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Assessing Radiometric Parameters at a Continental Global Atmosphere Watch (GAW) Station, Nagpur, in India

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Abstract: Several radiometric parameters viz. direct solar irradiance, long wave radiation, Angstrom turbidity and transmission coefficient for Nagpur have been analyzed and discussed based on data for the period of 1989-1998. Solar irradiance at Nagpur is the highest in winter and amongst the winter months in January due to cloudless sky and good transparency of the atmosphere. It is the least during the monsoons due to increased moisture content of the atmosphere and extended cloudiness. Diurnal variation in direct solar irradiance shows that for all the months the peak is reached between optical air masses 1.5 FN and 1.5 AN with a maximum value of about 700 W/m^2 in January. Turbidity values show fluctuations on yearly basis. During the study period, the lowest value was observed to be 0.082 in 1990 and the highest was 0.108 in 1996. In a year, winter season experiences lowest turbidity while the post-monsoon season witnesses the highest. Diurnal variation of turbidity indicates that optical air mass 3.0 FN is less turbid for all the months in a year while the peak is reached in between air masses 1.5 FN and 1.5 AN. It is seen that transparency of the atmosphere over Nagpur decreases from winter till May. This is to be attributed to the increasing dust content of the atmosphere over Nagpur. The atmosphere transmits only 65% of the incident energy. At early morning and late afternoon hours, transparency is found to be higher when compared to higher solar elevations. Rather, the transparency decreases from morning till noon and later increases. This could be attributed to convective activity during the maximum temperature epoch of the day. Net long wave radiation is found to be the highest in pre-monsoon (64-65 W/m^2). With the monsoon onset, it goes on decreasing, with the lowest value of 42.6 W/m^2 in August. This is mainly due to the extensive cloud cover and high humidity conditions. After the monsoon withdrawal again it starts rising.

Key words: Solar irradiance, turbidity, transmission coefficient, net longwave radiation.

Introduction

The quantity of solar radiation received at the earth's surface is a function of latitude, season, time and transparency of the atmosphere. Measurements of the same at normal incidence are of fundamental importance in meteorological, climatological and geophysical studies, in the analysis of the absorption and scattering of radiation in the atmosphere and in investigations of the degree of turbidity of the atmosphere and size distribution of its constituents such as dust and water vapour.

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Atmospheric turbidity may be conveniently thought of as a quantitative measure of the vertically integrated amount of dust and other suspended particulate matter in the atmosphere. The turbidity of the atmosphere is defined as the reduced transparency of the atmosphere caused by absorption and scattering of radiation by solid or liquid particles, other than clouds, held in suspension. Thus, atmospheric turbidity over a place can be taken as an index of the atmospheric pollutants/aerosols (McCormick and Baulch, 1962). In the context of heavy local industrial pollution in urban areas of the world, and in recognition of the present dangers and the possible long-term consequences of changes in the composition of the atmosphere, the studies on atmospheric turbidity have assumed great importance.

Mani and Chacko (1963) studied the diurnal and seasonal variation of Angstrom turbidity coefficient at Delhi and Poona for the year 1958 and found a pronounced maximum during the summer months at both places and a minimum during winter. The turbidity over Delhi was found to be 2-5 times that over Poona throughout the year, as a result of its proximity to the arid zones to its west (Chacko and Desikan, 1965). Ganesan (1973) found that direct solar irradiation was maximum during winter and minimum during the hot weather period for the same optical air masses and solar elevations. He further found very low turbidity values all over the country during winter (December-February) with cloud-free skies and good visibility and during hot weather period (March-May) the turbidity increased all over the country with a maximum over the northwestern part. Turbidity studies by Mani (1980) revealed that for the whole year, the values are higher over central and north India than that over the peninsula and they are highest during the hot, dry pre-monsoon summer months and least during winter over the subcontinent as a whole.

While analyzing the turbidity data of three years (1976-79), Krishna Nand and Maske (1983) found that the turbidity value was maximum (0.181) at Allahabad during summer. They also concluded that rains were quite effective in removing (20-30%) the atmospheric particulate matter with lower efficiency at Pune (23%) than that at Allahabad (33%) and Jodhpur (32%) possibly due to the fact that atmosphere at Allahabad and Jodhpur contained larger size particulate matter during summer. Padmanabhamurthy (1969) while studying the turbidity data (1957-67) at Pune found a decreasing tendency till 1960; after that a definite increasing trend was found indicating increase in the aerosol content in the atmosphere due to industrialization of the city. Iyer (1983) used the transmission factor or transparency of the atmosphere as a measure of air pollution over Jodhpur. Srivastava et al. (1992), while studying the turbidity values at BAPMoN (presently GAW) stations of India over the period from 1973 to 1985, found a general increasing trend in them at majority of these stations.

Keeping in mind the importance of the radiometric assessment, this paper aimed at assessing direct solar irradiances and net terrestrial radiant energy and the variations in the turbidity parameter and the atmospheric transparency as derived from irradiation measurements at a continental GAW station, Nagpur, in India.

Data and Methodology

In the Vidarbha region Nagpur is the only station for which direct solar radiation at normal incidence, net terrestrial radiant energy (long wave radiation) and Angstrom turbidity data are available. These data, available for the period 1989-98, have been utilized in this study.

Direct solar irradiation was measured using Angstrom compensation pyrheliometer following the methodology described in IGY Instr. Manual, 1957. Transmission coefficient or transparency q of the atmosphere was derived from the relation

$$S = S_0\, q^{m} \qquad (1)$$

where S is the irradiance measured and S_0 is the extraterrestrial irradiance in the solar wave length range 0.3 µm and 3 µm. 'm' is the absolute air mass, the optical path length through which the irradiation passes through the atmosphere, taking the zenith distance as a unit air mass.

Angstrom turbidity coefficient β and net terrestrial radiant energy were measured using Angstrom pyrheliometer and Angstrom pyrgeometer respectively.

The solar radiation and turbidity data are measured six times a day at different optical air masses. Monthly mean values in different years have been computed from these daily values. Seasonal values have been arrived at from the monthly mean values. However, values during the monsoon months are very few due to extensive and persistent clouding during this period and have not been considered for discussions.

Results and Discussions

Direct Solar Irradiance

Monthly mean values of irradiances at Nagpur for each year from 1989 to1998 are presented in Table 1.

Direct solar irradiances generally decrease as the summer advances and increase again from October onwards. The irradiances are generally higher in December than those in any other month. It is seen that March values do not show large fluctuations; but October values have more variations, perhaps due to the varying degrees of rainfall activities during the monsoon season and the persisting moisture in the atmosphere during October. The highest direct solar irradiance value of 674.3 W/m^2 was recorded during November, 1989 and the least was 469.9 W/m^2 in May, 1991. It is once again stressed that the values of the monsoon months have not been considered here.

Table 1: Monthly direct solar irradiances (W.m^{-2}) at Nagpur over different years

Month	*1998*	*1997*	*1996*	*1995*	*1994*	*1993*	*1992*	*1991*	*1990*	*1989*
Jan	571.8	586.6	525.1	658.6	573.9	-	556.9	660.7	-	671.1
Feb	642.2	616.3	541.3	634.0	560.1	588.8	565.6	517.5	-	-
Mar	576.0	536.9	508.2	539.2	584.5	-	507.3	590.3	565.6	-
Apr	559.9	540.9	476.5	587.9	608.6	553.1	519.8	540.2	542.5	608.6
May	526.1	541.9	496.8	563.3	527.3	478.7	472.9	469.9	578.4	477.3
Jun	501.9	456.8	517.2	596.0	-	534.3	460.0	-	-	463.5
Jul	475.2	-	-	-	-	585.9	444.5	-	-	530.8
Aug	497.8	-	-	-	-	512.9	-	-	617.1	562.2
Sept	529.9	526.6	574.8	482.6	525.9	627.1	507.5	445.7	614.1	512.6
Oct	581.0	549.9	550.7	610.0	580.7	581.0	524.7	491.6	587.7	662.8
Nov	-	541.6	608.7	586.0	564.3	542.2	565.8	-	609.2	674.3
Dec	668.2	615.0	620.8	545.5	594.4	569.4	600.2	492.5	611.5	-

Mean values of direct solar irradiances for specified air masses and for the main seasons, winter (Dec.-Feb.), summer (March-May), monsoon (June-Sept.) and post-monsoon (Oct.-Nov.) are presented in Table 2. The direct solar radiation is the highest (692.4 W.m^{-2}) during winter due to cloudless sky and good visibility conditions. In monsoon though the dust content of the atmosphere is reduced due to rainout and washout in precipitation yet increase in moisture reduces the intensity of solar radiation. In the post-monsoon season, it is seen that the direct solar irradiance increases substantially which is an indication that the atmosphere has been cleansed off its dust by precipitation. These values are generally higher than the summer months when the dust particles are carried upwardly by strong convection currents. The data for the monsoon months are presented to show the relative values but they are not included in discussions.

Annual march of mean daily values of direct solar radiation is presented in Figure 1. It shows that Nagpur gets the lowest intensity of 504.2 W/m^2 in June, whereas highest intensity of 600.6 W/m^2 observed in January. An interesting point is the sudden increase in irradiances in October when the skies become cloudless and the atmosphere becomes clean due to wash out by the monsoon rains. Unlike other stations (Delhi and Pune), January records higher irradiances than February (Desikan et al., 1994).

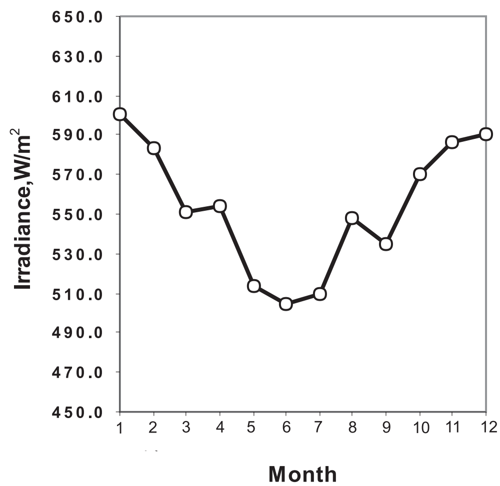

Figure 1: Annual march of direct solar radiation intensity (W.m^{-2}) at Nagpur.

Table 2: Seasonal values of direct solar irradiances (W.m^{-2}) for specified air masses at Nagpur

Air mass	*Winter*	*Summer*	*Monsoon*	*Post monsoon*
3.0 FN	499.6	476.5	467.2	475.1
2.0 FN	595.8	552.9	533.3	573.1
1.5 FN	690.2	637.7	596.5	662.3
1.5 AN	692.4	615.4	587.0	654.1
2.0 AN	599.0	535.6	542.7	569.5
3.0 AN	494.9	437.1	451.5	454.5

Diurnal variation of direct solar radiation from January to December is presented in Table 3. For all the months peak is reached at air masses 1.5 FN and 1.5 AN. Peak value is maximum in January (703.2 W/m^2). Sharp fall observed from April to May could be attributed to higher convective activities causing more turbid atmosphere and consequent favourable conditions for growth of particulate size leading to cloud formations.

Atmospheric Turbidity

Monthly and seasonal mean Angstrom turbidity coefficient (β) values for the years 1989-98 are presented in Tables 4 and 5 respectively.

The turbidity values (Table 4) generally increase from winter to summer months, though this increase is not large. Though direct solar irradiances showed increase in October due to washout by rains in the preceding monsoon months, yet turbidity (β) values did not decrease after the monsoon, as they were supposed to when the rains should have removed the particulate matter during the monsoon. A look into the variations in vapour pressure (vp) over Nagpur shows that vp value remains still high at 21.4 hPa in October. With relatively higher air temperature in October, the lingering moisture provides potential conditions for convective currents to be active, thereby causing more mixing of particulate matters. This may be one of the reasons for the higher β values during October.

The turbidity (β) values, in general, are relatively low during 1989-90. They show gradual increase in 1991-92 only to fall again during 1993. However, in absence of good rains/lingering moisture in the soil and air after the monsoon of 1993, β starts increasing by November-December to 0.107, the increase being more than 11 per cent. Even during 1995 when the irradiances showed large values compared to the previous years during this period (November-December), the β values remain reasonably high and it is the same case during 1996 as well. Here again the values during the monsoon period June to September are not considered.

The seasonal values (Table 5) indicate that winter values are the least and the highest ones are during the post-monsoon season. Winter values, however, are a steady indicator that the pollution is on the rise since 1989, though β values stabilize to a value less than 0.100 after peaking during 1996 and 1994.

Table 3: Diurnal variation of direct solar irradiances ($W.m^{-2}$) at Nagpur

Air mass	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*
3.0 FN	510.7	501.8	486.8	490.1	452.4	468.4	434.1	425.5	466.0	464.2	485.9	486.2
2.0 FN	590.1	597.4	562.0	564.7	532.0	543.8	514.4	535.3	522.9	558.9	587.3	599.8
1.5 FN	697.7	688.4	638.9	649.9	624.2	581.9	547.0	554.5	611.2	645.4	679.3	684.5
1.5 AN	703.2	688.2	626.8	624.0	595.3	579.6	489.9	531.5	594.4	647.0	661.2	685.7
2.0 AN	602.5	603.6	555.5	537.8	513.5	509.7	521.1	549.5	575.7	562.4	576.6	591.1
3.0 AN	499.3	506.0	450.1	458.4	402.9	442.9	348.4	500.3	460.1	454.3	454.7	479.4

Table 4: Mean Angstrom turbidity coefficient ß at Nagpur for different years

Month	*1998*	*1997*	*1996*	*1995*	*1994*	*1993*	*1992*	*1991*	*1990*	*1989*	*Mean*
Jan	0.125	0.103	0.120	0.096	0.104	-	0.103	0.079	-	0.078	0.101
Feb	0.094	0.088	0.116	0.089	0.115	0.090	0.091	0.075	-	-	0.095
Mar	0.091	0.096	0.113	0.105	0.080	-	0.106	0.073	0.088	-	0.094
Apr	0.106	0.095	0.120	0.104	0.075	0.097	0.103	0.087	0.076	0.083	0.095
May	0.109	0.092	0.108	0.092	0.099	0.095	0.124	0.089	0.068	0.094	0.097
Jun	0.122	0.086	0.109	0.087	-	0.081	0.113	-	-	0.123	0.103
Jul	0.119	-	-	-	-	-	0.129	-	-	0.101	0.116
Aug	0.106	-	-	-	-	-	-	-	0.079	-	0.093
Sept	0.111	0.110	0.091	0.109	0.124	0.127	0.116	0.089	0.083	0.114	0.107
Oct	0.103	0.105	0.103	0.103	0.119	0.091	0.091	0.131	0.096	0.113	0.105
Nov	-	0.121	0.106	0.106	0.107	0.107	0.097	-	0.085	0.128	0.107
Dec	0.073	0.095	0.099	0.097	0.095	0.107	0.095	0.119	0.080	-	0.095

Table 5: Seasonal Angstrom turbidity for different years at Nagpur

Season	*1998*	*1997*	*1996*	*1995*	*1994*	*1993*	*1992*	*1991*	*1990*	*1989*	*Mean*
Winter	0.097	0.095	0.112	0.094	0.105	0.099	0.096	0.091	0.074	0.078	0.094
Summer	0.102	0.094	0.113	0.100	0.085	0.096	0.111	0.083	0.078	0.088	0.095
Monsoon	0.115	0.098	0.100	0.098	0.124	0.104	0.119	0.103	0.081	0.113	0.105
Post-monsoon	0.103	0.113	0.104	0.104	0.113	0.099	0.094	0.131	0.091	0.120	0.107

Seasonal values give overall picture of variation in turbidity in different seasons. In order to get detailed information about the fluctuations in turbidity values within a day in different months, diurnal variation of the same are presented in Table 6.

For all the months early morning hours are less turbid and peak is reached around noon. This can be attributed to loosening of soil particles due to solar heating and lifting them up due to convection currents set up. The early morning values are generally lower than the late evening values though marginally, perhaps due to the stable layers of the late night and early mornings allowing the dust particles to settle down. This is evident as β values sharply shoot up for air mass at 2.0 FN. Similar changes i.e. sharp decreases are, however, not seen in the afternoons. The stable atmospheric conditions effectively prevent convective mixings in December as seen by the small changes in β as the day progresses.

Annual march of turbidity is shown in Figure 2. A notable feature is the very sharp decrease in β from 0.107 in November to 0.095 in December, again indicating the suppression of convective activities in the more stable atmospheric conditions at Nagpur and due to lower moisture content in the air.

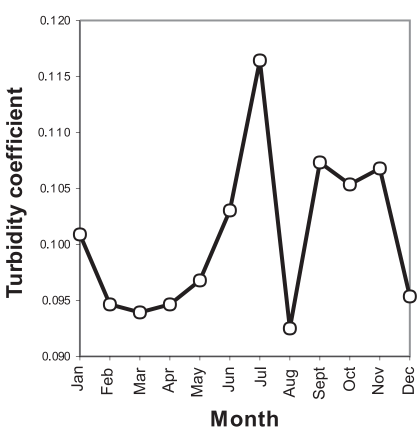

Figure 2: Annual march of turbidity coefficient β.

Transmission Coefficient (*q*)

The pollution status of the atmosphere can also be determined by looking at the transmission coefficient values which have been computed from the relation $S = S_0\, q^m$. The mean values of the same for different months at different optical air masses for the period 1989 to 1998 are given in Table 7.

The *q* values are highest during the winter months of January and February (0.662) and lowest in the pre-monsoon month of May (0.633). A notable feature is that variations during the year are very small and the mean transparency of the atmosphere over Nagpur is around 65 percent. A more industrialized station like Pune has a higher transparency of around 70 percent. This may perhaps be ascribed to the higher altitude of Pune and scavenging of dust by the sea breeze (though for limited durations) (Vasishtha, 2000).

Diurnal variation of *q* values further reveal that the values are higher in the early morning and late afternoon than those at higher solar elevations in all the months. The *q* values start falling from morning hours and reaches the lowest value by noon time only to go on increasing till sunset hours. This may be ascribed to loosening of soil particles by solar heating, increased convection and turbulent mixing during the day and stratification of the layers near the ground during the night and early morning. It is seen that the transparency of the atmosphere decreases, though marginally, from winter till summer. This may be attributed to the increasing dust content of the atmosphere over Nagpur as the season advances into summer.

Net Terrestrial Radiant Energy (TRE)

The emission of terrestrial radiant energy (long wave radiation) by the earth's surface and the atmosphere takes place continuously both during day and night. Measurements are, however, available only at night due to instrumental limitations. Based on the data collected

Table 6: Diurnal variation in Angstrom turbidity at Nagpur

Air mass	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*
3.0 FN	0.077	0.072	0.068	0.066	0.062	0.091	0.080	0.076	0.079	0.089	0.084	0.083
2.0 FN	0.108	0.102	0.090	0.099	0.094	0.106	0.116	0.133	0.119	0.115	0.106	0.097
1.5 FN	0.124	0.122	0.109	0.113	0.115	0.117	0.123	0.099	0.121	0.116	0.118	0.107
1.5 AN	0.114	0.115	0.118	0.113	0.120	0.101	0.131	0.132	0.119	0.116	0.121	0.107
2.0 AN	0.102	0.098	0.102	0.099	0.110	0.103	0.140	0.105	0.102	0.103	0.105	0.104
3.0 AN	0.081	0.066	0.081	0.080	0.085	0.081	0.127	0.072	0.076	0.082	0.091	0.079

at 2030 hours mean net TRE for 1989-98 for different months are presented in Table 8. The net TRE field is determined by the mean temperature of the air layers near the ground, its moisture content and the type and amount of clouds. The earth emits radiant energy in terrestrial wavelength ranges (3-50 μm). Major part of this is absorbed by the atmosphere due to selective absorption by water vapour, CO_2, O_3 and dust and smoke if they are concentrated. Thus, the layer which absorbs this radiant energy reradiates in the same wave length region, thereby reducing the radiation loss at the earth's surface. At a much higher level, clouds with their moisture content act as an opaque wall and reradiates energy back to surface of the earth. Thus higher moisture content and cloud amount lowers net TRE upwards to atmosphere.

Data in Table 8 reveal that net TRE is highest during pre-monsoon months (64-65 W/m^2). With the onset of monsoon it decreases rapidly till August when it reaches its lowest value of 42.6 W/m^2. From September onwards, as the monsoon starts withdrawing, net TRE starts increasing. The low values of not more than 70 W/m^2 shows the effect of dust load over Nagpur. A very striking feature seen is the very low values of TRE during the winter and pre-monsoon months of 1990 and 1995.

Table 7: Diurnal variation of transmission coefficient "q"

Month	*3.0 FN*	*2.0 FN*	*1.5 FN*	*1.5 AN*	*2.0 AN*	*3.0 AN*	*Mean*
Jan	0.712	0.646	0.624	0.628	0.653	0.707	0.662
Feb	0.710	0.653	0.622	0.622	0.656	0.712	0.662
Mar	0.706	0.637	0.597	0.590	0.633	0.688	0.642
Apr	0.712	0.644	0.611	0.595	0.629	0.696	0.648
May	0.696	0.630	0.601	0.582	0.619	0.670	0.633
Jun	0.707	0.640	0.577	0.576	0.620	0.694	0.636
Jul	-	-	-	-	-	-	-
Aug	-	-	-	-	-	-	-
Sept	0.701	0.621	0.588	0.578	0.652	0.698	0.640
Oct	0.696	0.637	0.603	0.604	0.639	0.691	0.645
Nov	0.703	0.648	0.618	0.607	0.642	0.687	0.651
Dec	0.701	0.652	0.617	0.618	0.647	0.697	0.655

Table 8: Net terrestrial radiant energy (W.m^{-2}) at Nagpur at 2030 IST

Month	*1989*	*1990*	*1991*	*1992*	*1993*	*1994*	*1995*	*1996*	*1997*	*1998*	*Mean*
Jan	-	37.9	60.5	64.7	51.0	70.6	41.1	-	70.8	59.7	57.0
Feb	73.4	38.5	60.9	67.0	60.9	75.4	48.5	-	89.6	63.4	64.2
Mar	56.2	39.9	66.7	71.9	68.1	78.9	37.4	75.5	85.2	67.1	64.7
Apr	82.9	55.3	55.5	61.5	82.1	63.0	43.7	-	72.7	72.7	65.5
May	80.8	44.2	63.4	55.2	31.9	68.8	45.3	92.3	74.3	66.7	62.3
Jun	-	36.3	42.2	-	65.9	69.3	49.2	30.0	52.4	64.2	57.4
Jul	35.8	38.8	-	32.1	59.0	48.6	39.3	44.5	45.8	50.8	43.9
Aug	28.4	39.8	42.7	28.6	54.9	45.4	36.1	39.2	58.5	52.5	42.6
Sept	34.3	44.9	49.1	40.5	48.0	46.1	48.5	58.7	64.6	49.6	48.4
Oct	47.2	48.6	52.5	35.2	61.6	51.3	50.0	70.6	57.4	47.9	52.2
Nov	54.7	59.6	51.8	42.4	66.5	59.6	43.7	59.4	51.3	39.6	52.9
Dec	-	-	60.4	49.3	70.7	50.3	-	60.6	50.9	23.7	52.3

Summary

(i) Direct solar irradiance at Nagpur is highest in winter due to cloudless sky and good visibility conditions; however, it was the least in monsoon due to substantial increase in moisture content of the atmosphere despite the reduction in dust content due to rainout and washout.

(ii) Diurnal variations in direct solar irradiances show that for all the months peak was reached by the noon. Maximum peak value was 703 W/m^2 in January.

(iii) Turbidity is maximum during the post-monsoon season, whereas it is minimum in winter.

(iv) Diurnal variations of turbidity reveal that early morning hours are less turbid whereas peak turbidity was reached around the noon hours.

(v) It is seen that transparency of the atmosphere over Nagpur decreases from winter till May. This could be attributed to the increasing dust content of the atmosphere over Nagpur. The atmosphere transmits only 65% of the incident energy.

(vi) The transparency is higher at early mornings and late afternoons when compared to high solar elevations. Rather, the transparency decreased from morning till noon only to increase later. This could be attributed to convective activity during the maximum temperature epoch of the day.

(vii) Net terrestrial radiant energy is highest during the pre-monsoon period (64-65 W/m^2). With the monsoon onset, it goes on decreasing with the lowest value in August. This is mainly due to the extensive cloud cover and high humidity conditions. After the monsoon withdrawal again it starts rising.

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