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# Spectral (direct) solar irradiance at Pune

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**सार** — सूर्य विकिरण मापी (डी.एस.आई.) से प्रत्यक्ष सौर किरणन मापे गए। चयनित फिल्टरों का प्रयोग करने पर स्पैक्ट्रल वितरण का परीक्षण किया जा सकता है। पुणे में लिए गए मापों से पता चलता है कि इस क्षेत्र में औद्योगिक प्रगति शहरीकरण में लगातार वृद्धि के और परिणाम स्वरूप भू-उपयोग की पद्धति में आए परिवर्तनों से ऐरोसॉल कणों के कारण संभवतः और स्पेक्ट्रम के नील-हरित क्षेत्र में बड़े पैमाने पर क्षीणन हो रहा है। पुणे में नमी के क्षेत्रों की भूमिका से वहां के आकाश में ताप संचरण प्रभावित होने का पता चला है। ऊर्जा अविकिरण की मात्रा पूर्वाहन की अपेक्षा अपराहन में सामान्यतः अधिक देखी गई है। तथापि मानसून पूर्व के महीनों में और कभी-कभी मार्च में भी पूर्वाह्नों में आई.आर. और पीत-नारंगी तरंगदैर्ध्यों में अधिक आभा पाई गई है। दोपहर के आस-पास किसी भी मेघहीन मौके पर एक वर्ष में आभा के 774 $Wm^{-2}$ देखे जा सकते हैं। वास्तविक आकाश और वायुमंडलीय अवस्थाओं पर आधारित होने से इसके अलग-अलग स्पैक्ट्रल मान भिन्न होते हैं। विभिन्न स्पेक्ट्रल क्षेत्रों में आभाओं के तुलनात्मक अध्ययन से दिन के समय ऐरोसॉल कणों के आकार में होने वाले परिवर्तनों का अनुमान लगाया जा सकता है।

**ABSTRACT**. Direct Solar Irradiation (DSI) measurements are made with pyrheliometers. When used with selected filters, the spectral distribution can be worked out. Measurements at Pune indicate that large scale attenuation takes place in blue-green region of solar spectrum likely due to aerosol particles injected by industrial advancement over the region, consequent rapid urbanisation and resultant changed land-use patterns. Values show evidences on the role played by moisture field on the transmission characteristics of the Pune skies. The afternoon irradiances are seen to be generally higher than the forenoon values. However, IR and yellow-orange wavelengths have higher irradiances in the forenoons during the premonsoon months and occasionally even in March. Over a year 774 $Wm^{-2}$ of irradiance can be expected on any cloudless occasion around noon time, the individual spectral values vary depending on the actual sky and atmospheric conditions. From the comparative study of the irradiances in the different spectral regions, inferences could be drawn on the changes that take place in the size distribution of aerosol particles during a day.

**Key words** — Solar irradiance, Size distribution.

## 1. Introduction

The direct solar irradiation reaching the ground is only a part of the total solar irradiation incident on the top of the earth's atmosphere. In its passage through the atmosphere, the radiation is attenuated by air molecules, suspended particles like dust, haze, smoke, water droplets and clouds of varying types and sizes. Measurements of the solar irradiances at normal incidence in selected spectral regions and in the entire spectrum are of great importance for the analysis of the attenuation of solar irradiance by the atmosphere due to scattering and absorption. From these studies it is possible to determine the attenuation of the solar radiation in different spectral bands and indirectly infer the role of various constituents that affect the passage of solar radiation through the atmosphere. They also provide the means for the determination of the atmospheric turbidity and the size distribution of the aerosol and water vapour content of the atmosphere.

Very few studies have been made on the spectral irradiances in India. Mani and Chacko (1963), Chacko and Desikan (1965), Mani and Chacko (1973) and Mani *et al.* (1977) had made studies in the direct solar irradiances for the total spectrum only. Krishnamurthy (1991) made an attempt to find out the spectral irradiance characteristics over Pune. The present paper attempts to provide a climatological picture of the spectral distribution of direct solar irradiances at Pune.

## 2. Data

Regular measurements of direct solar irradiances in different regions are being made by India Meteorological Department at its central observatory at Pune (18°32′ N. 73°51′ E, 555m amsl) for over four decades. The instrument used is an Angström pyrheliometer and band pass filters viz. orange OG1 (525-2900nm), red RG2 (630-2900nm) and dark red RG8 (690-2900nm). From these measurements it is possible to calculate the irradiances in other wavelength

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bands *viz* 290- 525nm ($S_{t1}$), 525-630nm ($S_{12}$), 630-690nm ($S_{28}$), 290-690nm (Visible $S_{t8}$). The last band above covers the region of the photosynthetically active radiation (PAR-Band). The average values of the data for the period 1977 to 1992 have been utilized in the present study. The observations used in this study have been carried out for fixed solar elevations corresponding to optical air masses 3.0 (h=19.3°), 2.0(h=29.9°) and 1.5(h=41.7°). The actual amount of irradiance at any given time depends on the path length through which the irradiation has to pass through.

## 3. Results and discussion

### 3.1. *Spectral variation of solar irradiance*

Pune, on an annual scale gets its highest direct solar irradiance ($S_t$) in the afternoon for optical path length of 1.5 with a value of 774 $Wm^{-2}$. This is about 57 per cent of the extra-terrestrial value. The lowest received is 505 $Wm^{-2}$ in the morning hours when the solar elevation is 19.3°. Table 1 makes an interesting reading. The annual values are always more in the afternoon than that in the forenoon. When we consider the total solar spectrum, the total irradiances are higher in the afternoon by 6 percent for air mass 3.0, 4 percent for air mass 2.0 and just 1 percent for air mass 1.5. A perusal of the variations in the infra-red ($S_8$) and visible ($S_{t8}$) wavelengths shows that the afternoon IR values ($S_8$) for m = 2.0 and 3.0 are lower probably due to the moisture brought by the setting of sea breeze, whereas the visible part ($S_{t8}$) shows an increase of 10 percent and 17 percent respectively. The particles are subjected to constant motion. In the process, some particles grow by coalescence process. In the presence of sufficient moisture the hygroscopic particles become condensation nuclei, absorb water vapour and grow in size. Thus, the smaller particles show decrease in their population. The scattering effect for the larger particles are not as significant as in the case of small-sized particles. As the moisture coating increases, the hygroscopic particles start dissolving and a salt solution in the form of droplets is left behind. These particles then start absorbing in the wings of red wavelengths and in the NIR regions. With slight falls in IR region, it is, therefore, clear that the smaller particles grow in size and thus are removed from the path of radiation. In fact, the increase in irradiance in the blue-green region is phenomenal, 21 percent from 122 to 148 $Wm^{-2}$ for m = 2.0 and 41 percent from 77 $Wm^{-2}$ in the forenoon to 109 $Wm^{-2}$ in the afternoon for m = 3.0. This is the wavelength range where small particles cause intense scattering. The increase in the irradiances in this range is a clear indication of the removal of the small particles, obviously by growth. The yellow-orange region and the red region show marginal changes only.

A study of the spectral distribution of the extra terrestrial irradiance shows that the visible and IR parts of solar spectrum have nearly 50 percent share in the total irradiance. The contribution of the blue-green range (300-525 nm) is around 28 percent, the yellow-red range (525-630nm) has 14 percent share while the red alone (630-700nm) contributes only 8 percent towards the total irradiance. The passage through the atmosphere modifies it very much by the scattering and more importantly by the selective absorption processes. Important contributions in the selective absorption is by (*i*) molecular oxygen (*ii*) ozone (*iii*) carbon dioxide and (*iv*) water vapour. Of these, the water vapour is a highly variable component. Besides, there are absorptions due to methane, oxides of nitrogen and other few gases have some absorptions.

**TABLE 1**

**Spectral direct solar irradiance ($Wm^{-2}$) at Pune (annual)**

| Air Mass | $S_t$ | $S_8$ | $S_{t8}$ | $S_{t1}$ | $S_{12}$ | $S_{28}$ |
|---|---|---|---|---|---|---|
| m = 3.0 FN | 504.9 | 286.5 | 218.4 | 77.1 | 76.9 | 64.4 |
| m = 2.0 FN | 645.0 | 344.5 | 300.5 | 122.4 | 100.1 | 79.7 |
| m = 1.5 FN | 764.0 | 384.0 | 380.6 | 167.5 | 118.9 | 96.2 |
| m = 1.5 AN | 773.6 | 386.2 | 387.4 | 172.8 | 119.5 | 96.1 |
| m = 2.0 AN | 673.5 | 342.4 | 331.1 | 147.7 | 99.3 | 84.0 |
| m = 3.0 AN | 537.4 | 281.5 | 256.5 | 108.8 | 73.6 | 73.6 |
| Extra-Terrestrial | 1367.0 | 678.4 | 688.6 | 373.2 | 190.4 | 125.0 |

**TABLE 2**

**Proportional irradiance with reference to extra-terrestrial irradiances-annual (Percentage)**

| Air Mass | $S_t$ | $S_8$ | $S_{t8}$ | $S_{t1}$ | $S_{12}$ | $S_{28}$ |
|---|---|---|---|---|---|---|
| m = 3.0 FN | 36.9 | 42.2 | 31.7 | 20.7 | 40.4 | 51.5 |
| m = 2.0 FN | 47.2 | 50.8 | 43.6 | 32.8 | 52.6 | 63.8 |
| m = 1.5 FN | 55.9 | 56.6 | 55.3 | 44.9 | 62.5 | 77.0 |
| m = 1.5 AN | 56.6 | 56.9 | 56.3 | 46.3 | 62.8 | 76.9 |
| m = 2.0 AN | 49.3 | 50.5 | 48.1. | 39.6 | 52.2 | 67.2 |
| m = 3.0 AN | 39.3 | 41.5 | 37.3 | 29.2 | 38.7 | 58.9 |

**TABLE 3**

**Percentage irradiance at Pune-annual**

| Air Mass | $S_8$ | $S_{t8}$ | $S_{t1}$ | $S_{12}$ | $S_{28}$ | $S_{t1}$ | $S_{12}$ | $S_{28}$ |
|---|---|---|---|---|---|---|---|---|
| m = 3.0 FN | 57 | 43 | 15 | 15 | 13 | 35 | 35 | 30 |
| m = 2.0 FN | 53 | 47 | 19 | 16 | 12 | 41 | 33 | 26 |
| m = 1.5 FN | 50 | 50 | 22 | 16 | 13 | 44 | 31 | 25 |
| m = 1.5 AN | 50 | 50 | 22 | 15 | 12 | 45 | 31 | 25 |
| m = 2.0 AN | 51 | 49 | 22 | 15 | 12 | 45 | 30 | 25 |
| m = 3.0 AN | 52 | 48 | 20 | 14 | 12 | 42 | 29 | 29 |
| Extra-Terrestrial | 50 | 50 | 27 | 14 | 14 | 54 | 28 | 18 |

Table 2 gives the proportion of the spectral irradiances (S) annually received at Pune, with reference to the extra-terrestrial values ($S_o$). When the measurements are made at m = 3.0, it is a mere 37 percent in the morning hours and 39 percent in the afternoon. This gradually increases to 56 percent around noon time for m = 1.5. The IR component ($S_8$) accounts for 42 percent for m = 3.0 and 57 percent for m = 1.5. It is 51 percent for m = 2.0. It is rather quite low, 32 percent for m = 3.0 FN for the visible spectrum ($S_{t8}$) which improves to 37 percent in the AN. The proportions in the sub-ranges of the visible part show a very low proportion in the shorter wavelengths (300-525 nm) ($S_{t1}$) and it is quite large for the red region (630-690 nm). For m = 3.0 FN, it is only 21 percent for $S_{t1}$, $S_{12}$ has a 40 percent of its extra-ter-

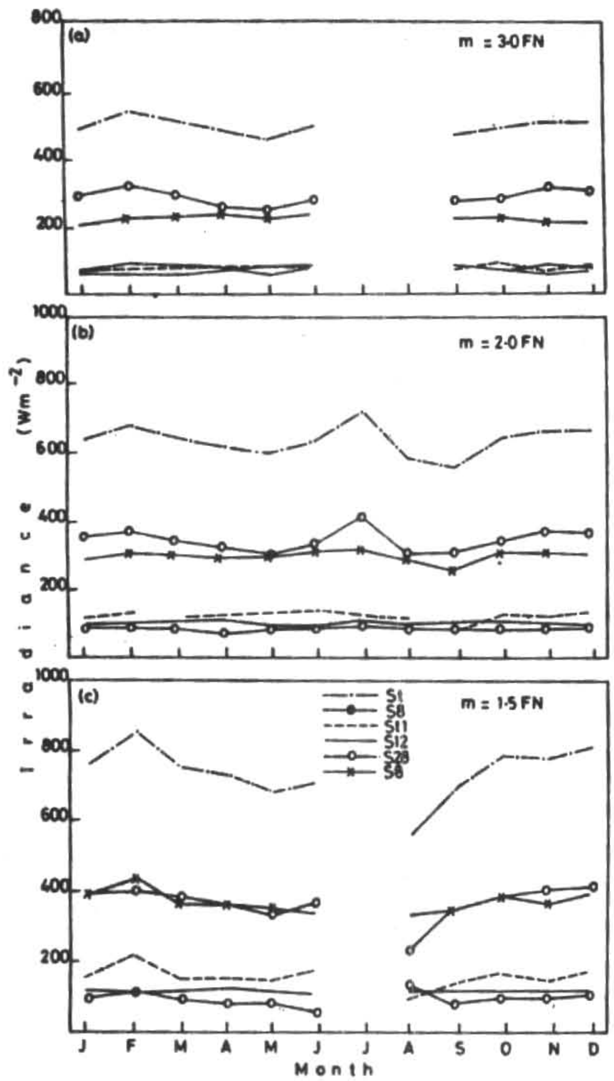


**Fig.1.** Variation of spectral irradiance in the forenoons

restrial value while it is a very high (52 percent) for $S_{28}$ region. This proportion with reference to corresponding extra-terrestrial values continues to be quite low, just around 45 percent for $S_{t1}$ at m = 1.5, $S_{12}$ has a larger proportion at m = 1.5 with 63 percent, it is 77 percent in the red region. This would then mean that the spectral scattering continues to be more significant to be controlled by the small particles; although in individual situations it may be otherwise.

A similar study (Table 3) of the spectral proportional distribution with respect to the total irradiance ($S_t$) indicates that IR accounts for more than 50 percent at all optical path lengths. IR component makes up as high as 57 per cent for m = 3.0 FN and this reduces to 50 percent for m = 1.5. Within the visible spectrum $S_{t1}$ and $S_{12}$ have just 15 percent for m = 3.0 FN and it is 13 percent for $S_{28}$. For other air masses $S_{t1}$ shows significant changes reaching a high 22 percent while $S_{12}$ remains constant nearly at 15 percent and $S_{28}$ at 12-13 percent. Thus, very significant role is played by the relative changes in concentration of smaller particles both in the morning and afternoon hours.

When we consider the irradiance in the visible spectrum, the proportions of $S_{t1}$, $S_{12}$ and $S_{28}$ with reference to $S_{t8}$, nearly 40 percent of the transmitted irradiances is accounted for by the blue-green wavelengths. It is just marginally above 30 percent for $S_{12}$ and 25 percent for $S_{28}$. These values will be different for each month depending on the effect of irradiation at the earth's surface and those of winds and humidity that prevail at individual hours.

### 3.2. *Temporal variations*

At air mass 3.0 in the morning hours about 500 Wm$^{-2}$ of irradiance (Fig.1) is received on an average. The maximum value 540 Wm$^{-2}$ is received in February, a time when the atmosphere over Pune is generally stable with cloudless skies and the air is at its driest. The increase of around 10 percent in February over the January values, is arrested in March with a drop of 4 percent to 519 Wm$^{-2}$. With dust particles raised by solar heating of the surface and incursion of the moisture as the season advances, the irradiance drops down to 463 Wm$^{-2}$ by May, a decrease of 14 percent from the February peak and 5 percent reduction over the April value. A monsoon washout of the dust particles increases the irradiance level to 500 Wm$^{-2}$ in October by about 8 percent more than the premonsoon level. The increasing trend continues up to December after which the sudden drop of 6 percent in January is caused by the dust particles trapped in the low level inversions characteristic of a cold winter month.

At air mass 2.0 FN there is an average increase of about 140 Wm$^{-2}$ amounting to 28 percent over that for m = 3.0 FN (Fig.1). The percentage variation during each month is, however, different from the other. The rise of 6 percent from 640 Wm$^{-2}$ in January to 682 Wm$^{-2}$ in February is arrested immediately and by May the irradiance in the total spectrum is reduced to 599 Wm$^{-2}$. The washout by monsoon causes an increase in the irradiance to 644 Wm$^{-2}$ in October, an increase of 8 percent over the pre-monsoon value. The variations in the infra-red range (690 nm and above) are little more, of the order of 7 percent for every succeeding month from an irradiance of 369 Wm$^{-2}$ of February to 300 Wm$^{-2}$ in May.

Though a large increase in irradiance in every part of the spectrum is expected, when the air mass changes from 3.0 to 2.0 the order of change is seen to be quite large. The increase is by 28 percent for the total spectrum. The division between the visible (39 percent) and IR (20 percent) indi-

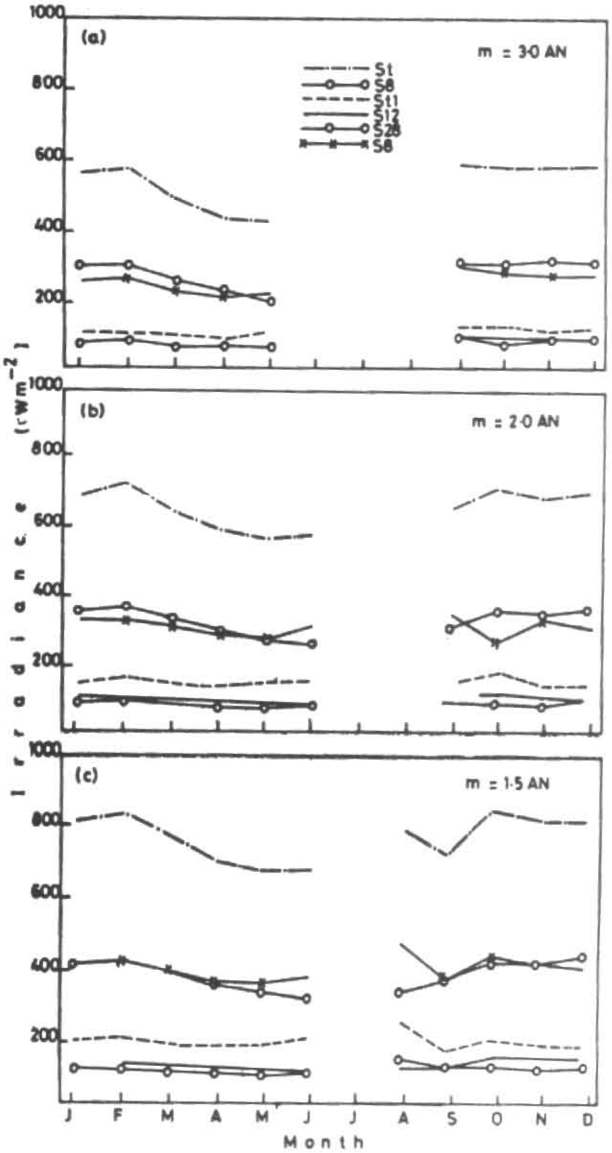


Fig.2. Variation of spectral irradiance in the afternoons

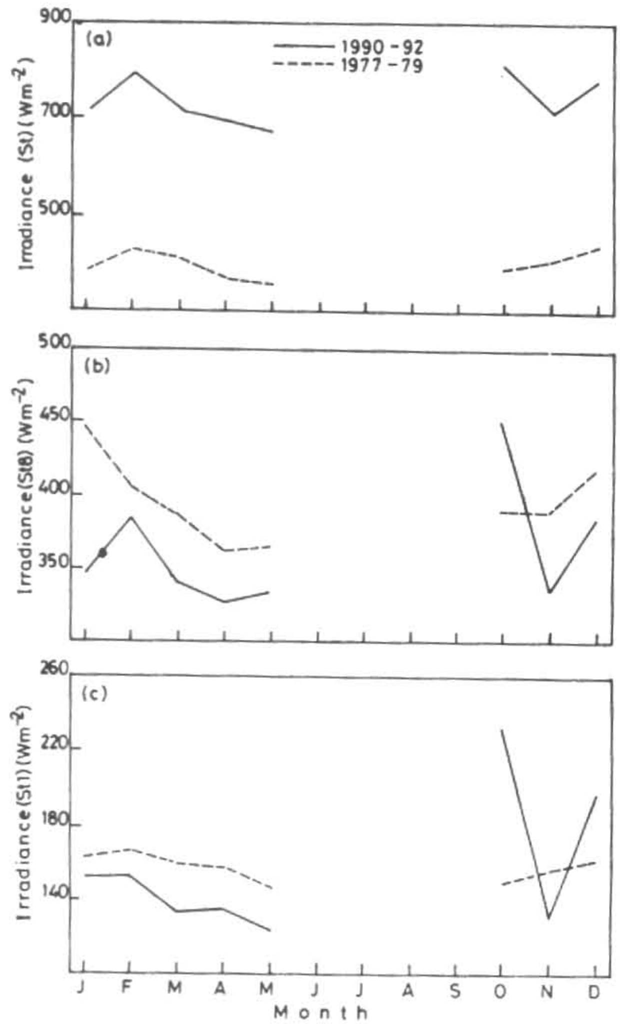


Fig.3. Comparison of irradiances during 1977-79 and 1990-92

cates the removal of small particles which scatter more at shorter wavelength. This is more evident from the proportionate distribution in the visible irradiances, 59 percent in the range $S_{t1}$, 31 percent in $S_{12}$ and 25 percent in IR.

At air mass 1.5 FN (Fig.1) the sun is at its highest point compared to m = 3.0 or 2.0. The irradiance levels should naturally be maximum. Pune records around 765 Wm$^{-2}$ on an average, the highest being recorded during February with a value of 848 Wm$^{-2}$ which is around 11 percent more than the mean. May has the lowest value of irradiance at 682 Wm$^{-2}$. The average value of 765 Wm$^{-2}$ is about 19 percent more than that for m = 2.0 FN. The prominent feature is the 12 percent increase in February from January s 759 Wm$^{-2}$ and then immediate fall by 11 persent to 751 Wm$^{-2}$ in March. The corresponding changes for m = 2.0 FN were 6 percent increase from January to February and 5 percent reduction after February. Irradiance values continue to decrease steadily to 682 Wm$^{-2}$ in May about 20 percent lower than the February value. The monsoon cleansing of the dust raises the irradiance to 774 Wm$^{-2}$ in October, an increase of the order of 13 percent. A striking feature in almost all spectral regions is the steady fall in January when compared to December. The total irradiance decreases from 804 to 759 Wm$^{-2}$ in January, a 6 percent reduction.

The infra-red irradiance ($S_8$) also follows similar trends, it is 50 percent of total irradiance $S_t$. Complimentary changes take place in the visible part of the irradiance ($S_{t8}$). However, the order of changes in mean spectral irradiances from month to month are different.

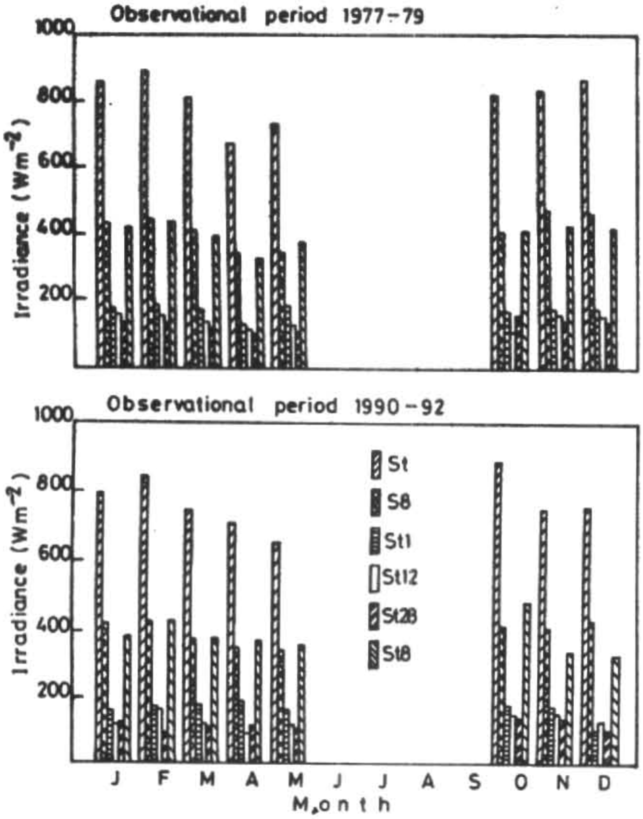


Fig.4. Comparative values of direct solar irradiances at Pune for m = 1.5 AN

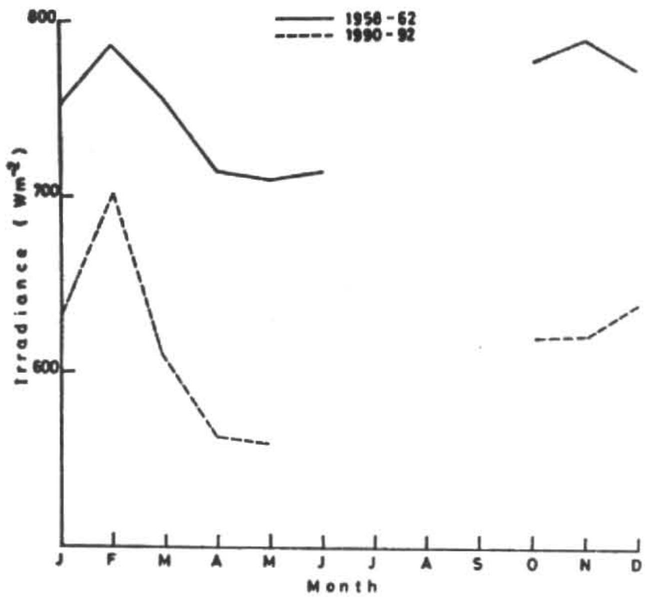


Fig.5. Mean irradiance during a day in 1958-62 and 1990-92

At 1.5 AN the total solar irradiance at m = 1.5 AN (Fig.2) is almost same as that for the forenoon time. It is so for every wavelength range as well. The increase in irradiance in February in every wavelength range excepting in $S_{12}$ range is seen as usual and so is the fall towards March. The order of increase and decrease is nearly the same for $S_t$, $S_8$ and $S_{t8}$. February shows a marginal decrease in $S_t$ to 827 $Wm^{-2}$ at m = 1.5 AN from 848 $Wm^{-2}$ at m = 1.5 FN. The main contribution to this should be due to the still preponderant small particles causing sharp falls in the shorter wavelength ranges $S_{t1}$ and in the $S_{28}$ range possibly due to the increasing sizes of the particles to cause attenuation in the red wavelength.

The cleansing effect on the atmosphere by the monsoon rains and the sharp drop in the moisture content in the atmosphere afterwards cause increase in irradiance values in all wavelengths.

On an average 673 $Wm^{-2}$ is received (Fig.2) in the afternoons when the optical path length is 2.0. This value is about 14 percent less than that for m = 1.5 AN and just 4 percent more than the irradiance at m = 2.0 FN (645 $Wm^{-2}$). The usual February peak, now at an irradiance value of 731 $Wm^{-2}$ is just 5 percent more than the January level of 698 $Wm^{-2}$. The drop to the March value of 645 $Wm^{-2}$ is, however, by 11 percent. This trend continues into April with a further fall of 9 percent to 593 $Wm^{-2}$ which then reduces by another 4 percent to 571 $Wm^{-2}$ in May. With good cleansing by the monsoons, the October value shoots up to 725 $Wm^{-2}$, a jump of 30 percent after which the value stabilizes around 700 $Wm^{-2}$ till February. A somewhat same trend is seen in the irradiance levels in the visible and infra-red parts of the spectrum each making up a percentage of 49 and 51 respectively.

At m = 3.0 AN, on an average 537 $Wm^{-2}$ of solar irradiance is received in the afternoons (Fig.2). The usual decrease in the irradiances from December to January and the following increase in February is seen for this air mass also, but the order of change is quite small just within 5 percent in either case and for all wavelengths. However, this value decreases sharply in March except for $S_{t1}$ where it is just a 5 percent decrease from 109 to 103 $Wm^{-2}$. This is to be ascribed to the removal of small particles by some mechanism like coalescence and absorption. The decreases in $S_{12}$ and $S_{28}$ are correspondingly higher at 22 and 23 percent respectively.

A comparison of data during 1977-79 and 1990-92 is worth a study (Figs.3 & 4). It is found that there is a considerable (8 percent) decrease in $S_t$ values. The reduction in IR irradiances is of the order of 4 percent. The major effect- more than 12 percent is seen in shorter wavelengths, blue-green ranges. Fig.4 depicts the change in the spectral irradiances over the two periods 1977-79 and 1990-92 in the form of bar charts for air mass m = 1.5 AN only. It is clearly seen that there is a drastic decrease in the irradiances for $S_t$

and more specifically for $S_{tl}$. This effect is seen in the relative values of irradiances in the visible spectrum. It is noticed that April and October have higher irradiances during 1990-92. This is due to the rainfall activity during April and the near drought conditions during the monsoons of 1977-79 over Pune. The comparison with 1958-62 is more evident (Fig.5).

## 4. Conclusions

(*i*) There is a large decrease in the irradiances in recent years as compared to what was being received in seventies.

(*ii*) The irradiances generally show a tendency to increase from January to February and decrease in March.

(*iii*) The cleansing effect of the pre-monsoon thunderstorm activities could easily be identified when the irradiance in $S_t$ shows sharp increase over the value prior to such an activity.

(*iv*) The irradiance in all wavelength bands shows sharp increase after the monsoon season. The total irradiance increases by more than 20 percent.

(*v*) As the air becomes more dry by November, the red and IR wavelengths record increase in their irradiances, whereas blue- green wavelengths record a steady decrease.

(*vi*) About 52-56 percent of the extra-terrestrial irradiance is attenuated by the atmosphere over a year. The maximum attenuation is noticed in the $S_{tl}$ region.

(*vii*) The irradiances in the afternoon are generally higher than those of forenoon for corresponding air masses. The variations seen in different wavelengths, however, are different from each other, obviously due to the aerosol distribution concentration as well as size distribution.

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