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Effect of clouds and particulates on infrared radiative fluxes in the atmosphere over India

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ABSTRACT. Measurements of infrared radiative fluxes using balloonborne radiometersondes at four stations in India are presented. Typical vertical profiles of flux and cooling rates for dry, cloudless winters, dusty summers and cloudy monsoon months are analysed to isolate the effects of dust, water vapour and clouds on the infrared radiative flux and cooling. Computations of net flux and cooling rate on the basis of a numerical model incorporating the effects of water vapour, carbon dioxide, ozone and clouds but no dust, are compared with the observations. The comparison shows that the warming rate at the base of a dense dust layer and the cooling rate at the top can be as high as 10°C/day.

1. Introduction

Considerable theoretical and experimental work which characterises quantitatively the influence of clouds and particulates on radiative transfer has been done by various workers in different parts of the world. A complete study of their influence on radiative transfer would involve direct and independent measurements of the vertical distribution of both clouds and of the aerosol concentration, composition and size distribution and of the shortwave and longwave radiative fluxes in the atmosphere, by means of complex experimental programmes similar to that suggested by Kondratyev *et al*. (1972). However, a simpler solution can be found and the effect of dust and cloud on the radiative flux and radiative cooling rates can be isolated and independently assessed, if measurements can be made at suitable locations and during suitable seasons, when either the dust or cloud is absent or minimal.

The natural division of the year over north and central India into mainly dry, cloudless winters (except during the passage of western disturbances in the north), dry, dusty cloudless summers and cloudy monsoon months enables one to study independently the effect of dust , water vapour and cloud on the radiative cooling and warming rates in the atmosphere. An attempt has been made in the present study to compare the observed values of net flux and cooling rates at various levels with numerical computations made with a model which incorporated effects of water vapour, carbon dioxide, ozone and clouds but no dust. The same model with data for the monsoon season but with the assumption of a cloud-free atmosphere was used to study the effect of cloud layers.

2. Observations

Measurements of infrared radiative fluxes using radiometersondes were started in India in 1963 and continued at one station, *viz*., Poona more or less regularly till 1971, when regular fortnightly soundings were started at three stations roughly along the 75°E meridian, at Trivandrum, Poona and New Delhi, 8°, 18° and 28° north of the equator. The radiometersonde used is of the Suomi-Kuhn type made in the Instruments Research Laboratories at Poona.

Trivandrum, on the sea coast 8°north of the equator, has a tropical maritime climate, with uniformly high temperatures and humidities throughout the year. Poona, on the Deccan Plateau 555 m above sea level on the lee side of the Western Ghats, has a comparatively dry, cool climate with generally clear skies, except during the monsoon and thunderstorm seasons. Delhi, lying on the northern Indo-Gangetic Plain east of the Rajasthan desert, has a continental climate with an exceptionally dry, dusty atmosphere in summer. The winter months are generally cloud-free except during the passage of western disturbances.

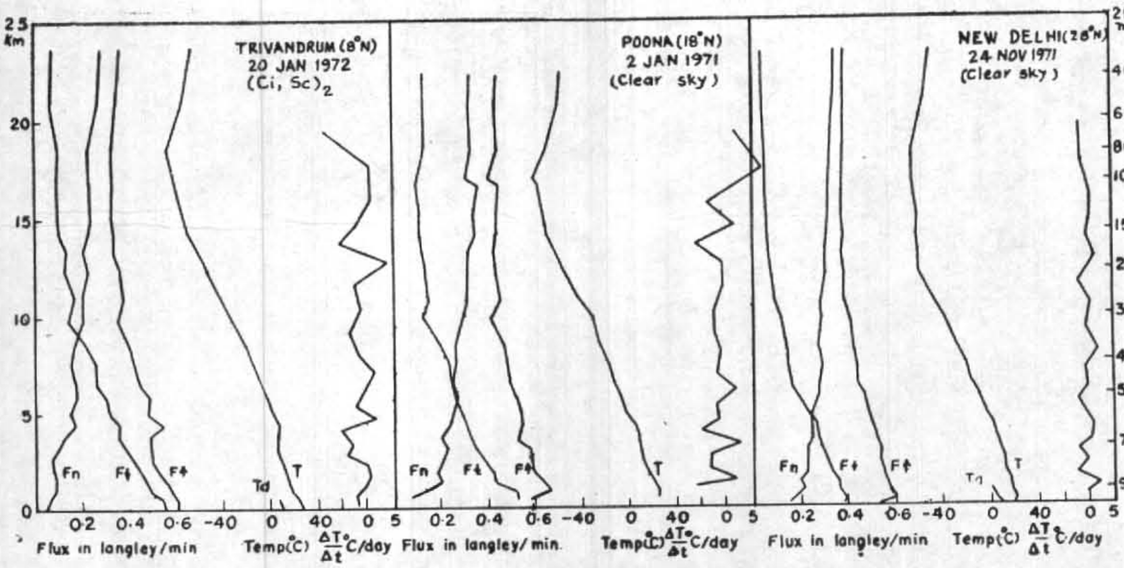

Fig. 1. Radiometersonde ascents on winter nights

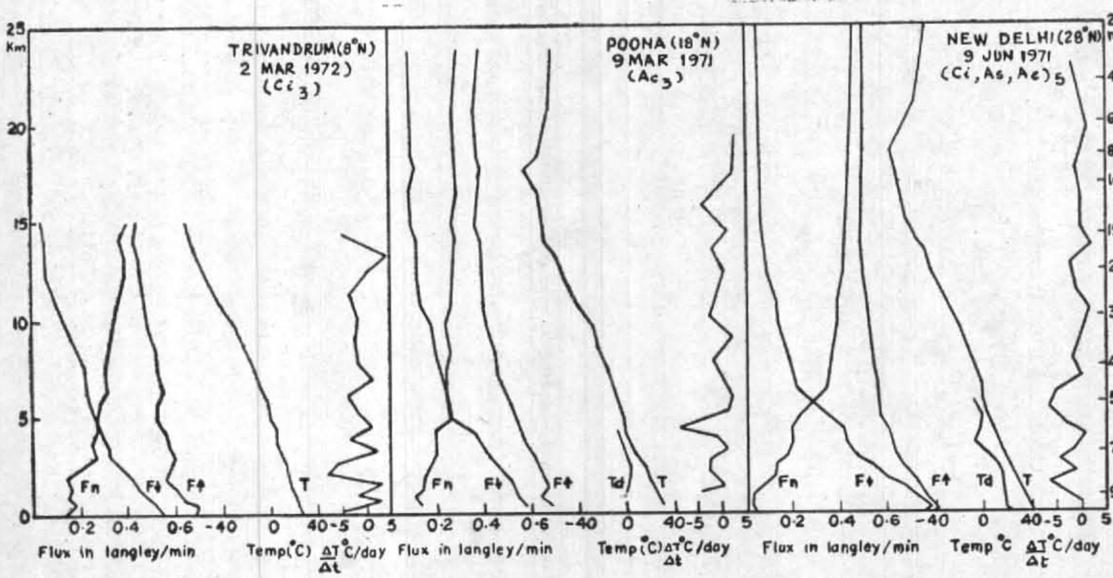

Fig. 2. Radiometersonde ascents on summer nights

Fortnightly soundings were made on alternate Wednesdays at all three stations. With an average rate of ascent of 300 m/min, temperature and humidity data are obtained every 100 m. The upward, downward and net radiative fluxes $F\uparrow$, $F\downarrow$ and F_n were computed from the top and bottom radiation sensor temperatures and air temperature; and radiative cooling and heating rates were calculated using the usual formula, for 50-mb thick layers upto 200 mb and 25-mb thick layers above 200 mb, from the observed radiative flux divergences at various levels.

3. Results

The seasonal variations of the infrared radiative fluxes and cooling rates over Poona have been described in earlier papers (Mani *et al.* 1965). Fig. 1 shows typical nocturnal soundings for clear winter nights at Trivandrum, Poona and New Delhi. In each the infrared upward radiative flux $F\uparrow$, the downward flux $F\downarrow$ and the net flux F_n, in Langleys/min are plotted against height in km, with air temperature T and dewpoint temperature T_d. The radiative temperature change $(\triangle T/\triangle t)$ in °C/day are plotted at the extreme right.

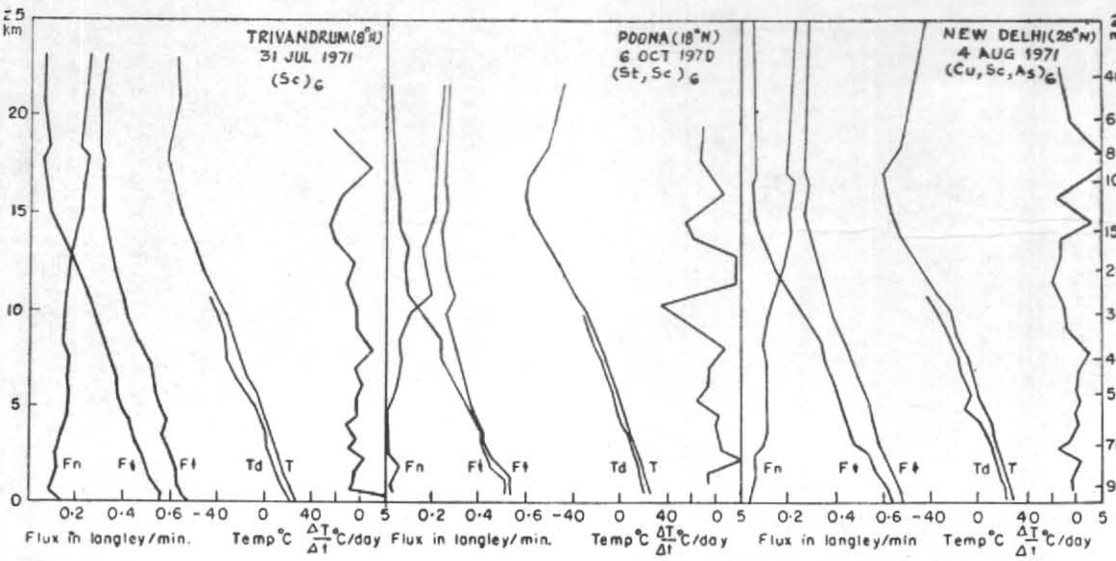

Fig. 3. Radiometersonde ascents on monsoon nights

Fig. 2 shows nocturnal soundings for typical summer nights at the three stations, while Fig. 3 shows similar soundings on monsoon nights with more or less overcast skies at the three stations.

The vertical profiles of radiation fluxes show marked variations, at the three stations and during the three seasons, although the basic pattern remains the same, with the net radiative flux increasing with height till a maximum is reached at about 12 km, decreasing till the tropopause is reached and increasing again in the stratosphere till steady values are reached at about 25 km. Cooling generally decreases with height, drops almost to zero at 12 km, becomes warm below the tropopause with large and variable cooling above, in the stratosphere.

During the winter months, the temperature inversion near the ground and the consequent trapping of pollutants in the lowest layers are responsible for the low values of $F\uparrow$ and F_n in the first kilometre at Poona and Delhi. Above the inversion the air is comparatively dry, with values of relative humidity lower than that measurable by the radiosonde. In the absence of clouds, the variations in the vertical profiles of three fluxes at Poona and Delhi are to be ascribed to the presence of aerosol layers at various levels. The marked changes in $F\uparrow$ and F_n just below the tropopause over Poona may be associated with the existence of cirrus clouds at these levels.

In the pre-monsoon summer months, the predominant influence is that of dust over Delhi and Poona. As a result of the dust concentration in the lower troposphere, cooling above the dust layer is of the order of 7°/day.

During the monsoon months, the outgoing infrared flux is reduced to about 0.24 Langleys/min as the result of clouding at all the stations.

4. Effect of water vapour and cloud on infrared cooling

The largest contribution to the infrared cooling of the atmosphere is known to come from water vapour while the most important radiator energetically is the cloud and it has a more pronounced effect on the radiative heat balance of the atmosphere.

The most striking feature of the distribution of water vapour in the atmosphere over India is its seasonal variation. In winter the maximum concentration occurs over the equatorial region with the lowest values over northwest India. In July the situation is reversed with the maximum over north and northwest India and the minimum over the equator. This reversal arises from the large seasonal changes in the water vapour mixing ratios. For example, at the 850-mb level, the values over northern India vary during the year from 3 to 16 gm/kgm, while over the equator the values remain more or less constant at about 10-12 gm/kgm.

The distribution of total cloud amount over India also shows variations similar to that of water vapour. During January-April the total cloud amount is 3 octas or less over most of central India with slightly higher amounts in the north and south

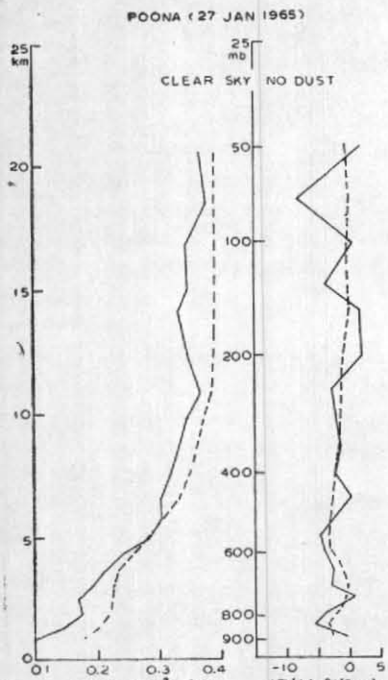

Fig. 4

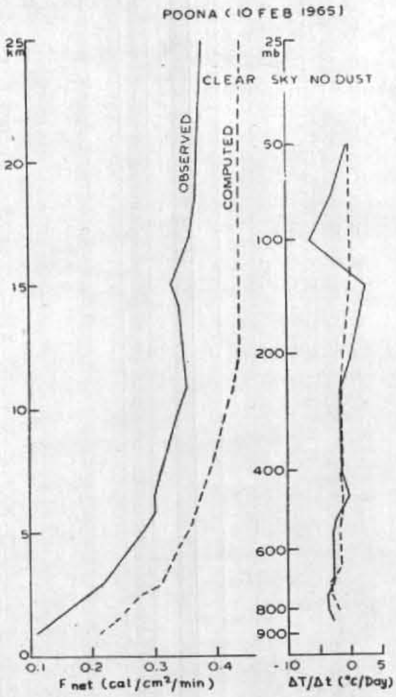

Fig. 5

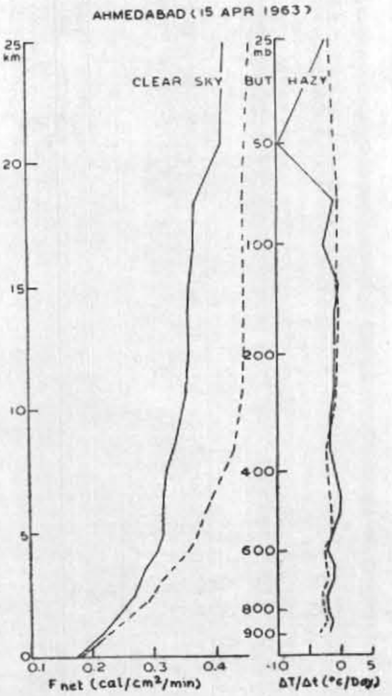

Fig. 6

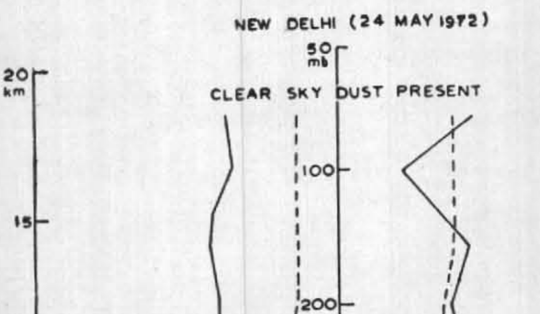

Fig. 7

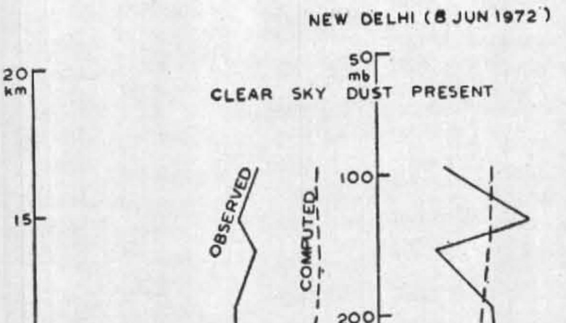

Fig. 8

Figs. 4-8. Observed and computed net radiative fluxes and cooling rates

In July when the monsoon is established over almost the whole of India, cloud cover exceeds 6 octas throughout India, except in the northwest. High values of the order of 5-6 octas persist over south India in October with values diminishing rapidly to almost zero in the northwest.

The radiative cooling is greatest in regions of high specific humidity, with values of 2-3°/day over the equatorial regions represented by Trivandrum, while it is only of the order of 1°/day over the northern plains or the Deccan Plateau represented by Delhi and Poona in winter (Fig. 1). On a cloudfree monsoon night at Delhi on the other hand the cooling rate far exceeds that over Trivandrum at the same time.

The effect of clouds is such that the top of the cloud loses heat by radiation and the base gains heat. The net effect is to increase the cooling at most points in the atmosphere but to diminish it at or near the ground. This is clear from the monsoon soundings at all three stations (Fig. 3). Regions close to cloud top level exhibit large infrared cooling values of 3°C/day while the cloud base region shows warming. With the increase of clouding over the tropics during the monsoon, the cooling rate increases to 5°/day or more. The level of maximum cooling is the average height of the middle clouds.

5. Effect of dust and aerosols on infrared cooling

The effect of dust and aerosols on infrared radiation is similar to that of clouds. Particularly strong effects are noticed in the surface layers where dust is typically concentrated. Dust not only attenuates but re-emits infrared radiation. The cooling is marked above the dust layer with relative warming below and is prominent in the pre-monsoon soundings at Delhi and Poona when the skies are clear but hazy (Fig. 2).

Bryson *et al.* (1964) measured the vertical distribution of longwave radiative fluxes at several places in northwest India during March-April 1963 and also calculated the radiative fluxes based on the observed water vapour and assumed ozone and carbon dioxide distribution. Measurements were also made recently by Sargent *et al.* (1973). They found the calculated diabatic cooling to be significantly less than that observed and suggested that dust plays an important role in the maintenance of a steady monsoon circulation over north India. Since these measurements were made during the pre-monsoon summer months and the aerosol content becomes insignificant during the monsoon months with the removal of dust by rainout and washout, the importance attached by Bryson *et al.* (1964) to dust in the monsoon circulation would appear to be misplaced.

6. Numerical computations

6.1. *Method of computation*

The infrared radiative fluxes and cooling rates in the atmosphere for a number of nights when radiometer soundings were made at the stations were computed, following the numerical model developed by Kelkar (1970). The model considers the effect of absorption by water vapour, carbon dioxide and ozone as well as clouds. It also takes into account the overlapping of water vapour absorption bands with those of carbon dioxide and ozone. The absorptivities of the three gases have been compiled from recent data and their dependence on pressure and temperature has been incorporated in the model. The effect of the presence of dust and aerosols in the atmosphere has, however, been disregarded.

Computations were made at 24 levels in the vertical, *viz.*, 0, 10, 25, 50, 75,......, 150, 200, 250 ......, 900 mb and surface. Air temperature reported by the radiometersonde were directly used for the computations and the reported dew-points were used to construct the vertical distribution of water vapour. At those levels where the water vapour concentration was too small to be sensed by the humidity sensor of the radiometersonde, the relative humidity was assumed to be 10 per cent. Carbon dioxide was considered to have a uniform distribution of 0.456 gm/kgm. The vertical distribution of ozone was obtained from ozonesonde measurements made at the three stations.

6.2. *Comparison of observed and computed data*

The net infrared radiative fluxes and cooling rates, computed for seven soundings made at Poona, Ahmedabad, New Delhi and Trivandrum on typical clear winter, dusty post monsoon and cloudy monsoon nights, are plotted (Figs. 4-10) with actual observed net infrared radiative fluxes and cooling rates obtained from radiometer soundings.

The study was made in three parts in order to isolate the effects of water vapour, clouds and particulates on the radiative flux divergence and radiative cooling.

(*i*) With no cloud and no likelihood of dust at stations like Poona and Ahmedabad during the winter months to isolate the effect of moisture (Figs. 4, 5 and 6).

(*ii*) With no clouds and very little moisture but with a very dusty atmosphere at a

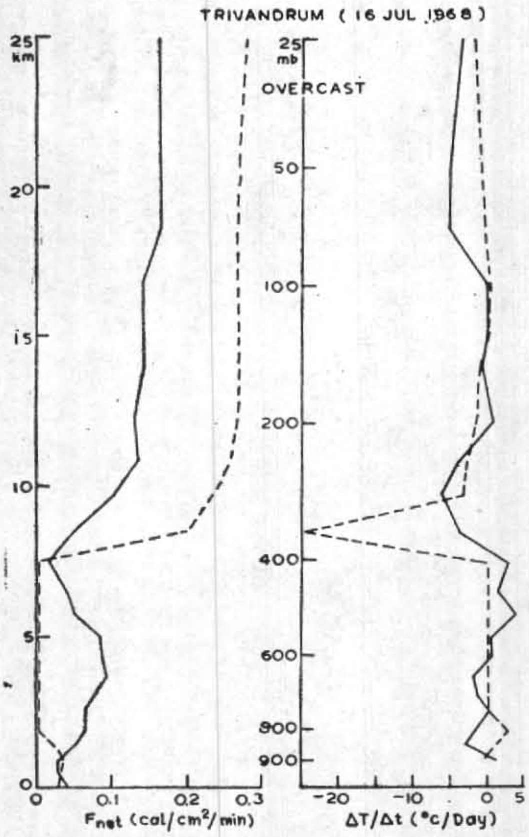

Fig. 9

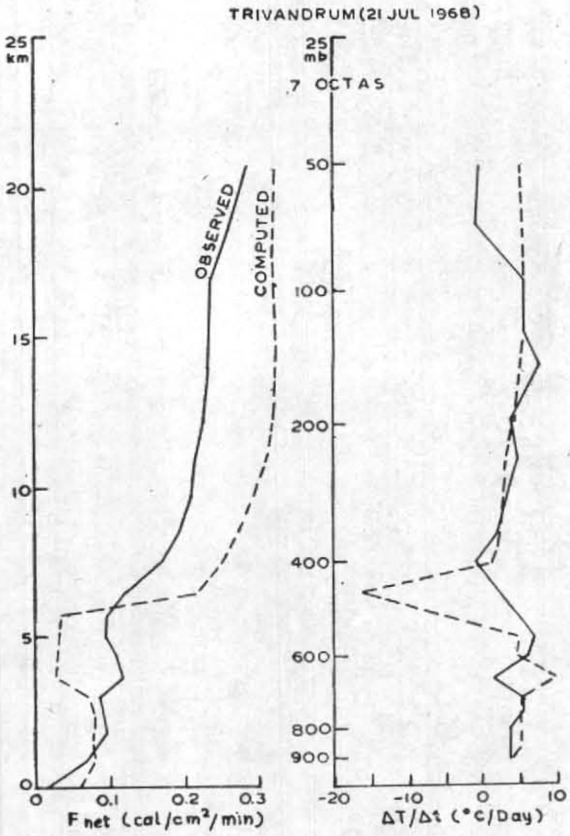

Fig. 10

Figs. 9 & 10. Observed and computed net radiative fluxes and cooling rates

station like Delhi in the pre-monsoon summer months to isolate the effect of dust (Figs. 7 and 8).

(*iii*) With overcast skies and no likelihood of dust, at a station like Trivandrum during the monsoon months to isolate the effect of clouds (Figs. 9 and 10).

(*i*) *Effect of water vapour* — Figs. 4 and 5 show the vertical profiles of net radiative flux and cooling observed and computed for 27 January and 10 February 1965 at Poona. With clear skies both the observed and computed values of both the net flux and radiative cooling show good agreement. Both observed and computed values show uniform cooling through most of the troposphere.

Fig. 6 shows similar profiles for 15 April 1963 at Ahmedabad when the skies were clear but the atmosphere was hazy. The cooling rates, computed and observed, show excellent agreement, although the net fluxes show some difference, indicating that the model taking into consideration the effects of absorption by water vapour, carbon dioxide and ozone explains quantitatively the vertical distribution of radiative cooling in the atmosphere. The computed values do not show any warming below the tropopause or large cooling just above it.

(*ii*) *Effect of dust* — Figs. 7 and 8 show the observed and computed values of the net radiative flux and cooling rates at Delhi on 24 May 1972 and 8 June 1972, when the skies were clear but dust was present in the atmosphere. The observed values of cooling show large fluctuations in both magnitude and sign in the lower troposphere, probably as the result of dust, while the computed values, which do not take the effect of dust into cosideration, does not show them. The large cooling in the observed profile indicates the top of the dust layer over Delhi about 4-5 km above the ground level. The net observed fluxes are lower than the computed values by about 0.1 ly/min at all levels. The assumption of relative humidity of 10 per cent in the troposphere and stratosphere where no actual measurements were available may also be responsible for the difference in this case as well as for those illustrated in Figs. 5 and 6.

(*iii*) *Effect of clouds* — Figs. 9 and 10 show the vertical profiles of F_n and radiative cooling for 16 and 21 July 1968 at Trivandrum on monsoon nights, when the skies were overcast. The base and top of the cloud were taken as 1.4 and 9.7 km for the first sounding and 3.1 and 5.3 km for the second, from the observed cooling profiles, where large cooling and warming is noticed.

The observed and computed net fluxes are uniformly low. The cooling rate profiles show fairly good agreement, which cannot naturally be expected with the meagre data available on the type and thickness of the clouds.

7. Concluding remarks

(*i*) An attempt has been made to study the effects of water vapour, clouds and dust on the infrared radiation balance by taking advantage of the large seasonal variation in these parameters at four stations in India.

(*ii*) Numerical computations of the infrared flux and cooling rate show good qualitative as well as quantitative agreement with observations. By neglecting dust in the numerical model, it has been shown that in the real atmosphere, dense dust layers can produce cooling or warming of the order of 10° C/day at tropospheric levels.

(*iii*) Precise measurements of the dust content over northwest India, including mineralogical analyses, are necessary for making a detailed study on the role of dust in the radiation balance over the region.

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