz (1969) discusses the errors in measurement of temperature by statistical methods and they show that 70 percent of the differences between SIRS derived temperatures and observed temperatures by radiosonde in the Northern Hemisphere are generally between 1.5° to 2°C. The largest temperature errors in the lower troposphere is due to the influence of clouds. Similar errors occur in the tropopause region due to the weak sensitivity of radiance observations to the small scale vertical features of the profile. Considering the difference arising due to the difference in times of observations and the passage of Nimbus III not exactly through the stations considered, the results of comparison are quite encouraging.

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