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Vertical temperature distribution of the atmosphere from the Indian (Tropical) radiosonde stations from Nimbus III satellite infra-red spectrometer (SIRS) measurements

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ABSTRACT. Satellite Infra-red Spectrometer (SIRS) measurements obtained from Nimbus III offer for the first time an opportunity to estimate the vertical temperature distribution over the Indian (Tropical) region. The vertical temperature distribution at three Indian R. S. stations (New Delhi, Bombay and Visakhapatnam) on 14 and 15 May 1969 have been calculated from the radiation data taken by SIRS spectrometer in the 15 micron carbon dioxide band, close to these three stations. The calculated values show good agreement upto 100 mb.

1. Introduction

The satellite infra-red spectrometer (SIRS) has been developed for the purpose of indirect determination of the vertical temperature profiles of the atmosphere. The output of the SIRS is transformed to spectral radiances, 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 between 11 and 15 microns of CO_2 gas. These are centred at 11·12, 13·33, 14·01 14·16, 14·31, 14·45, 14·76, 14·95 mocrons of CO_2 gas. Fig. 1 shows the atmospheric weighting functions for the radiances measured in these eight intervals.

In this paper an attempt has been made to calculate the temperature profiles at New Delhi, Bombay and Visahkapatnam on 14 and 15 May 1969 from the radiation data taken by the SIRS close to the radiosonde stations at Visakhapatnam and New Delhi.

2. Method of calculation of the temperature profiles from SIRS radiation data

For a non-scattering cloudless atmosphere, in local thermodynamic equilibrium the spectral radiance observed at the top of the atmosphere can be written in the form (Wark Fleming 1966)

$$I\ (\nu) = B\ (\nu, T_s)\ \tau\ (\nu,\ p_s) - \int_1^{\tau\ (\nu, p_s)} B\left[\nu, T\ (p)\right] d\tau(\nu,p) \qquad (1)$$

where $B\ (\nu,\ T)$ is the Planck function at wave number and temperature T, p is pressure and τ is the transmissivity between the level P and the top of the atmosphere. The subscript s refers to surface values. For details the reader is referred to a paper by Wark and Fleming (1966).

Direct inversion of the radiative transfer equation to obtain temperature profiles from spectral radiances does not yield a practical solution. A mathematically more stable solution is achieved by relating SIRS radiance to atmospheric temperature through statistical equations. The statistical equations are derived by regression from large samples of satellite radiance measurements and *coincident* radiosonde observations. The statistical samples for the tropics and northern hemisphere contain about 700 sheets of observations extending over a two-week period. The SIRS measures radiance over a filed of view approximately 225 km square, hence the temperature profile represents an average over this area. Techniques have been developed by Smith (1969) which yield the statistically most probable atmospheric temperature distribution and cloud condition associated with the radiance and surface temperature observations. The temperatures obtained below the clouds result largely from the statistical relation of these temperatures with those observed above the clouds and at the surface.

Table 1 shows the correlations of SIRS radiances with radiosonde temperature observations between 35°N and 55°N based on 700 soundings from 29 May to 15 June 1969 as given by Smith *et al.*, (1969). The eight SIRS radiances are very highly correlated with the temperatures at eight different pressure levels between the earth's surface and middle stratosphere. It is the vertical independence of the different spectral radiance observations which allow a temperature profile to be determined. The

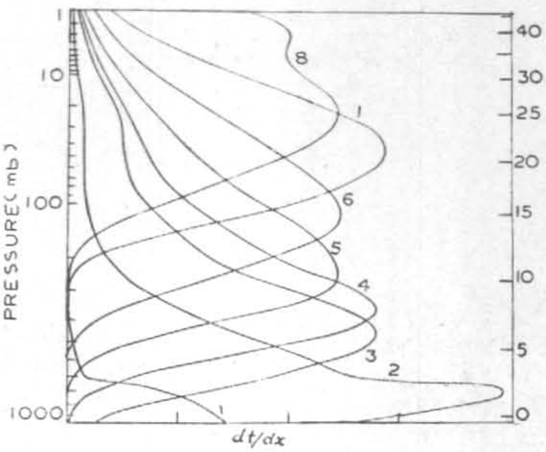

Fig. 1

Atmospheric weighting functions for the radiance measured in the eight SIRS spectral intervals. The weighing functions (dt/dx) were determined from theoretical calculations assuming a standard atmospheric temp. & water vapour conditions

TABLE 1

Correlation of SIRS radiances with radiosonde temperature observations (700 soundings : 35°N-55°N, 29 May-15 June 1969)

Pressure level of highest individual correlation (mb)	Highest individual correlation		Mutiple correlation with all SIRS channels
	SIRS Channel	Correlation	
1,000	1 (11·1 μm)	0·97	0·98
850	2 (13·3 μm)	0·91	0·93
500	3 (14·0 μm)	0·92	0·96
250	4 (14·2 μm)	0·63	0·76
200	5 (14·3 μm)	0·87	0·92
100	6 (14·4 μm)	0·95	0·97
50	7 (14·8 μm)	0·89	0·91
30	8 (14·9 μm)	0·77	0·81

TABLE 2

Mean values for regression coefficients

Black body-temperature (T_B)		Isobaric-layer temp. ($\overline{T}_p$)		Isobaric-layer temp. ($\overline{T}_p$)	
Wave (ν) No.	Temp. (°K)	Pressure (mb)	Temp. (°K)	Pressure (mb)	Temp. (°K)
1	295·9	1000	297·9	200	220·1
2	231·5	850	291·9	150	210·5
3	222·8	700	282·3	100	205·1
4	221·1	500	265·6	50	214·5
5	225·5	400	254·2	30	220·4
6	237·1	300	238·6	10	234·5
7	250·7	250	229·6	1	255·8
8	276·9			0·1	230·0

multiple correlations for almost all pressure levels below 10 mb are greater than 0·90. The detailed vertical profile is determined from a simultaneous solution involving all eight spectral radiances.

The temperature at any level for clear conditions is given by —

$$T'(p) = \sum_{i=1}^{8} [c_1\ (p)\ T'_B(\nu_1) + c'_1(p)\ T'_B(\nu_1)^2] \quad (2)$$

where $c_1(p)$ and $c_1'(p)$ are the linear and non-linear regression coefficient for the eight spectral radiance measurements, $\nu_1 = 899$ cm^{-1}, $\nu_2 =$ 669 cm^{-1}, $\nu_3 = 677·8$ cm^{-1}, $\nu_4 = 692·3$ cm^{-1}, $\nu_5 = 699·3$ cm^{-1}, $\nu_6 = 706$ cm^{-1}, $\nu_7 = 714·3$ cm^{-1}, $\nu_8 = 750·0$ cm^{-1}, and T_B is the equivalent black body temperature for each frequency.

$$T'(p) = T(p) - \overline{T}(p) \quad (3)$$

$$T'_B(\nu) = T_B(\nu) - \overline{T}_B(\nu) \quad (4)$$

3. Data and computations

Table 2 gives the mean values of the black body temperature for each wave number and for each isobaric level for use in calculating the regression

TABLE 3

Regression Coefficients

Reg. coeff.	Pressure (p) in mb												
	1000	850	700	500	400	300	250	200	150	100	50	30	10
c_1	·422	·174	·047	—·021	·049	·031	·043	·022	·020	—·040	—·006	—·011	—·035
c_1'	—·024	·048	·025	—·004	—·003	·004	·001	—·001	—·001	—·003	·001	·003	·024
c_2	—·022	·760	·932	·395	—·405	·318	·191	—·756	—·790	—1·160	—·351	·013	·057
c_2'	—·105	·548	·210	—·010	·036	·177	·018	—·191	—·077	·224	·023	—·125	·085
c_3	1·413	—1·279	—·422	·507	·617	·224	—·658	—1·237	—1·193	·793	1·075	·381	—·432
c_3'	·191	·014	—·011	·045	·131	—·019	—·268	—·223	·066	·167	·015	·072	·029
c_4	—3·787	·526	—·365	—1·638	—2·853	—2·875	—2·067	·722	3·445	2·771	·235	·348	·515
c_4'	—·015	—·507	—·245	—·074	—·206	—·197	·157	·295	—·043	—·223	·047	—·061	·107
c_5	2·842	1·138	—·007	—·088	1·976	2·880	3·792	2·821	·472	— 977	—·128	—·172	—·288
c_5'	—·082	000	·061	·071	·201	·340	·367	·097	—·024	·252	—·163	—·035	—·007
c_6	—1·022	—1·423	—·172	·814	·114	·015	—·608	—1·011	—·994	—·471	·082	·054	·119
c_6'	·121	·067	·013	·037	·109	·161	·028	·047	·009	—·199	·020	·003	—·157
c_7	—·732	1·237	1·074	·063	·714	·317	·392	·619	·211	—·357	·222	·226	—·049
c_7'	—·070	—·007	·023	·020	—·002	—·038	·017	—·051	—·007	·073	—·019	—·017	·005
c_8	·555	·345	·172	—·022	—·264	—·215	—·145	—·129	—·016	·255	—·096	—·057	·075
c_8'	·095	—·040	—·030	·009	—·015	—·008	—·005	·005	·003	—·011	—·010	·004	—·104

coefficients applicable to tropical latitude stations *viz.*, New Delhi, Bombay and Vishakapatnam in India. Table 3 gives the regression coefficients for each channel at various isobaric levels.

Table 4 (a—f) gives the measurements of radiances, corrected radiant temperature using Planck's Law and the actual temperature calculated using equations 2, 3 and 4 for each isobaric level for comparison with radiosonde observations taken at New Delhi, Bombay and Visakhaptnam (for both 00 and 12 GMT) on 14 and 15 May 1969. Sample computations are shown in Appendix .

Figs. 2 to 7 give the comparison of the temperature profile obtained from SIRS radiances and the temperatures measurements obtained from radiosonde observations taken at 00 GMT and 12 GMT on 14 and 15 May 1969 at New Delhi, Bombay, and Visakhapatnam.

4. Analysis

Figs. 2 to 7 show general broad-scale agreement between the computed and observed temperatures. A more detailed comparision between calculated and observed temperatures shows that about 60 per cent of the differences are less than 3°C. Positive and negative differences are nearly equal in frequency with slight preponderances for the later.

It may be mentioned that Nimbus III satellite (SIRS) observations near the above three stations were taken at 18 GMT, 19 GMT on 14 and 15 May 1969 and the calculated temperature values are compared with the radiosonde observations taken at 12 GMT previous day evening and 00 GMT next day morning. The position of Nimbus III Satellite though practically near the same latitudes of the

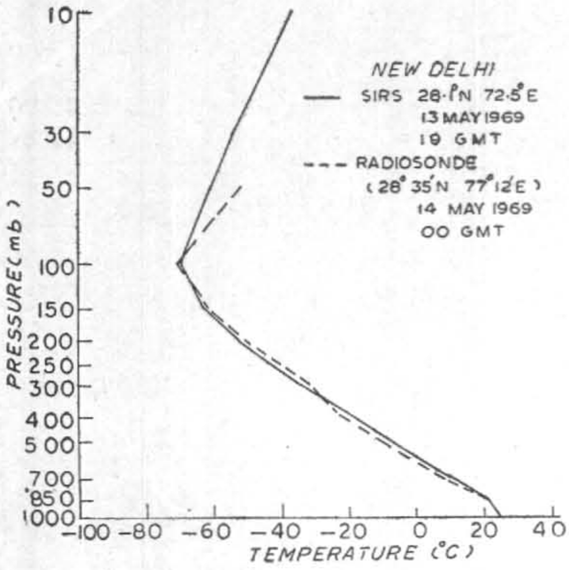

Fig. 2

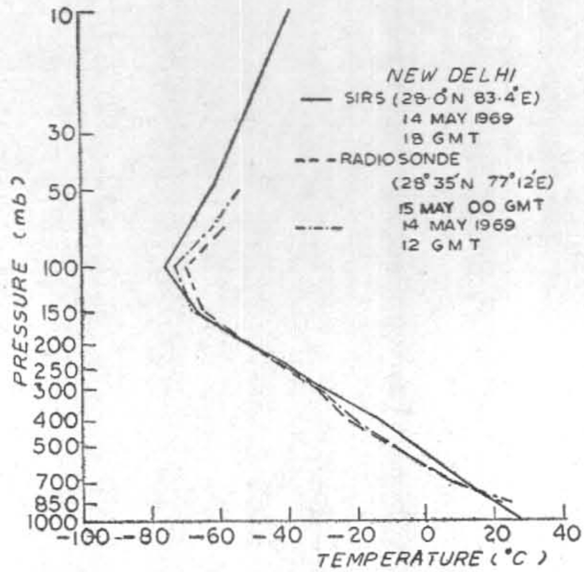

Fig. 3

Comparison of a SIRS (calculated) and New Delhi radiosonde (observed) temperature profile

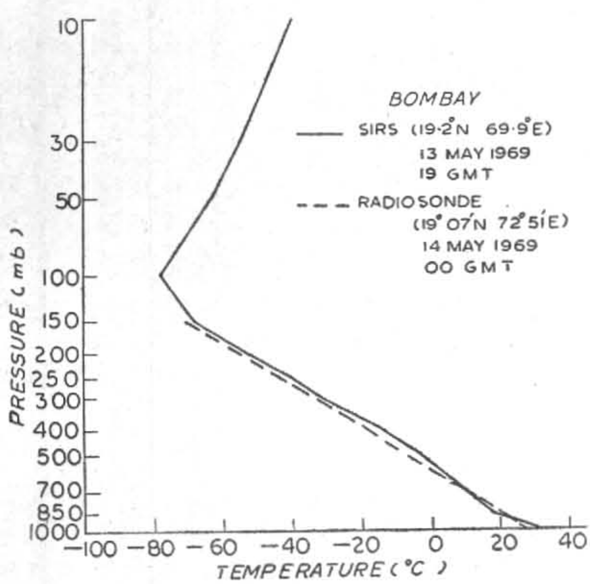

Fig. 4

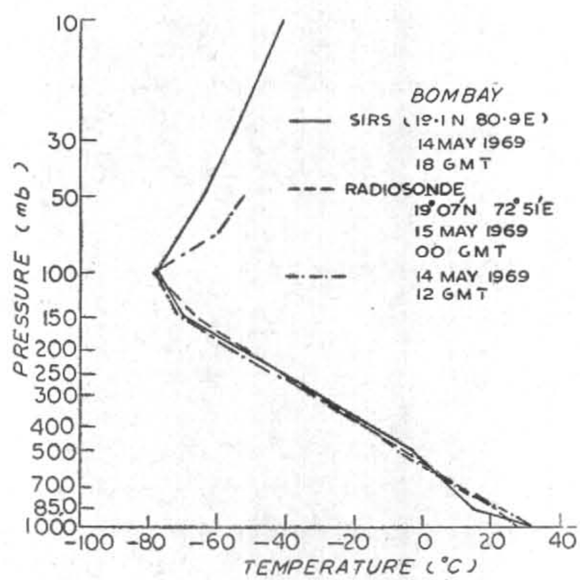

Fig. 5

Comparison of a SIRS (calculated) and Bombay radiosonde (observed) temperature profile

TABLE 4

(a) Date : 13 May 1969, Time : 1900 GMT, Lat. 28·1°N Long. 72·5°E (Near New Delhi 28·4°N, 77·1°E)

Channel (cm⁻¹)	899·3	669·3	677·3	692·3	699·3	706·3	714·3	750·0
Radiances	104·93	56·21	45·10	43·40	47·13	58·07	72·14	104·61
Calculated cloud pressure (mb)	Clear							
Corrected radiant temp.	292·38	231·09	220·55	220·25	225·05	236·66	249·83	277·23

Pressure (mb)	1000	850	700	500	400	300	250	200	150	100	50	30	10
Temp. (°K)	297·6	293·8	282·7	264·9	253·8	238·2	229·9	219·7	210·2	203·4	211·8	219·4	235·8

(b) Date: 14 May 1969, Time: 1800 GMT, Lat. 28·0°N, Long. 83·4°E (Near Delhi 28·4°N, 77·1°E)

Channel (cm⁻¹)	899·3	669·3	677·3	692·3	699·3	706·3	714·3	750·0
Radiances	101·89	56·01	44·44	42·33	47·18	58·68	72·18	99·69
Calculated cloud pressure (mb)	300	01	250	11				
Corrected radiant temp.	296·09	230·90	219·83	219·14	225·57	238·67	252·48	278·47

Pressure (mb)	1000	850	700	500	400	300	250	200	150	100	50	30	10
Temp. (°K)	300·7	292 5	283·9	269·1	259·1	242·8	233·6	220·8	207·1	197·4	211·5	219·2	234·2

(c) Date: 31 May 1969, Time: 1900 GMT, Lat. 19·2°N, Long. 69·9°E (Near Bombay 19·1°N, 72·5°E)

Channel (cm⁻¹)	899·3	669·3	677·3	692·3	699·3	706·3	714·3	750·0
Radiances	115·45	55·59	43·74	41·33	46·71	59·72	75·66	109·99
Calculated cloud pressure (mb)	Clear							
Corrected radiant temp.	298·75	230·49	219·06	217·92	224·61	238·19	252·71	280·77

Pressure (mb)	1000	850	700	500	400	300	250	200	150	100	50	30	10
Temp (°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

(d) Date: 14 May 1969, Time: 1800 GMT, Lat. 19·1°N, Long 89·9°E (Near Bombay 19·1°N, 72·5°E)

Channel (cm⁻¹)	899·3	669·3	677·3	692·3	699·3	706·3	714·3	750·0
Radiances	65·84	55·60	43·76	40·25	43·01	50·26	58·08	70·91
Calculated cloud pressure (mb)	300	36	250	43				
Corerected radiant temp.	299·98	230·50	219·08	217·04	222·83	236·59	251·37	278·40

Pressure (mb)	1000	850	700	500	400	300	250	200	150	100	50	30	10
Temp. (°K)	303·2	287·4	280·2	269·3	257·2	241·2	232·3	219·0	202·8	195·5	209·6	217·5	232·7

(e) Date: 13 May 1969, Time: 1900 GMT, Lat. 17·5°N, Long. 69·5°E (Near Visakhapatnam 17·4°N, 83·1°E)

Channel (cm⁻¹)	899·3	669·3	677·3	692·3	699·3	706·3	714·3	750·0
Radiances	115·67	55·18	43·51	40·95	46·50	59·72	75·67	108·75
Calculated cloud pressure (mb)	Clear							
Corrected radiant temp.	298·88	230·09	218·80	217·49	224·38	238·19	252·71	279·96

Pressure (mb)	1000	850	700	500	400	300	250	200	150	100	50	30	10
Temp. (°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

(f) Dite: 14 May 1969, Time: 1800 GMT, Lat. 17·3°N, Long. 80·4°E (Near Vishakhapatnam 17·4°N, 83·1°E)

Channel (cm⁻¹)	899·3	669·3	677·3	692·3	699·3	706·3	714·3	750·0
Radiances	70·99	55·39	43·40	40·25	43·64	51·18	59·84	73·19
Calculated cloud pressures (mb)	300	65						
Corrected radiant temp.	297·93	230·29	218·56	216·84	222·71	235·77	250·57	277·21

Pressure (mb)	1000	850	700	500	400	300	250	200	150	100	50	30	10
Temp. (°K)	303·9	286·8	278·4	268·2	257·2	241·0	232·3	219·1	203·4	195·5	208·9	217·2	232·2

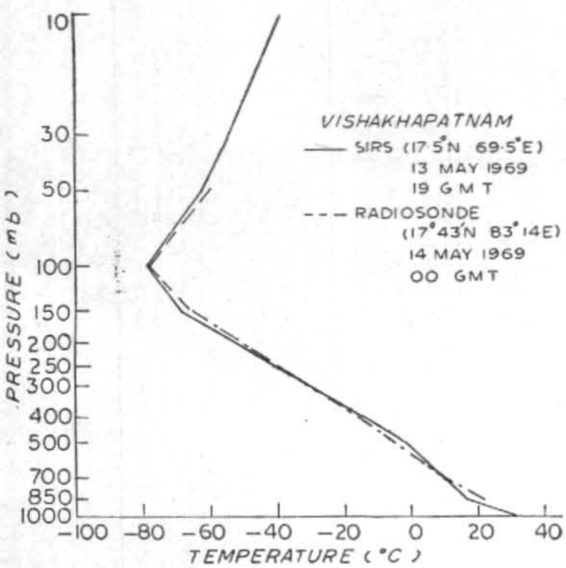

Fig. 6

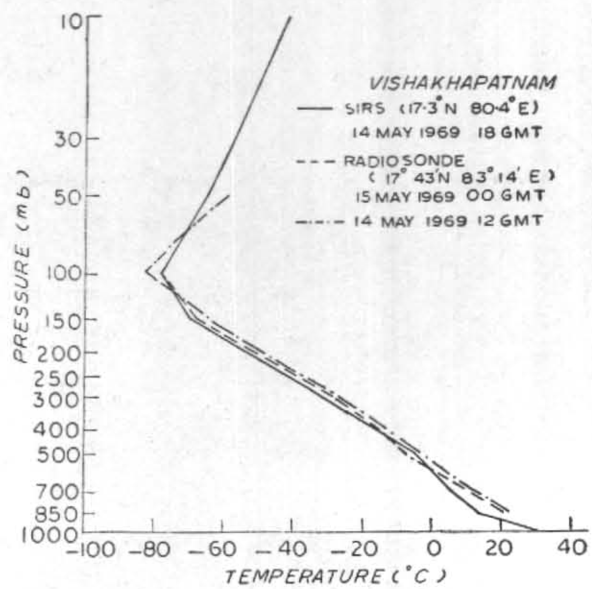

Fig. 7

Comparison of a SIRS (calculated) and Vishakhapatnam radiosonde (observed) temperature profile

three stations on 14 and 15 May 1969, the longitudinal position is away from these stations by 2 to 3 degrees. In a paper by Smith *et al.* (1969) it has been mentioned that the results of verification programme indicate that 70 per cent of the differences between SIRS derived and radiosonde observed temperatures in the northern hemisphere are generally between 1·5° and 2·0°C. The largest errors of temperature occur in the lower troposphere 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 differences due to the times of observations and that Nimbus III positions differed longitudinally by 2° to 3°, the results of comparison should indeed be regarded as very encouraging.

This is the first study in this field in India. It is hoped that the when radiance observations are transmitted under WWW scheme, computation of vertical temperature profiles would become a regular feature. These observations will be ot great help in providing upper air temperature information over sparse data regions like the Indian Ocean.

Acknowledgement

The author express their sincere and grateful thanks to Dr. W. L. Smith, Chief, Radiation Branch, Meteorological Satellite Laboratory, USA for supplying the SIRS radiation data close to New Delhi, Bombay and Visakhapatnam on 14 and 15 May 1969, together with the temperature profiles calculated from these radiance measurements, regression coefficients applicable to tropical latitudes for calculating temperature profiles.

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Appendix I

Sample calculation

According to Planck's Law of Radiation expressed in terms of wave number (ν)

$$R d\nu = 2\,h\,c^2\,\nu^3\,1/(e^{hc\nu/kT}-1)d\nu$$

Writing $\quad c_1 = 2\,hc^2 = 1{\cdot}191 \times 10^{-5}$

and $\quad c_2 = hc/k = 1{\cdot}439$

$$T = c_2\,\nu/\log_e\left(\frac{R + C_1\nu^3}{R}\right)$$

where,

R is the intensity of radiation (erg cm^{-2} sec^{-1} cm^{-1} per steradian)

h=Planck's constant=$6{\cdot}625\times10^{-27}$ erg second

c=Velocity of light=$2{\cdot}998\times10^{10}$ cm/sec.

k=Boltzmann's constant=$1{\cdot}38\times10^{-16}$ erg/degree

ν=Wave number in cm^{-1}

T=Absolute temperature (°K)

Calculation of temperatures by using the regression equation for 700 millibars

Near New Delhi (Lat. 28·4°N, Long. 77·1°E) ; Time : 1900 hrs.

$$\begin{aligned}
T'(700) = {} & {\cdot}047\times(292{\cdot}38-295{\cdot}9)+{\cdot}932\times(231{\cdot}09-231{\cdot}5)\\
& +(-{\cdot}422)\times(220{\cdot}55-222{\cdot}8)+(-{\cdot}365)\times(220{\cdot}25-221{\cdot}1)\\
& +(-{\cdot}007)\times(225{\cdot}05-225{\cdot}5)+(-{\cdot}172)\times(236{\cdot}66-237{\cdot}1)\\
& +1{\cdot}074\times(249{\cdot}83-250{\cdot}7)+{\cdot}172\times(277{\cdot}23-276{\cdot}9)\\
& +{\cdot}025\times(292{\cdot}38-295{\cdot}9)^2+{\cdot}210\times(231{\cdot}09-232{\cdot}5)^2\\
& +(-{\cdot}011)\times(220{\cdot}55-222{\cdot}8)^2\\
& +(-{\cdot}245)\times(220{\cdot}25-221{\cdot}1)^2\\
& {\cdot}061\times(225{\cdot}05-225{\cdot}5)^2+{\cdot}013\times(236{\cdot}66-237{\cdot}1)^2+\\
& {\cdot}023\times(249{\cdot}83-250{\cdot}7)^2+(-0{\cdot}030)\times(277{\cdot}23-276{\cdot}9)^2\\
= {} & {\cdot}05564.
\end{aligned}$$

$$\overline{T}\,(700) = 282{\cdot}3$$

$$\begin{aligned}
\text{Therefore, } T(700) &= \overline{T}\,(700)+T'(700)\\
&= 282{\cdot}3+{\cdot}056\\
&= 282{\cdot}356
\end{aligned}$$

DISCUSSION

DR. A. S. RAMANATHAN remarked that if the absorption of CO_2 and water vapour have been taken into account, no more refinement by taking other scattering constituents of the atmosphere is possible, since we do not always get clear conditions. We get cloudy conditions also and therefore a certain approximation goes into the calculations.

PROF. K. R. RAMANATHAN drew attention to the constituents of the atmosphere, particularly the varying elements like water vapour whose distribution varies by day and night, dust etc. and the errors introduced thereby. He suggested their exact evaluation by a good ground based infra-red radiometer.

DR. P. KOTESWARAM remarked that IRIS data have also been used for comparison and evaluation of coefficients necessary for calculating vertical profiles.

DR. S. RANGARAJAN pointed out that in all the cases presented by the speaker the thermal structure of the atmosphere was characterised by continuous decrease of temperature with height. But when inversions or isothermal layers occur in the troposphere the solution may not be satisfactory.