Mausam, (1994), **45**, 4, 361-368

551.521.32 : 551.510.528

Terrestrial radiant energy exchanges across tropopause over Pune

V. DESIKAN, K. JAYARAMAN and S.P. BHAGWAT
Meteorological Office, Pune

(Received 3 December 1992, Modified 2 February 1994)

सार — पुणे में सूर्यास्त के बाद प्रत्येक पखवाड़े में विकिरणमापी के उपयोग से वायुमंडलीय परिज्ञापन (साउंडिंग) लिए जा रहे हैं। क्षोभ मंडलीय सीमा के पार की स्थलीय विकिरण ऊर्जा के विनिमय (अवरक्त विकिरण अभिवाह विनिमय) की स्थिति ज्ञात करने के लिए, 1978-1985 तक, आठ वर्षों के आंकड़ों के साथ परिज्ञापन के समताप मंडल पर पहुंचने की स्थिति के दौरान लिए गए आंकड़ों का अध्ययन किया गया। यह ज्ञात हुआ कि मानसून अवधि को छोड़कर बाकी समय पूरे वर्ष क्षोभ मंडलीय सीमा से ऊर्जा निकलती रहती है। क्षोभ मंडलीय सीमा से कुल 1.4 डब्ल्यु एम$^{-2}$ विकिरण ऊर्जा निकलती है। मानसून पूर्व और मानसून के बाद की अवधि में क्षोभ मंडलीय सीमा से क्रमश: 3.4 डब्ल्यु एम$^{-2}$ और 4.2 डब्ल्यु एम$^{-2}$ ऊर्जा निकलती है। जबकि मानसून ऋतु के दौरान उसकी ऊर्जा में 5.2 डब्ल्यु एम$^{-2}$ की बढ़ोतरी होती है। शीत ऋतु में उससे 6.6 डब्ल्यु एम$^{-2}$ ऊर्जा निकल जाती है। तथापि, ये मान आकाश के आच्छादन और जल वाष्प की गहराई के अनुसार भिन्न-भिन्न होते हैं।

ABSTRACT. Fortnightly atmospheric soundings with radiometer are being made at Pune after the sunset. The data obtained over an eight year period, 1978-1985 and on occasions when these soundings reached stratosphere have been studied in order to obtain a picture of the terrestrial radiant energy exchanges (infrared radiative flux exchanges) across the tropopause. It is found that the tropopause generally loses energy almost throughout the year except during the monsoon period. The net loss in radiant energy by the tropopause is 1.4 Wm^{-2}. The losses in the pre-monsoon and the post-monsoon periods are respectively 3.4 Wm^{-2} and 4.2 Wm^{-2}, whereas the gain during the monsoon season is 5.2 Wm^{-2}. Winter losses amount to 6.6 Wm^{-2}. These values, however, vary widely in individual cases depending upon the sky cover, and the depth of water vapour column.

Key words — Terrestrial radiant energy, Variations, Seasonal effect of clouds and humidity.

1. Introduction

The concept of tropopause as a layer of discontinuity in lapse rate of temperature is very meaningful in the studies of upper atmosphere. The height and the temperature of the tropopause varies with synoptic situations. The tropopause layer separates regions of the atmosphere with different sources of driving energy. "The region below the tropopause receives its energy principally from surface heating, which is then distributed throughout the troposphere by convective motions of the atmosphere. Above the tropopause, energy is absorbed in a bulk fashion by atmospheric interaction with solar and terrestrial radiant flux" (Webb 1966). The heat input due to these sources are closely related to the radiative thermal field as well as to the atmospheric absorbing parameters. In addition the absorption of solar irradiances do affect to some extent. The results of the study on the terrestrial radiant energy measurements at Pune over an eight year period are presented here.

2. Data source

Regular fortnightly measurements of the vertical profile of the terrestrial radiant energy during the night time are being made at eight locations in India using balloon borne radiometers. The radiometer used is an economic Soumi-Kuhn radiometer and has two independent surfaces. Two rod thermistors attached to thin aluminised foils on either side of an expanded polystyrene head to sense the equilibrium temperature arising out of the exchange of radiant energy with the surrounding by the aluminium foils. Balloon borne measurements of the radiation field are being made regularly at Pune since 1963. The data up to 1969 have been published by Srivastava and Srinivasan (1969, 1971). Bhagwat (1990) studied the radiant energy across the tropopause for two years. The radiometersonde data obtained at Pune over the eight year period, 1978-1985 have been analysed. The measurements obtained when the sondes reached sufficiently high levels well beyond the tropopause are only chosen and studied.

If $E_{lB}\uparrow$ represents the radiant energy reaching the bottom layer of the tropopause from the troposphere and $E_{lB}\downarrow$ is the radiant energy emitted into the troposphere by the bottom layer, $E^*_{lB}=E_{lB}\uparrow-E_{lB}\downarrow$ gives the net radiant energy at the bottom boundary of the tropopause. Similarly $E^*_{lT}=E_{lT}\uparrow-E_{lT}\downarrow$ gives the net radiant energy at the top of the tropopause layer, where, subscript T stands for the top boundary. E_{li} is the energy entering into the tropopaues, being the sum of $E_{lB}\uparrow$ and $E_{lT}\downarrow$. E_{le} is the energy exiting out of the tropopause given as the sum of $E_{lB}\downarrow$ and $E_{lT}\uparrow$. The

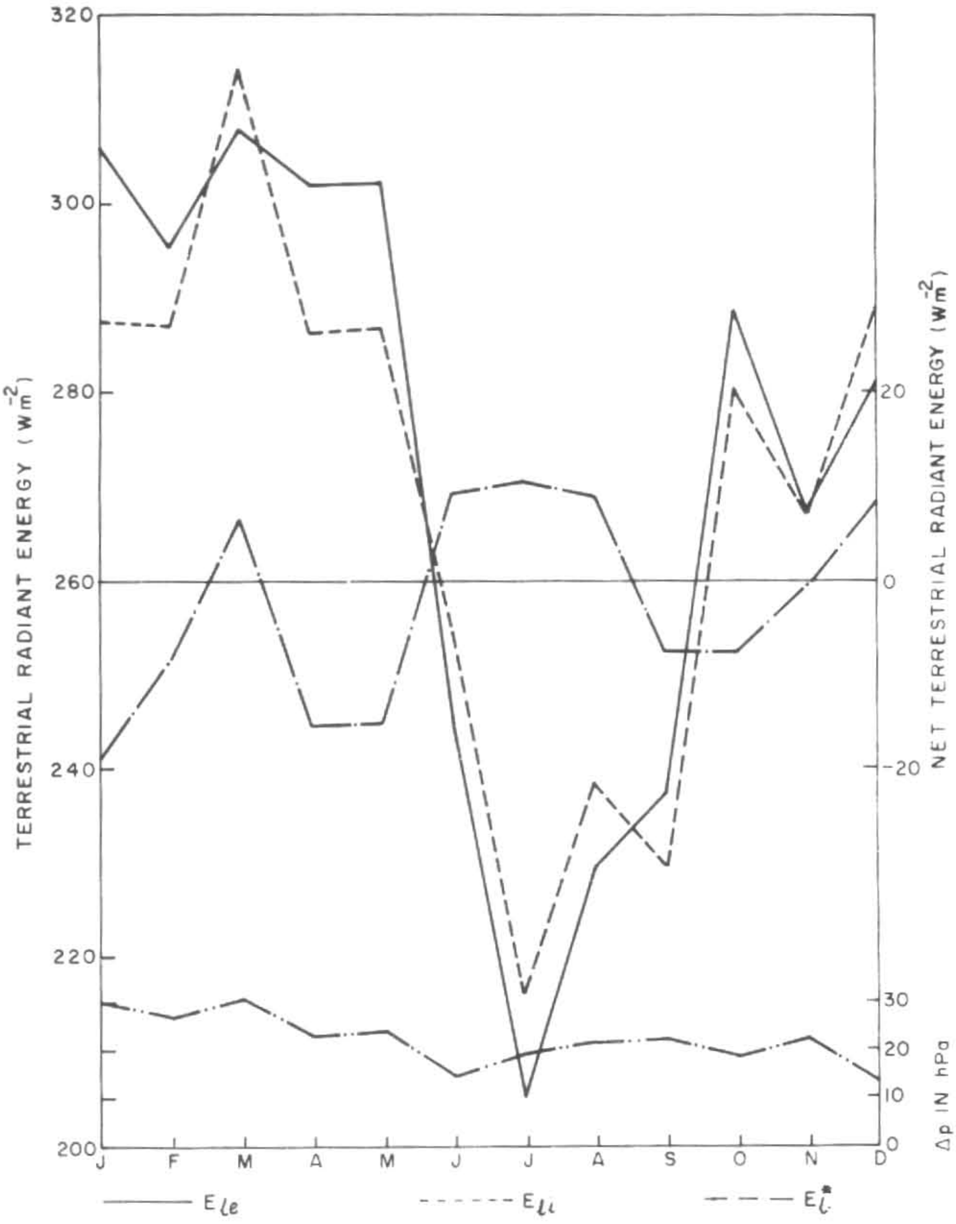

Fig. 1. Mean radiant energy across the tropopause

TABLE 1

Mean seasonal values of radiant energy (Wm^{-2}) across the tropopause

	E_{li}	E_{le}	E_l^*
Pre-monsoon	295.7	299.1	−3.4
Monsoon	234.5	229.3	5.2
Post-monsoon	273.6	277.8	−4.2
Winter	287.7	294.3	−6.6

TABLE 2

Mean seasonal values of radiant energy (Wm^{-2}) in the tropopause

	Bottom boundary			Top boundary		
	$E_{lB}\uparrow$	$E_{lB}\downarrow$	E^*_{lB}	$E_{lT}\uparrow$	$E_{lT}\downarrow$	E^*_{lT}
Pre-monsoon	274.4	23.9	250.4	275.2	21.4	253.9
Monsoon	207.6	26.2	181.4	203.1	26.9	176.2
Post-monsoon	248.4	28.9	219.5	248.9	25.4	223.7
Winter	263.2	27.3	235.9	267.0	24.5	242.6

TABLE 3

Terrestrial radiant energy (Wm^{-2}) across tropopause under clear sky conditions

Lower boundary			Upper boundary			Depth of water vapour column
$E_{lB}\uparrow$	$E_{lB}\downarrow$	E^*_{lB}	$E_{lT}\uparrow$	$E_{lT}\downarrow$	E^*_{lT}	
299.1	29.5	269.6	294.9	17.1	277.8	dry
279.4	24.6	254.7	277.5	25.7	251.8	900-800 hPa
285.7	17.8	268.0	285.6	16.3	269.4	700-800 hPa
279.3	26.1	253.2	280.8	36.0	244.8	600-700 hPa
202.0	13.8	188.2	204.8	15.2	189.6	> 400 hPa

difference between E_{li} and E_{le}, *i.e.*, $E_l^* = E_{li} - E_{le}$ will determine if the radiant energy is lost by the tropopause or retained in it.

3. Results and discussion

3.1. *Mean radiative energy across the tropopause*

3.1.1. Fig. 1 gives the radiant energy entering into (E_{li}) and exiting out (E_{le}) of the tropopause layer and the net radiant energy (E_l^*) retained in the tropopause. Negative values of E_l^* indicates that the tropopause is losing radiant energy. Also plotted is the pressure thickness of the tropopause layer over the entire 1978-1985 period. It is seen that the radiant energy entering into the tropopause is less than that is passing out, particularly in the pre-monsoon and post-monsoon periods. During the monsoon period, however, the radiant energy is retained in the tropopause leading to E_l^* being positive. E_{li} remains nearly constant within about 280-290 Wm^{-2} during January to May when E_{le} is around 300 Wm^{-2}. March, however, records a higher value of 314 Wm^{-2} for E_{li} and 307 Wm^{-2} for E_{le}. The total thermal energy, both E_{li} and E_{le} are reduced quite sharply during the monsoon. E_{li} reduces by 11 per cent from 287 Wm^{-2} in May to 254 Wm^{-2} in June and then to 216 Wm^{-2} in July. The fall in E_{le} is more with 19 per cent drop, 302 Wm^{-2} of May to 245 Wm^{-2} in June. July again records the lowest 205 Wm^{-2}. After the monsoons the values increase again in October by about 20 per cent.

3.1.2. Fig. 2 gives the mean values of the radiant energy passing through the top and bottom of the tropopause layer. A striking feature is that the values of downward radiant energy $E_{lT}\downarrow$ and $E_{lB}\downarrow$ are both too small—around 10 per cent of the upward or the net component. Kühn *et al.* (1959) found that $E_l\uparrow \gg E_l\downarrow$. They advocated that E_l^* can be equated to $E_l\uparrow$ at the tropopause and above than finding E_l^* from $E_l\uparrow - E_l\downarrow$. This means that the upward terrestrial radiant energy is affected only slightly by the stratosphere. It is seen that the radiant energy emitted by the top layer is more than that at the bottom, perhaps, due to the higher temperature of the air at the top of the tropopause. During the monsoon, however, the bottom layer emits more than the top layer. In the case of net radiant energy E_l^*, the trend is of the reversed order, the monsoon shows higher values for the top surface than that for the bottom surface of the tropopause.

3.1.3. A study of the seasonal values of the radiant energy field shows that about 1.4 Wm^{-2} is lost by the tropopause annually. Table 1 shows the mean total energy received and lost by the tropopause layer during the different seasons of the year. The tropopause looses radiative heat of about 3 Wm^{-2} during the pre-monsoon season. It receives 296 Wm^{-2} and gives out 299 Wm^{-2} during this season. It is one of gaining of 5 Wm^{-2} during the monsoons. It receives 235 Wm^{-2} as against the loss of 229 Wm^{-2}.

Table 2 gives the radiant energy passing through the top and bottom surfaces of the tropopause layer. 267 Wm^{-2} is the upward terrestrial radiant energy $E_{lT}\uparrow$ from the top of the tropopause in winter while 263 Wm^{-2} enters it from the troposphere, giving rise to a loss of 4 Wm^{-2} in the radiative energy. Compared to this 27 Wm^{-2} is emitted to the troposphere from the tropopause and the layer receives 25 Wm^{-2} from the stratosphere leading to 2 Wm^{-2} loss of energy. The total loss of 6 Wm^{-2} to the surrounding agrees well with the measured value of 7 Wm^{-2}. Similarly the upward fluxes cause a net loss of 4 Wm^{-2} and the downward fluxes a 3 Wm^{-2} loss. The total loss of 7 Wm^{-2} compares well with 8 Wm^{-2} as measured. During monsoon it was a gain of 5 Wm^{-2} from the upward fluxes and 1 Wm^{-2} from the downward fluxes. The total gain of 6 Wm^{-2} agrees with the measured 5 Wm^{-2}. The 1 Wm^{-2} loss due to the upward fluxes add up with the downward flux loss of 4 Wm^{-2} in the post-monsoon season to give a net loss of 5 Wm^{-2} as against the measured value of 4 Wm^{-2}

3.2. *Variations from year to year*

Large variations from the mean values are seen in the radiative energy transactions across the tropopause when individual years are considered. Almost in all years, the first four months of an year show (Fig. 3) very high values for E_{le} or E_{li}, values being around 300 Wm^{-2}. During the monsoons the values come down very low, around 200 Wm^{-2}. The values after 1982 are, however, specifically much lower, around 150 Wm^{-2} during July. In a different study [Desikan *et al.*

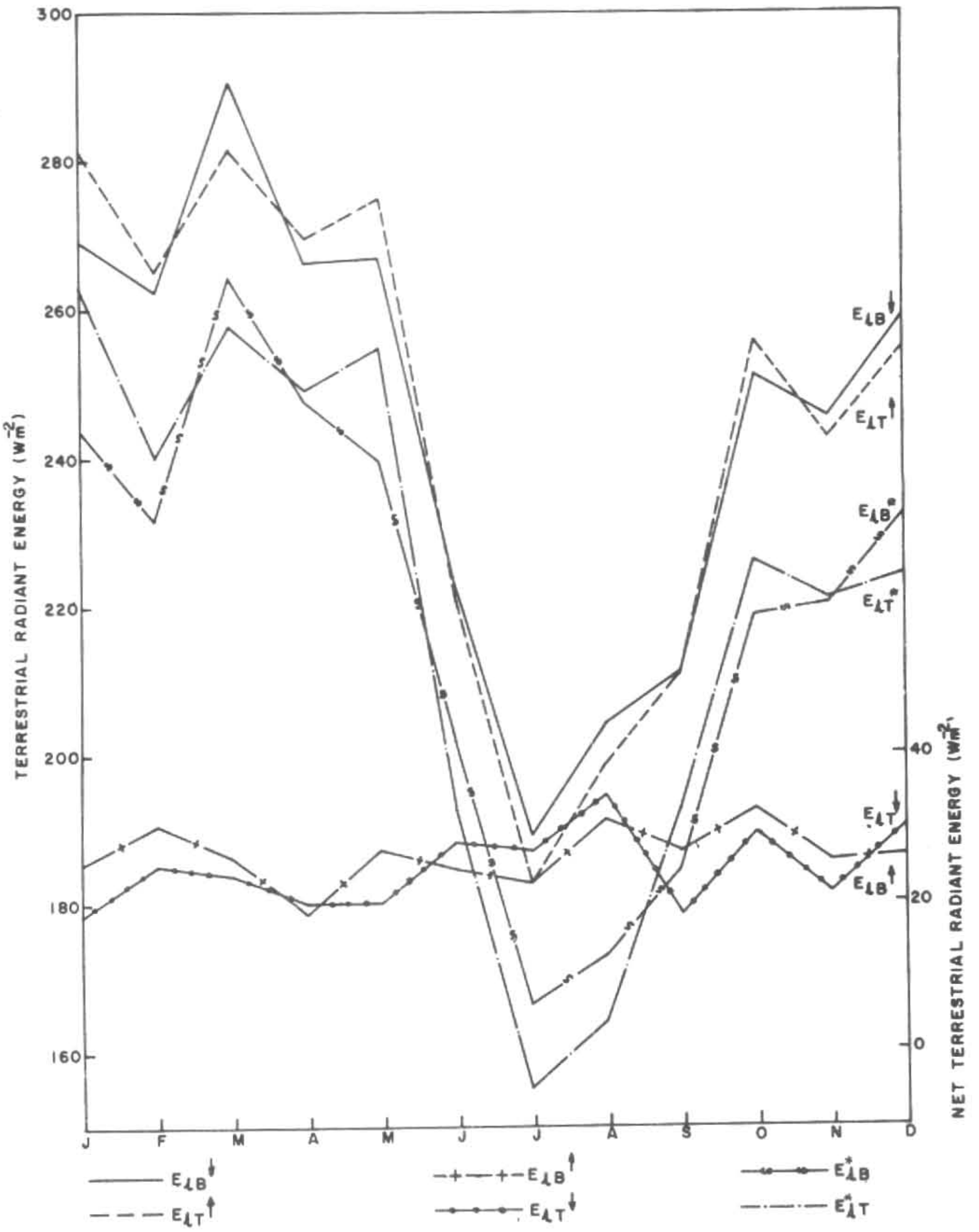

Fig. 2. Mean radiant energy in the tropopause over Pune

1994 (a & b)] one of the authors discusses the possible role of the atmospheric pollutants on the relative values of the components of radiant energy. A particular feature to be seen is the near uniform fluxes around 270 Wm^{-2} almost during the whole year of 1982 except for December 1982 and January 1983. The rains were very much below normal during 1982 — 16 per cent deficient. The associated clouding activity is obviously not strong to reduce the radiative exchanges resulting in nearly uniform radiant energy fluxes across the tropopause throughout the year.

3.2.1. No such grouping is possible when the sky is cloudy, particularly when medium clouds are present. Table 4 gives the specific values of the radiant energy at the lower and upper boundaries of the tropopause alongwith the levels up to which water vapour measurements were possible. The values have, however, been arranged in two sets, one with *Ac* tops and the other with *As* tops. The gradation seen in the values with the extent of depth of moisture and when there was no clouds, is no more possible. Obviously besides the genera, the amount of radiant energy

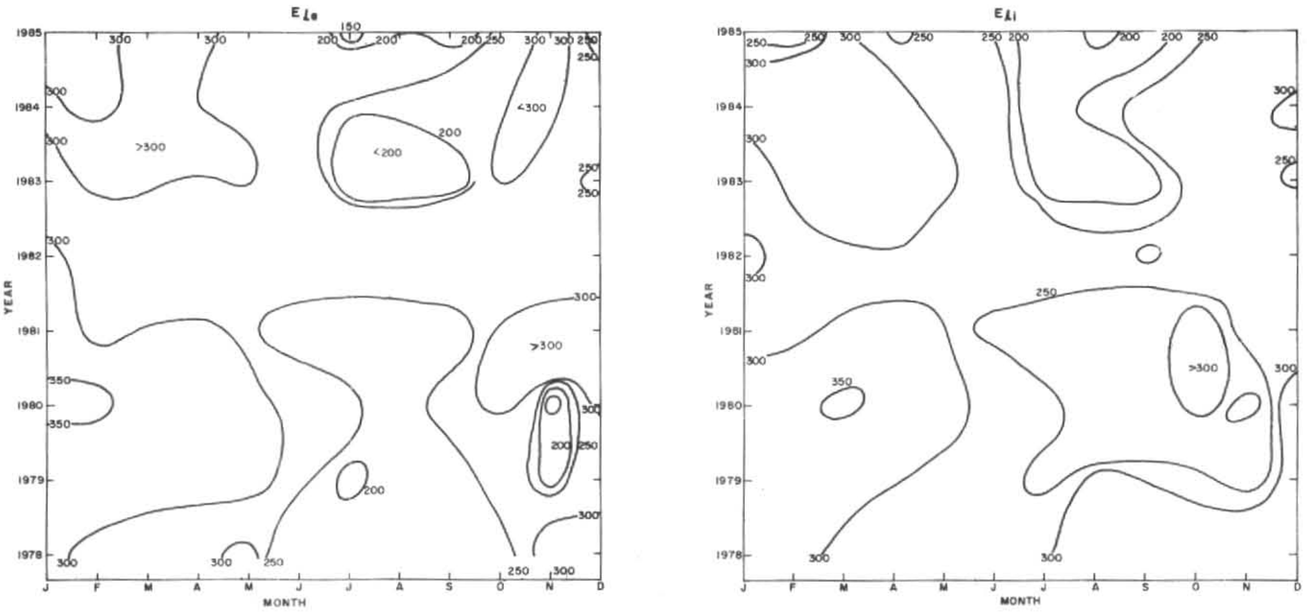

Fig. 3. Isopleths of radiant energy (Wm^{-2}) in the tropopause

TABLE 4

Terrestrial radiant energy (Wm^{-2}) at tropopause over Pune under cloudy conditions

Date	Lower boundary				Upper boundary							Cloud type	Water vapour available upto (height in hPa)	Rainy condition
	Pressure (hPa)	$E_{lB}\uparrow$	$E_{lB}\downarrow$	E^*_{lB}	Pressure (hPa)	$E_{lT}\uparrow$	$E_{lT}\downarrow$	E^*_{lT}	E_{li}	E_{le}	E_l^*			
9 Mar '78	100	204.3	23.0	181.3	81	207.7	7.8	199.9	212.1	230.7	−18.6	AC_6	—	Rain on 8th
30 May '85	100	263.7	1.1	262.6	82	260.0	8.2	251.8	271.9	261.1	10.8	Cu_1AC_5	400	Nil
21 Jun '79	100	229.3	31.8	197.5	80	209.1	24.7	184.3	254.0	240.9	13.1	$SC_2AC_2Ci_3$	250	Nil
17 Jul '79	100	248.7	34.5	214.2	82	252.1	14.9	237.2	263.6	286.6	−23.0	SC_4AC_2	500	Nil
17 Jul '80	103	247.4	11.4	236.0	91	254.6	21.9	232.7	269.3	266.0	3.3	SC_4AC_4	300	Rain on 16th & 18th
23 Mar '84	125	161.1	51.0	110.1	89	151.1	48.0	103.0	209.1	202.1	7.0	SC_5AC_2	450	Rain ,on 23rd & 24th
24 Sep '81	103	218.4	21.5	196.9	89	220.8	20.4	200.4	238.8	242.3	−3.5	SC_4AC_2	400	Rain on 24th
5 Sep '85	115	161.2	15.3	145.9	90	159.3	21.8	137.5	183.0	174.6	8.4	$SC_3AC_2Ci_2$	300	Rain on 5th & 6th
20 Nov '80	113	131.6	38.4	93.2	108	103.8	22.0	81.8	153.6	142.2	11.4	SC AC CS_8	300	Rain on 20th
12 Dec '85	100	192.3	21.4	171.0	75	147.6	18.6	129.0	210.9	169.0	41.9	AC_1Ci_4	300	Nil
21 Dec '85	100	253.4	59.6	193.9	60	261.9	15.9	249.4	269.3	321.5	−52.2	AC_1	650	Nil
18 Jun '81	102	188.1	20.7	167.4	95	192.7	37.1	155.5	225.2	213.4	11.8	$SC_4AC_1AS_3$	250	Rain on 19th & 20th
19 Jun '80	103	246.2	18.6	227.7	89	239.5	16.4	223.1	262.6	258.1	4.5	SC_3AS_4	400	Rain on 18th
31 Jul '79	103	127.2	36.8	90.4	93	48.7	65.9	−17.2	193.1	85.5	107.6	SC_4AS_4	250	Rain on 30th & 1, 2 Aug.
12 Jul '84	125	180.8	45.6	135.2	97	164.8	−1.2	166.0	179.6	210.4	−30.8	SC_4AS_4	250	Rain on 13th
25 Jul '85	125	111.0	38.8	72.2	102	102.8	42.9	59.9	153.9	141.6	12.3	SC_3AS_5	350	Rain on 24, 25, & 26th.
1 Aug '80	98	188.5	44.6	143.9	80	197.7	24.1	173.6	212.6	242.3	−29.7	SC_5AS_3	300	Rain on 31 July & 1, 2 Aug
8 Sep '83	110	138.7	56.2	82.5	97	134.6	39.9	94.7	178.6	190.8	−12.2	SC_5AS_8	250	Rain on 9th

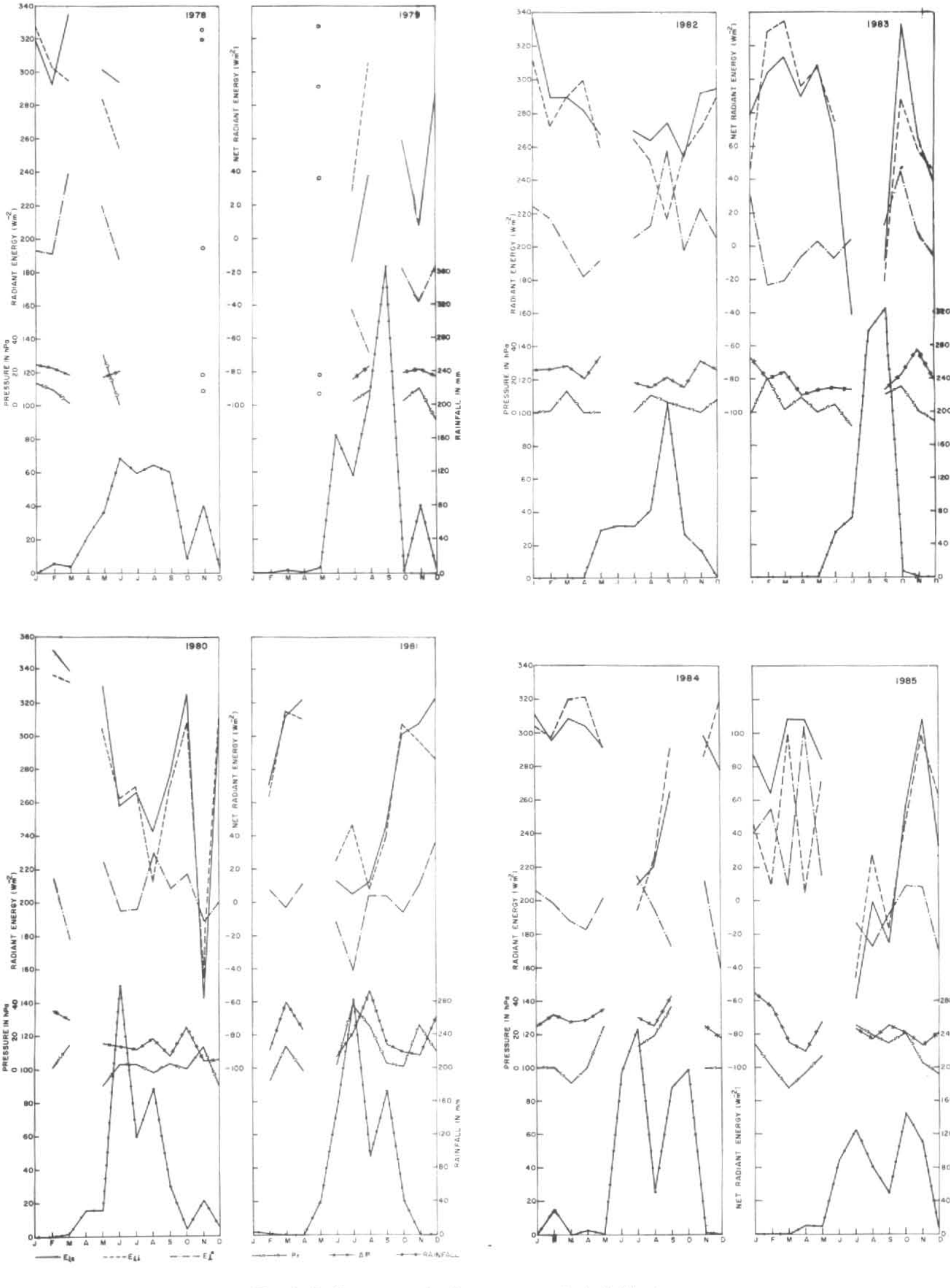

Fig. 4. Radiant energy in the tropopause in individual years

reaching the tropopause is possibly very much dependent on the cloud depth and its moisture content.

Taking the case when *Ac* clouds formed the upper layer, the values of upward and net terrestrial energy are seen to be generally higher whenever there had been no rain on the day of measurement or on the following day. On three occasions *Ac* clouds were the only clouds. When only one octa of *Ac* cloud was present, the radiant energy reaching the tropopause from below is high, 253 $\mathrm{Wm^{-2}}$, as if there was no clouding. The depth of moisture is up to 650 hPa and this compares well with the values in Table 3. The humidity sensor did not function properly in the case of March sounding, when *Ac* was covering 75 per cent of the sky. With *Ci* clouds overlaying and the moisture present at least up to 300 hPa, the upward energy has come down to 192 $\mathrm{Wm^{-2}}$

If there had been precipitation around the day of measurement, *As* clouds in the upper layers seriously disturb the values near tropopause. When there had been good rain on the previous day, the June value of $E_{IB}\uparrow$ (19 June 1980) had reached 246 $\mathrm{Wm^{-2}}$, the moisture extending up to 400 hPa. $E_{IB}\downarrow$ values are much lower (less than 190 $\mathrm{Wm^{-2}}$), on the other hand, when there had been rains on the day or on subsequent to the day of measurement. The downward radiant energy $E_{IB}\downarrow$, however, are generally higher than that when the sky is clear or when it had an *Ac* ceiling.

A study of Fig. 4 indicates that the net terrestrial radiative flux $E_l{}^*$ in the tropopause layer generally increases whenever there is an increase in the precipitation on the next day. Of course this is restricted to April-November period only. Because of the two or three measurements in each month and since not all balloon ascents reached the tropopause level, there are few discontinuities in the data. This puts a restraint in a positive statement on the possibility of any connection between the net radiant energy field of the tropopause and the precipitation at the earth's surface.

4. Tropopause radiant energy under different sky conditions

The terrestrial radiant energy in the atmosphere is highly affected by variations, amongst other, in water vapour, carbon dioxide and dust particles. Of these the role of water vapour is very important. It is to be expected that the depth of water vapour column is likely to reduce the effective terrestrial radiant energy loss. Table 3 gives few examples of the different situations obtained as means of few balloon borne measurements. A lower energy transaction is seen in the tropopause even when the moisture content as measured was restricted to layers below 800 hPa. A careful study into individual ascents showed that the freezing point of water was reached at heights much lower than 550 hPa; two of the measurements were made during winter. More interesting point is the very low values seen when the moisture depth extends to great heights even to levels higher than 400 hPa. Incidentally it is worth mentioning that while it was a clear sky on 8 November 1989, the depth of moisture was so much (giving rise to higher amount of precipitable water) that it caused precipitation on subsequent two days. In the case of dry atmospheric condition given in the table, the surface air had only 17 per cent relative humidity.

5. Concluding remarks

The tropopause occurs over Pune at a pressure altitude of about 100 hPa. They show a marginal lowering by about 10 hPa during the monsoons. The terrestrial radiant energy entering into it is on an average 245.0 $\mathrm{Wm^{-2}}$ from the troposphere while about 244.4 $\mathrm{Wm^{-2}}$ leaves it towards the stratosphere. This amounts to about 0.6 $\mathrm{Wm^{-2}}$ being retained by the layer. Stratosphere sends down only 24.7 $\mathrm{Wm^{-2}}$ on an average into the tropopause which is just 10 per cent of what it receives from the latter. Troposphere, however, receives 26.4 $\mathrm{Wm^{-2}}$ from the tropopause, being 10.8 per cent of its supply to tropopause. The downward flux thus results in a loss of 1.7 $\mathrm{Wm^{-2}}$, the net radiant energy lost by the layer amounting to 1.4 $\mathrm{Wm^{-2}}$ only.

The monsoon season shows a retention of radiant energy by the layer as compared to the losses during the other parts of the year. This picture does not hold good in individual years. Depending on the depth of moisture, the degree and nature of clouding and the rainfall distribution, the values of net energy change. During the two years 1982 and 1985, when there had been deficiency in rainfall during the monsoon season (June-September), the tropopause was seen to be losing energy 25.0 $\mathrm{Wm^{-2}}$ during 1982 (rainfall 17 per cent below normal) but it gained 16.1 $\mathrm{Wm^{-2}}$ during 1985 (rainfall 30 per cent below normal). A check on the rainfall distribution shows that distribution was more even during 1985 which probably ensured even mixing of water vapour in the atmosphere. The late heavy rainfall of September 1982 has possibly affected the net energy of tropopause to become positive in October-November period. Similarly the excess of rains in November 1985 had caused a higher energy residence in the tropopause during winter — 31.5 $\mathrm{Wm^{-2}}$.

When the skies are clear the terrestrial radiant energy fluxes are seen to be higher than those under cloudy conditions. However, these fluxes vary with the depth of moisture. A dry (humidity less than 20 per cent) condition in the troposphere contributes 299 Wm^{-2} to the tropopause while the presence of moisture reduces it. When the depth of moisture extended beyond 400 hPa, the upward energy reaching the tropopause was reduced to 202 Wm^{-2}. Skies with altrostratus (*As*) ceiling clouds were found to cause a much diminished radiant energy at the tropopause as compared with conditions with *Ac* cloud cover.

Possibly a more frequent and careful probing of the atmosphere with radiometers would give a clearer picture of the energy transactions between the two distinct atmospheric layers—troposphere and stratosphere and the linkage between them provided by the tropopause.

References

Bhagwat, S.P., 1990, "The vertical profile of the infrared radiation over Pune", M.Sc. thesis submitted to the University of Poona.

Desikan, V., Chivate, V. R., and Abhyankar, V. V., 1994(a) "Reaction of radiometric parameters to atmospheric pollution: Pant I—Variation over time", *Mausam*, **45**, 1, pp. 79-86.

Desikan, V., Chivate, V.R. and Abhyanker, V.V., 1994(b). "Reaction of radiometric parameters to atmospheric pollution, Part II—A Comparative study between pairs of stations", *Mausam*, **45**, 2, pp. 139-148.

Kuhn, P.M.., Soumi, V.E. and Darkow, G.I., 1959, Soundings of terrestrial radiation flux, *Mon. Weath. Rev.* **87**, 4.

Srivastava, G.P. and Srinivasan, V., 1969, "Radiometersonde observations over India", **1** (1963-66) Sci. Rep. No. 85, India Met. Dept.

Srivastava, G.P. and Srinivasan, V., 1971, "Radiometersonde observations over India", **11** (1967-69), Sci. Rep. No. 88, India Met. Dept.

Webb, W. L., 1966, "Structure of the stratosphere and mesosphere", Academic Press, New York, 60 pp.