

First time observation of latitudinal and vertical distribution of infra-red radiative flux using radiometer sonde over Indian Ocean during the INDOEX IFP-1999 and its comparison with other Indian stations

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Latitudinal distribution of radiative flux at different layers has been measured for the first time over the Indian Ocean from 15°N to 20°S during intensive field phase of INDOEX 1999. Simultaneously measurements have been made over three Indian ground stations, viz. Delhi, Pune and Trivandrum. The basic feature of radiative flux over the Indian Ocean, Delhi, Pune and Trivandrum is similar, i.e. the radiative flux increases with altitude and reaches a maximum value at 15 km and after that the increasing rate slows down. The most striking feature of this observation is the existence of radiative flux between 12 and 15 km of height near the equator (1.75°N, 62.98°E) which may be due to the combined effect of partly cloudy sky, presence of aerosol and ozone. In addition, at 13.3°N, 60.5°E a similar feature has been observed at a height of 14–15 km, which may be due to the increment of ozone by 25 Dobson Unit (D.U.) during the onward journey since no aerosol was observed. During the return journey, at 12°S, 60.4°E global warming is also observed at a height of 13–15 km, which may also be due to the combined effect of partly cloudy sky and the presence of aerosol and increment of ozone.

INDOEX (Indian Ocean experiments) is designed to study the natural and climatic forcing by aerosols and feedbacks on regional and global climate. Aerosol cooling (from aerosols such as sulphates, soot organic carbon, mineral dust) has a large element of uncertainty, which complicates our understanding of the combined impact of increasing GHGs and aerosols. INDOEX addresses by focusing on a region in the Arabian Sea and the Indian Ocean during January to March at a time when the 'polluted' air from the Indian subcontinent and the pris-

tine air masses from southern Indian Ocean meet over the tropical Indian Ocean at latitudes between 0° and 15°S¹.

Above 100 km, the wavelengths below 100 nm, radiation is almost completely absorbed by molecular, atomic oxygen and by molecular nitrogen. At larger wavelengths, the solar spectrum is subdivided into regions of absorption by the principal absorbing species such as O₂ and O₃. The first species absorbs O and the radiation at wavelength less than 2412.2 nm. The second species is abundant in the stratosphere, absorbs the radiation primarily below 200–300 nm and also to some extent in the visible and even in the infra-red².

In the longwave region, the surface temperature, atmospheric temperature structure and background concentrations (ozone, CO₂, CH₄, etc. the suspended aerosol particles), water vapour and clouds, as well as the altitude at which the change of absorbing material takes place are important factors in radiative processes. Consequently the transfer phenomenon becomes complex. A detailed study of the spectral variation in the thermal radiation field is highly desirable, which requires a very high order of specialized instrumentation involving huge expenditure. A simple radiometer attached to a radiosonde balloon provides an inexpensive device to obtain a vertical distribution of the thermal radiation field. Aerosol particles absorb longwave (infra-red) radiation, but this effect is usually small because the opacity of aerosols decreases at longer wavelengths and because the aerosols are most concentrated in the lower troposphere, where the atmospheric temperature which governs emission, is particularly the same as the surface temperature³. Ozone is radiatively active in the longwave as well as the shortwave region. In the presence of clouds, the greenhouse effect decreases as the background atmosphere becomes less transparent. The quantification of the radiative forcing due to tropospheric ozone change is critically dependent on the altitude of ozone change, predominantly

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through the longwave characteristics^{4,5}. Therefore, a reliable estimate for the longwave radiative forcing can only be established when tropospheric ozone changes are computed at the correct altitude, especially in the vicinity of the tropopause, where the sensitivity is largest. The atmospheric humidity and the cloud conditions determine the actual net radiation loss. The presence of cloud, particularly the low cloud, suppresses the heat loss by re-radiation to the earth's surface. In addition to water vapour and clouds, the thermal infra-red calculations include the absorption by nitrous oxide, methane and carbon dioxide, the effect of overlap with these species is small (less than 5%), as the main absorption band of ozone (at 9.6 μm) is well away from the strongest absorption bands of these gases⁶.

The net flux (0.1 W/m²) near the ground shows a general rise with height, although minor variations are present at 600 and 450 hPa. It reaches a maximum value in the troposphere (~ 15 km) and remains roughly constant up to the tropopause, where it again increases with height, reaching a steady value at 25 km. Decrease in the net flux at 250 hPa is presumable caused by a thin cirrus layer⁷.

Although fairly extensive measurements of the infra-red radiative fluxes in the atmosphere with balloon-borne radiometer sondes have been made in the middle latitudes, observations in the tropics are meager. A programme of radiometer sounding on-board *Sagar Kanya* over the Indian Ocean was therefore initiated in January/March 1999. The main purpose of the soundings made was to study the effect of the infra-red radiative fluxes in the deep, dense layer of dust, which lies over northern and central India during the INDOEX programme. The programme of sounding consisted of simultaneous ascents made at *Sagar Kanya* during INDOEX cruise #141 and three ground-based stations, New Delhi (29°N, 77.217°E), Pune (19°N, 73.85°E) and Trivandrum (8.483°N, 76.95°E), which lie in a north-south line across north and central India.

Field experiments

Radiometer soundings have been performed on-board *ORV Sagar Kanya* from 15°N to 20°S during onward and return journey during INDOEX-IFP in January/March 1999. Total of 16 radiosondes were performed, out of which 6 are during onward and 10 are during return journey. In addition, measurements of radiative flux were also observed over Delhi, Pune and Trivandrum

The radiometer used for this purpose is a Soumi-Kuhn type economic radiometer^{8,9}. The radiometer sonde is the conventional radiosonde with the radiometer head and a sensor for measuring radiation. It measures the downward and upward infra-red radiative fluxes in the atmosphere. It consists of one upward and one downward-facing blackened sensors, the temperatures of which are measured by means of rod thermistors. These sensors are supported by two identical blocks of light, rigid material of low heat capacity and of low thermal conductivity. Convection losses are minimized by the use of two very thin layers of polyethylene film, which serve as convection shields and by radiation windows. The upward, downward and net radiative fluxes are calculated from the top and bottom temperature sensors, which allow the heat to transfer through conduction within the system. For the calculation of radiative cooling and warming above 200 hPa, uniform thickness of 50 hPa is kept for various levels^{10,11}. From the values of the top, bottom sensor and air temperatures, the upward, downward and net radiative fluxes $F \uparrow$, $F \downarrow$ and F_N are calculated:

$$F \uparrow = s T_b^{4+} (I dT_b/d_t) + C_l - C_b;$$

$$F \downarrow = s T_t^4 + (I dT_t/d_t) - C_l - C_b,$$

$$F_N = F \uparrow - F \downarrow,$$

where, $s = 0.18 \times 10^{-10}$ ly/min/cm²/deg A (ref. 12), T_b is absolute temperature of the bottom sensing surface, T_t is

Table 1. Satellite observations during INDOEX IFP-1999

Date	Lat./long.	Relative humidity (%)	Aerosol	Cloud	Ozone (Dobson Unit)
21/01/99	13.33°N, 73.2°E	18-20	0.7-1.2	Fair	250-275
23/01/99	8.87°N, 76°E	40 (2.5 km)	Absent	Fair	..
26/01/99	2.4°N, 76.5°E	50-60	0.7-1.2	Cloudy	..
28/01/99	1.5°S, 77°E	60-70	Absent	Cloudy	..
30/01/99	6.33°S, 77°E	80-90	Absent	Partly cloudy	275-300
05/02/99	20°S, 74.48°E	70-75	0.7-1.2	Clear sky	..
18/02/99	18.1°S, 60.4°E	50-60	0.7-1.2	Partly cloudy	250-275
21/02/99	10.96°S, 62.96°E	65	Absent	Clear	..
25/02/99	1.75°N, 62.96°E	65-70	0.7-1.2	Partly cloudy	..
28/02/99	10°N, 61.5°E	30-40	Absent	Clear	225-250
01/03/99	13.3°N, 60.5°E	40-50	Absent	Clear	250-275
03/03/99	15°N, 65.3°E	40	Absent	Clear	..
04/03/99	11.23°N, 74.26°E	15-20	0.7-1.2	Clear	..
07/03/99	11.27°N, 74.26°E	20-30	Absent	Clear	..
09/03/99	16.03°N, 69.55°E	40-45	Absent	Clear	..

absolute temperature of the top sensing surface, and $I = 0.01015$.

Soumi-Kuhn radiometer sonde is operating on 72 Me/s, and its top and bottom temperature sensors are switched on every 20 s, with air temperature and relative humidity, by a clock-driven sequencing switch. The principle and the error of the Soumi-Kohn radiometer sondes have been treated in detail by Suomi *et al.*⁸ and Kuhn⁹.

From the measurements of the top, bottom and air temperatures, we have calculated the upward, downward and net radiation:

$$(\Delta T/\Delta t) = (-g/C_p) [(R_{NU} - R_{NL})/\Delta p],$$

where R_{NU} and R_{NL} are the net radiation fluxes at the upper and lower surfaces of an atmospheric layer of thickness Δp , C_p is the specific heat of air at constant pressure and g is the gravity field strength¹³.

Results and discussions

Figure 1 shows the meridional cross-section of vertical distribution of net radiative flux. It increases with altitude up to 12–15 km approximately during the onward journey. Although net radiative flux shows a flat structure, warming between different layers calculated shows patchy layers during onward and return journey. Three events will be discussed here elaborately.

First: at 1.75°N, 62.98°E on 25 February 1999, large radiative flux was observed near the equator at the altitude of 12–15 km (Figure 2). It was partly cloudy. Aerosol index, relative humidity and ozone were noticed at 0.7–1.2, 65–70% and 250 D.U. (Table 1, Figure 5), respectively. Krishna Moorthy *et al.*¹⁴ observed that aerosol optical depth at the near IR wavelengths remains nearly the same during INDOEX FFP-98. Moreover, Coakley *et al.*³ showed that the influence of aerosol on infra-red radiation is generally smaller than the influence on solar radiation. Clouds reduce the thermal infra-red radiative forcing role of other factors, e.g. ozone increment at a particular height becomes more important since the change of CO₂, CH₄ and other minor species remains reasonably uniform over the globe¹⁵.

Second: at 13.3°N, 60.5°E on 1 March 1999, the large radiative flux was noticed also at the height of 14–15 km (~ 100 hPa). Sky was clear with relative humidity of 40–50% (Table 1). No aerosol was present but an increment in ozone (250–275 D.U. (Figure 6)) was noticed. The net radiative flux also increases with height (Figure 3). It has already been mentioned that aerosol has little role in infra-red (longwave) radiation, therefore, the increment of ozone may have a role in this warming. Theoretical calculation^{6,16} suggests that tropospheric ozone increases contribute about 15% of the radiative forcing, which is equivalent to 0.28–0.31 Wm⁻². An increase in tropospheric

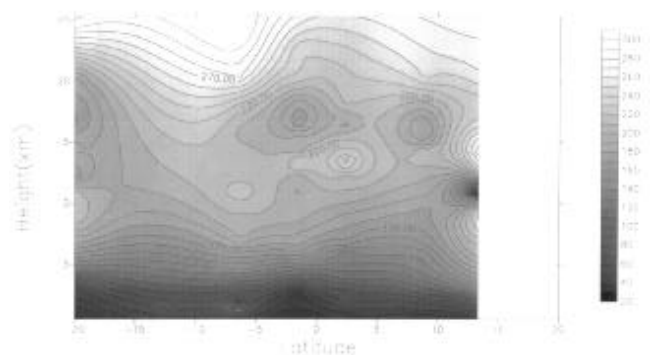


Figure 1. Latitudinal variation of net radiative flux over Indian Ocean during onward journey of INDOEX IFP-1999.

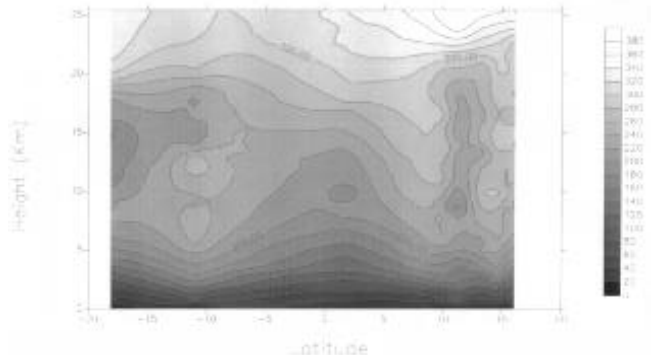


Figure 3. Latitudinal variation of net radiative flux over Indian Ocean during return journey of INDOEX IFP-1999.

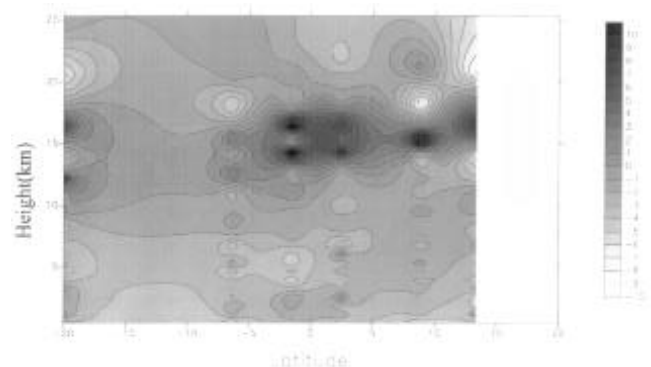


Figure 2. Latitudinal global warming over Indian Ocean during onward journey of INDOEX IFP-1999.

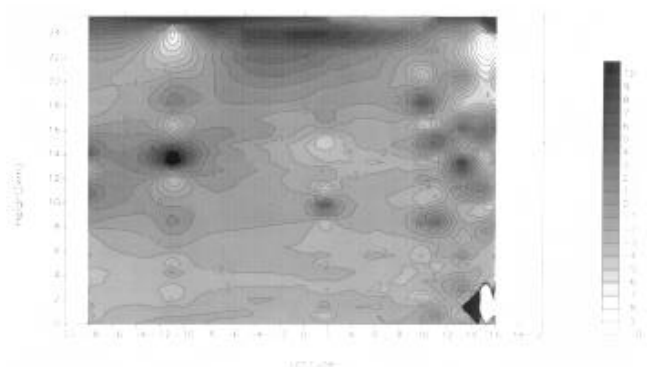


Figure 4. Latitudinal global warming over Indian Ocean during return journey of INDOEX IFP-1999.

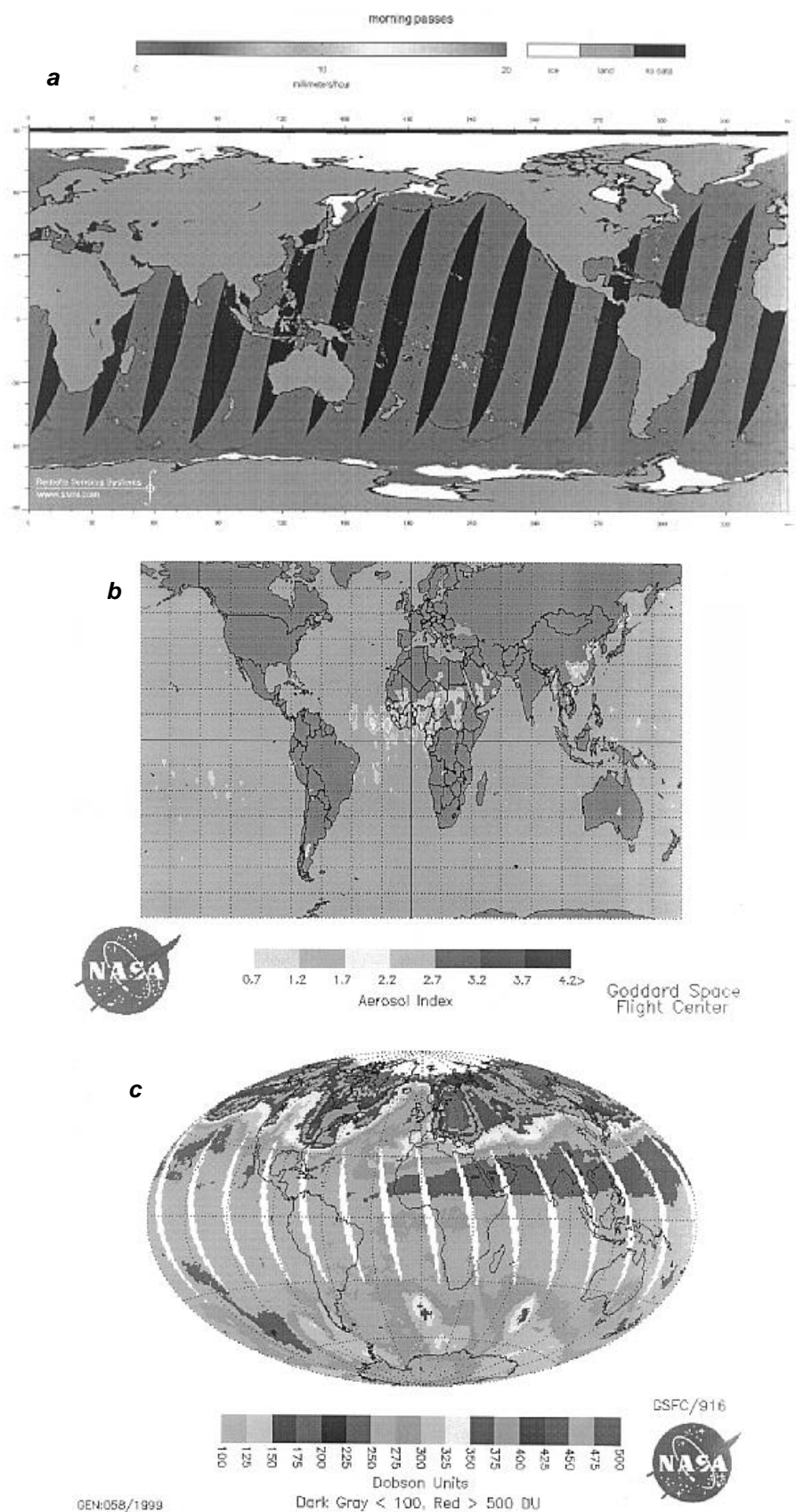


Figure 5. (a) Cloud picture on 25 February 1999 obtained from TRMM satellite; (b) Contour/picture of aerosol index on 25 February 1999 obtained from Earth Probe TOMS; and (c) Contour diagram of total ozone on 25 February 1999 obtained from Earth Probe TOMS.

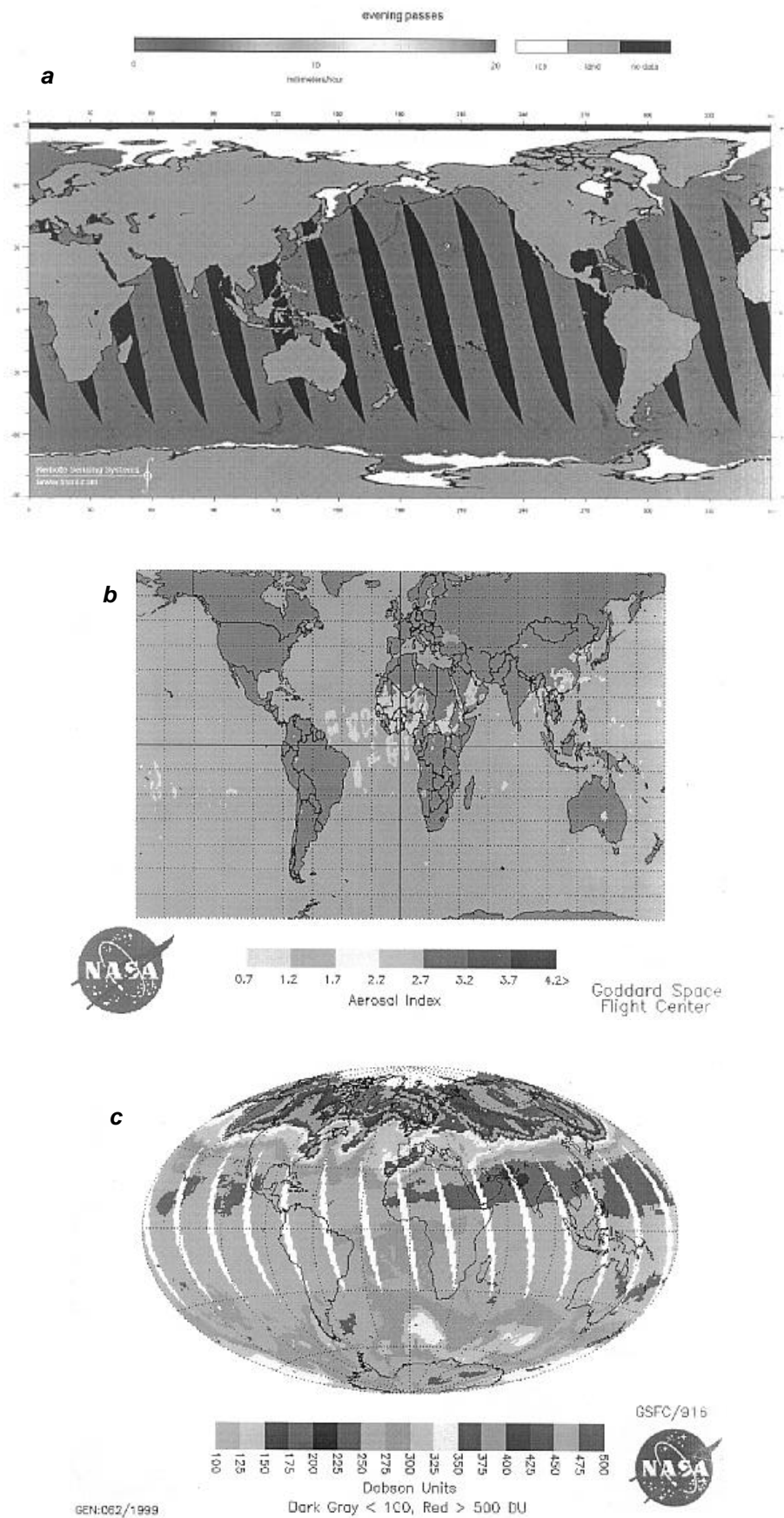


Figure 6 a-c. Same as Figure 5, but on 1 March 1999.

ozone leads to a reduction in the upwelling thermal infra-red irradiance reaching the lower stratosphere, which acts to cool the stratosphere. This cooling reduces the thermal infra-red emission from the stratosphere¹⁷, and from the surface-troposphere system, whereas clear sky conditions allows the thermal infra-red radiative. These lead to increased radiative forcing around the tropopause. In addition, indirect effect of relative humidity through the effect on aerosol may have effect of infra-red (longwave) radiative forcing.

Third: during the return journey, a large radiative flux was observed at 12°S at the height of 13–15 km. It was partly cloudy in addition to the presence of aerosol index (0.7–1.2) and increment of ozone (275–300 D.U.), with relative humidity 50–60% (Table 1). This is a complicated case as the combined effect of clouds, increment of ozone and presence of aerosol provided the warming at this altitude. Similarly, slight radiative flux was observed at 14°N, at height 14–15 km, which may be due to the presence of ozone (250 D.U.) with relative humidity 40–50% (Figure 4).

It has been found that relative humidity over the Indian Ocean during onward and return journey decreases from 80 to 40% with altitude. Air, top and bottom temperatures of *Sagar Kanya* during the cruise decreases up to the height of 16 km approximately and then rise. The up and down radiative fluxes decrease with altitude and then remain constant (225 W/m² and 20 W/m², respectively),

whereas the net radiative flux increases with height and reaches a maximum at a height 15 km approximately (Figure 7).

The variations of the infra-red radiative fluxes over *Sagar Kanya* have been observed with the simultaneous measurements over New Delhi, Pune and Trivandrum. In all cases the infra-red upward radiative flux $F \uparrow$ (Figure 8), the downward radiative flux $F \downarrow$ (Figure 9) and the net flux F_N (Figure 10) in W/m² are plotted against height. Marked variation is observed in radiative fluxes at the three stations, viz. Delhi, Pune and Trivandram as well as the Indian Ocean during INDOEX IFP-1999. The net radiative flux increases with height and reaches the maximum value up to 15 km (100 hPa), whereas, the up and down radiative flux decrease with height and reach a minimum value at the height of 12 km (200 hPa) approximately over the Indian Ocean as well as over all the three Indian stations.

Within the ‘exchange layer’ near the ground, the upward, downward and net radiative fluxes may be modified by the water vapour and dust present, resulting in a relative warming below and marked cooling (4°C/day) above, with a maximum at about 725 hPa. The layer of dust at and below the inversion behaves like a relatively cloud-warming on the underside and relatively cooling above in comparison with clean air.

Above the ‘exchange layer’ with an atmosphere comparatively free from dust and water vapour, the variations

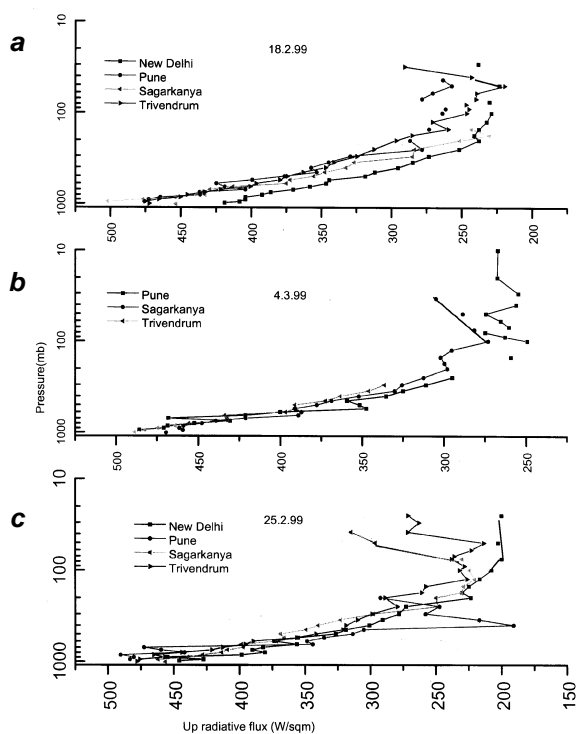


Figure 7. Latitudinal variation of up, down and net radiative fluxes over Indian Ocean during INDOEX IFP-1999.

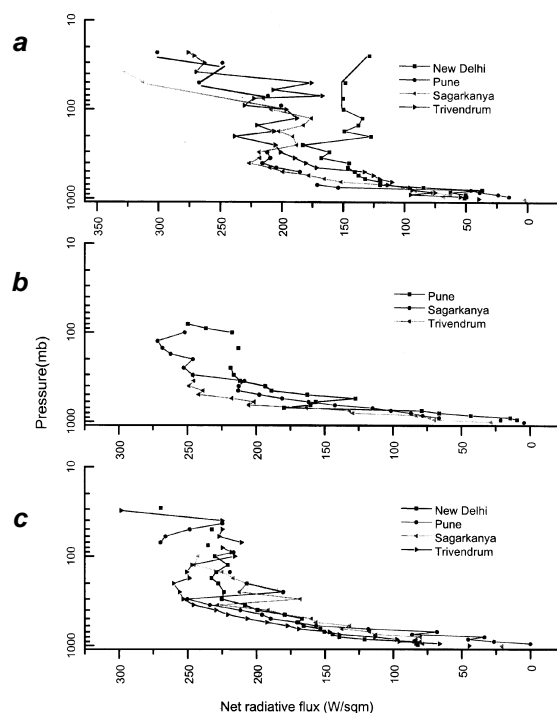


Figure 8. Comparison of latitudinal variation of down radiative flux of *Sagar Kanya* with other Indian stations, viz. Delhi, Pune and Trivandrum.

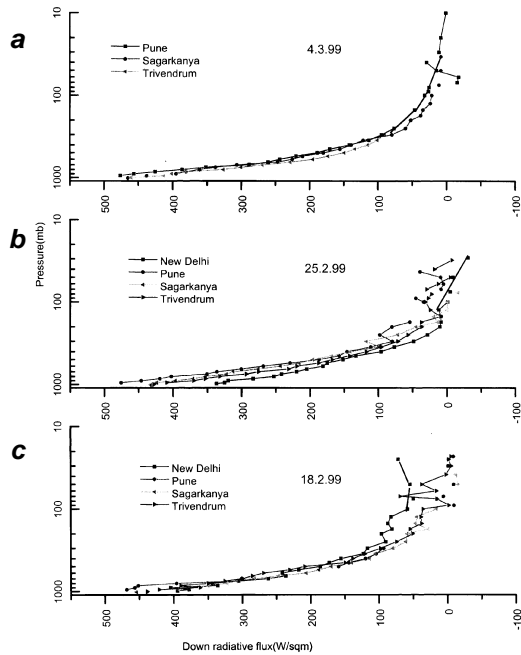


Figure 9. Comparison of latitudinal variation of up radiative flux of *Sagar Kanya* with other Indian stations, viz. Delhi, Pune and Trivandrum.

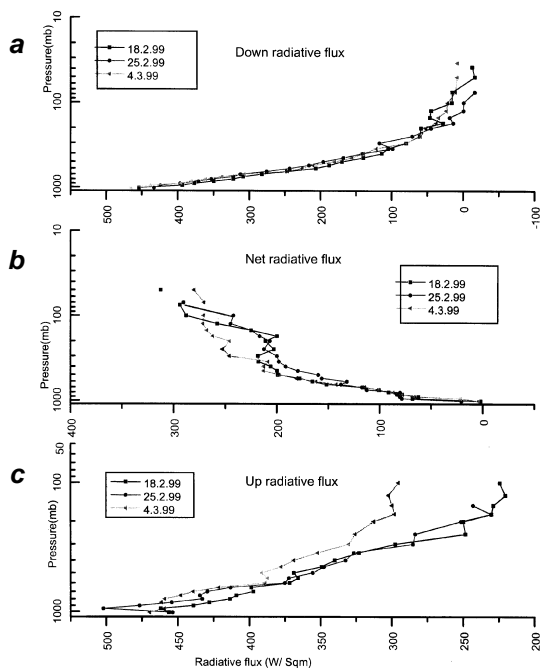


Figure 10. Comparison of latitudinal variation and net radiative flux over Indian Ocean and other stations, viz. Delhi, Pune and Trivandrum.

are mainly due to changes in the lapse rate of temperature. Cooling is of the order of 1.6°C/day from 600 to 250 hPa, where it changes to relative warming.

Conclusion

For the first time radiative fluxes were measured at different atmospheric layers over the Indian Ocean on-board

Sagar Kanya using radiometer sonde, simultaneously, observations were also made over three Indian stations Delhi, Pune and Trivandrum. Some key features are noticed during IFP-99:

1. The basic features of radiative flux of different layers over *Sagar Kanya* are very similar to the observation over Delhi, Pune and Trivandrum.
2. During onward journey, global warming was noticed between 14 and 15 km height near the equator. The combined effect of cloud, aerosol and ozone may be the cause of this warming.
3. There is another incident of global warming, observed during return journey between 13 and 15 km. Though no aerosol was noticed, however, increment of total ozone cloud could be one of the reasons.

Further detailed analysis is required for a better interpretation; in addition, it is necessary to correlate this observation to vertical distribution of the other measurements, i.e. aerosol as well as ozone.

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ACKNOWLEDGEMENTS. We thank all crew members of *ORV Sagar Kanya* for their help. We also thank Mr K. Shaikkaiya, Mr Jatin Kumar, Mr L. D. Mahapatra and Mr Harisingh Sisadia. We are grateful to DG India Meteorological Department, New Delhi for providing radiometer sonde data and Director, National Physical Laboratory, New Delhi for providing the infrastructure. We are also grateful to NASA TOMS processing team for providing the TOMS data.