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# Observational evidence of solar dimming: Offsetting surface warming over India

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[1] Monthly mean surface reaching solar radiation (S) measurements under all sky conditions have been evaluated for 12 stations, which are widely distributed over the Indian region, for the period 1981-2004. It is noteworthy that all the stations showed decline in S ranging from $-0.17$ to $-1.44$ W/m$^2$ per year. The average solar dimming observed over India for the period 1981–2004 is $\sim-0.86$ W/m$^2$ per year while during winter, pre-monsoon and monsoon seasons it is $\sim-0.94$, $\sim-1.04$ and $\sim-0.74$ W/m$^2$ per year, respectively. Decadal monthly mean S for the two decades 1981–1990 and 1991–2000 showed strong decline during the second decade with an average reduction of 5% per two decades. Despite the drastic decrease in S, the all India averaged surface maximum and minimum air temperatures have been increasing. But, the change in increase in maximum temperature from the first decade to second decade is only marginal under the present situation of drastic increase in greenhouse gas emissions, while the increase in minimum temperature has been doubled.
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## 1. Introduction

[2] Solar radiation reaching the earth's surface (direct + diffuse radiation), also known as global radiation or insolation (S), is the primary energy source to sustain life on earth. Apart from the well-known concept of global warming, global dimming, which refers to the widespread and significant reduction in S, has received prominent attention because of its possible climatic and environmental implications. Various studies over different locations showed significant changes in S from dimming to brightening on decadal time scales [*Dutton et al.*, 1991; *Gilgen et al.*, 1998; *Stanhill and Cohen*, 2001; *Liepert*, 2002; *Wild et al.*, 2004, 2005]. The long-term satellite data on a global scale showed an overall increase in S from 1983 to 2001 at a rate of 0.16W/m$^2$ per year. This change is a combination of a decrease until about 1990, followed by a sustained increase [*Pinker et al.*, 2005]. Atmospheric aerosols from anthropogenic air pollution are considered to be important contributors to these changes [*Streets et al.*, 2006]. At the earth surface, both scattering and absorbing type of aerosols reduce the amount of solar radiation reaching the surface. Also, aerosols contribute to additional dimming by acting as nuclei for cloud droplets that enhance scattering of solar radiation. The emissions of aerosols and aerosol precursors from human activity have increased drastically since the pre-industrial times, and hence the aerosol and cloud optical depths have also increased. It has been estimated that during the dry winter monsoon season over the Indian Ocean region, anthropogenic aerosols, especially the absorbing aerosols, can decrease the average S by 15–35 W/m$^2$ [*Ramanathan et al.*, 2001].

[3] S is a key determinant of surface temperature. Despite solar dimming, the mean annual surface air temperature, averaged over the entire globe, has been increasing in the past 150 years [*Jones and Moberg*, 2003]. But, from 1980 onwards greater warming has been observed over land [*Houghton et al.*, 2001], due to increasing abundance of greenhouse gases (GHG) in the atmosphere as a result of human activities. The greater warming since the 1980s was favored by a widespread decline of solar dimming, which, in contrast to earlier decades, no longer masked the greenhouse effect and revealed its full dimension [*Wild et al.*, 2007]. According to the theoretical predictions made 100 years ago [*Arrhenius*, 1896], the accumulated greenhouse gases raise the surface air temperatures. Several other suggestions and theories on natural and man made forcing are investigated to explain the warming of our planet such as changing solar and volcanic activity [*Crowley*, 2000], cloud amounts [*Laut*, 2003] and amounts and types of aerosols [*Anderson et al.*, 2003].

[4] A recent study showed that strong greenhouse forcing outweighs decreasing solar radiation, driving rapid surface temperature increases in central Europe [*Philipona and Dürr*, 2004]. In the present study, we elucidate data on the spatial and decadal changes in S under the global warming scenario for the period 1981–2004, over different stations in India. A continuation of solar dimming over India up to present has been noted by *Wild et al.* [2005] and *Ramanathan et al.* [2005]. This will be investigated in more detail in the present study, as well as its effect on temperature evolution over India.

## 2. Observational Data

[5] Monthly mean (mean of 24 hrs daily averages) S data measured under all sky conditions over Indian region were collected from India Meteorological Department (IMD). Thermoelectric pyranometers were utilized to acquire the radiation data in the wavelength range from 0.3 to 4.0$\mu$m. The absolute accuracy of the standard instrument is about ±0.3%, while the accuracy of the instruments in the network is about ±1%. The continuous data available for the years 1981 to 2004 for the stations Trivandrum, Chennai, Goa, Visakhapatnam, Pune, Mumbai, Nagpur, Kolkatta, Ahme-

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**Table 1.** The Observed Reduction in Surface Reaching Solar Radiation for Annual, Winter, Pre-Monsoon, and Monsoon Seasons During the Period 1981–2004 Over the Indian Stations[a]

| Station | Lat/Long | Annual, $W/m^2/yr$ | Winter, $W/m^2/yr$ | Pre-Monsoon, $W/m^2/yr$ | Monsoon, $W/m^2/yr$ |
|---|---|---|---|---|---|
| Trivandrum(SI) | 8.48°N, 76.95°E | −1.03 (0.26) | −0.93 (0.36) | −1.42 (0.48) | −0.60 (0.35) |
| Chennai (SI) | 13.0°N, 80.18°E | −0.22 (0.19) | −0.15 (0.42) | −0.91 (0.47) | 0.34 (0.28) |
| Goa(WC) | 15.48°N, 73.82°E | −0.71 (0.26) | −1.15 (0.35) | −1.36 (0.36) | 0.22 (0.34) |
| Visakhapatnam(EC) | 17.72°N, 83.23°E | −1.40 (0.16) | −1.50 (0.34) | −1.88 (0.23) | −1.19 (0.24) |
| Pune (IP) | 18.5°N, 73.9°E | −0.17 (0.19) | −0.37 (0.20) | −0.06 (0.39) | −0.18 (0.36) |
| Mumbai(WC) | 19.12°N, 72.83°E | −0.59 (0.20) | −0.55 (0.27) | −0.68 (0.35) | −0.62 (0.29) |
| Nagpur(IP) | 21.10°N, 79.05°E | −0.48 (0.18) | −0.21 (0.29) | −0.17 (0.13) | −0.85 (0.42) |
| Kolkatta(NE) | 22.39°N, 88.27°E | −1.28 (0.18) | −1.36 (0.25) | −1.27 (0.27) | −1.02 (0.26) |
| Ahmedabad(NW) | 23.07°N, 72.63°E | −1.20 (0.26) | −0.92 (0.25) | −1.37 (0.35) | −1.35 (0.48) |
| Varanasi(NC) | 25.45°N, 83.02°E | −0.67 (0.32) | −1.10 (0.34) | −1.08 (0.38) | −0.53 (0.54) |
| Jodhpur(NW) | 26.3°N, 73.01°E | −1.17 (0.22) | −1.51 (0.22) | −1.04 (0.27) | −1.13 (0.37) |
| New Delhi(NW) | 28.58°N, 77.20°E | −1.44 (0.27) | −1.47 (0.35) | −1.29 (0.31) | −2.01 (0.48) |
| Average dimming over India | | −0.86 | −0.94 | −1.04 | −0.74 |

[a]Winter, DJF; pre-monsoon, MAM; monsoon, JJAS. The value in the parenthesis represents standard error on slope at 95% confidence level. SI, Southern India; WC, West Coast; EC, East Coast; NE, North East; NW, North West; NC, North Central; IP, Interior Peninsula. Varanasi, Jodhpur, and New Delhi are located in the IG plains.

dabad, Varanasi, Jodhpur, and New Delhi are used in the present study. These stations (coordinates given in Table 1) are distributed over northern, southern, eastern, western and central India. In addition to the above data, all India averaged maximum and minimum air temperature data has been collected from the IITM website (http://www.tropmet.res.in) for the years 1981 to 2003.

## 3. Results and Discussion

[6] Annual mean S has been computed from the monthly mean values for all the selected Indian stations. The time series of annual means has been subjected to linear regression analysis. The linear trends in S for annual, winter (DJF), pre-monsoon (MAM) and monsoon (JJAS) seasons during the period 1981–2004 over all the selected Indian stations are found decreasing (except Chennai and Goa during monsoon) and their slopes are given in Table 1. For annual means the slopes are ranging from −0.17 to −1.44 $W/m^2$ per year, statistically significant at 95% confidence level. The stations New Delhi (urban-industrialized, frequent dust storms) and Visakhapatnam (coastal-urban-industrialized), showed strong decline in S. The stations Kolkatta and Ahmedabad (densely populated and industrialized cities), Jodhpur (increasing anthropogenic activities and frequent dust storms) and Trivandrum (under the influence of long range transport of anthropogenic activities during NE monsoon) showed the next highest decline in S. The average solar dimming observed over India for the period 1981–2004 is found to be approximately −0.86 $W/m^2$ per year (estimated as an average of the slopes shown in Table 1) or −20.64 $W/m^2$ for the entire period. Also all India average annual mean S (one composite time series from all stations) plotted in Figure 1 shows the temporal evolution of S observed over India. A significant continued dimming is observed over India, whereas the other parts of the world showed increasing trends since the mid 1980s, mostly in Northern Hemisphere, Australia and Antarctica [*Wild et al.*, 2005]. It is believed that aerosols emitted as a result of human activities are the most likely cause of solar dimming. The changes in aerosol burden due to changing patterns of anthropogenic emissions of $SO_2$ (as a precursor of sulfate aerosol) and black carbon (BC), which together contribute about one-third of global average aerosol optical depth (AOD), are likely contributing to the trends in S [*Streets et al.*, 2006], because sulfate aerosol is a strong scatterer and BC is a strong absorber of solar radiation. In India $SO_2$ and BC emissions are estimated to have increased by about 10% or more per year during 1980–2000 [*Ramachandran and Jayaraman*, 2003]. AOD trends are found to be increasing over all major cities in India. The AOD over the northern part of India is found to be higher than over the southern part of India due to increasing population, urbanization and industrialization [*Sarkar et al.*, 2006]. Over the coastal stations Trivandrum and Visakhapatnam, the anthropogenic contribution to the 5-year (1996–2000) mean AODs was found about 84% and 87% respectively [*Ramachandran*, 2004].

[7] The average solar dimming observed during the winter, the pre-monsoon and the monsoon seasons from

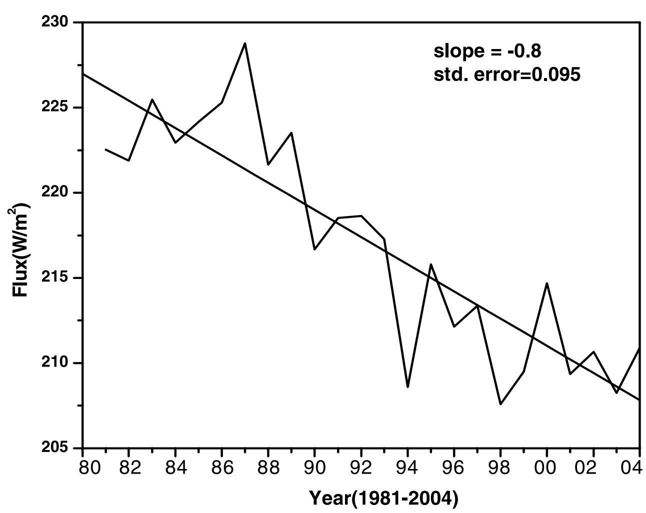


**Figure 1.** All India averaged annual mean surface reaching solar radiation.

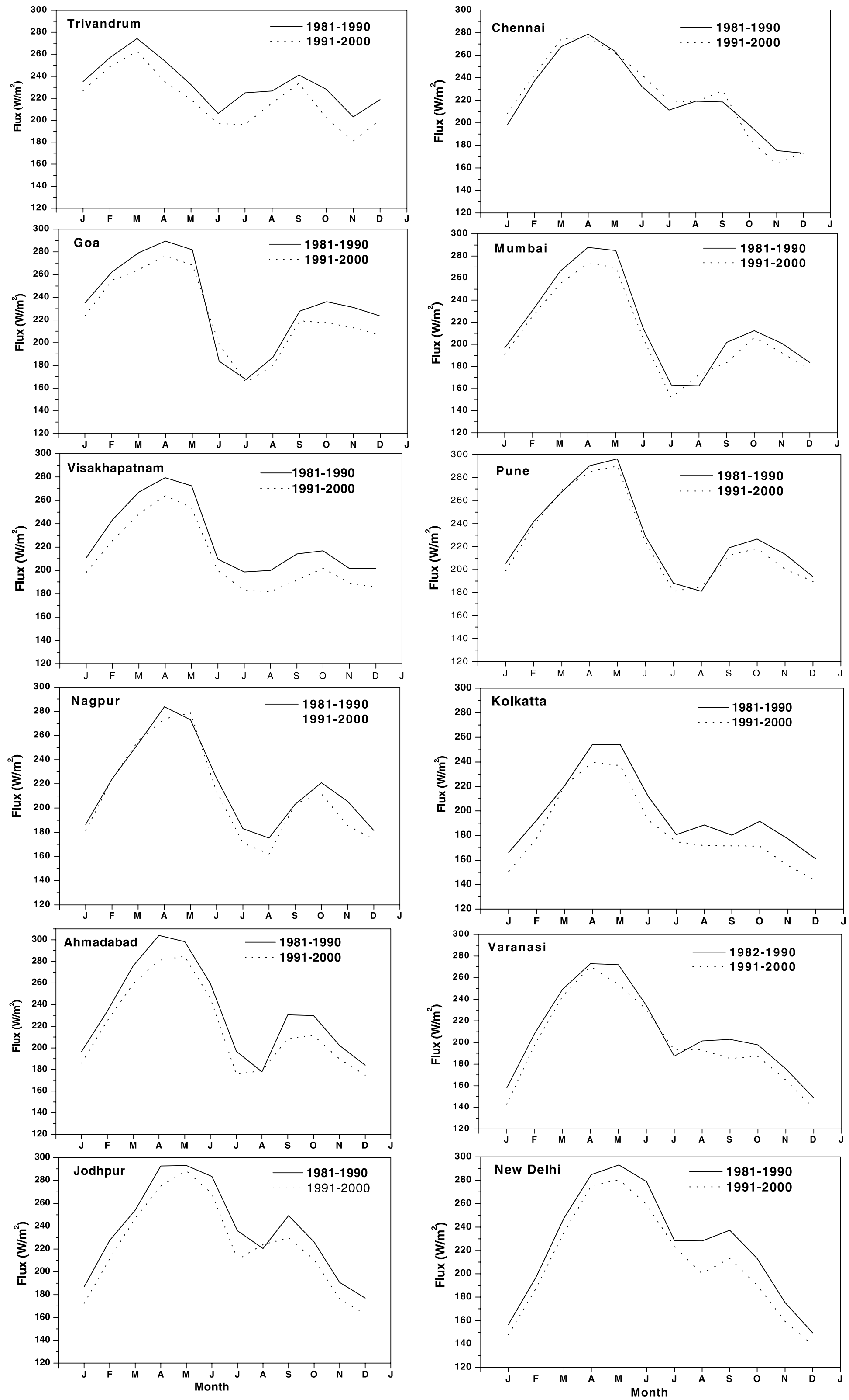


**Figure 2.** Monthly mean surface reaching solar radiation for the two decades 1981–1990 and 1991–2000 over different Indian stations.

1981 to 2004 is ∼−0.94, ∼−1.04 and ∼−0.74 W/m$^2$ per year, respectively. The dimming during winter and pre-monsoon indicates an enhanced aerosol direct effect, because in these seasons aerosol loading builds up and also maximum number of clear sky days were present. During monsoon aerosol burden is small due to washout and scavenging influence of the summer monsoon precipitation. Hence, the dimming during monsoon might be due to cloud

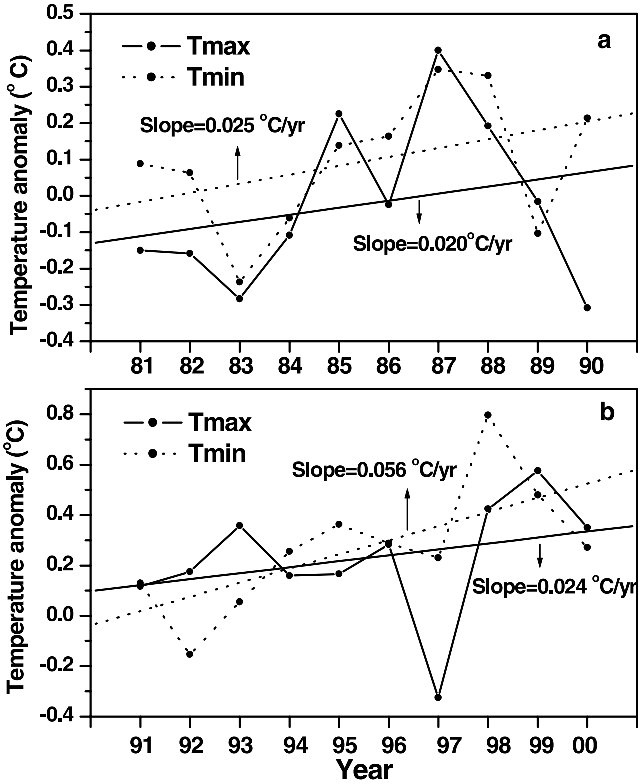


**Figure 3.** All India annual mean Maximum and Minimum temperature anomalies (deviations from 1961–1980 mean) for (a) the decade 1981–1990 and (b) the decade 1991–2000. The values on the trend line represent slopes.

absorption or aerosol indirect effect. From the Table 1 it is evident that all the stations located to the north of 20° latitude showed more reduction in S during winter, except Ahmedabad, while the stations located to the south of 20° latitude showed more reduction during pre-monsoon, except Pune. The anthropogenic emissions, particularly BC and sulfate aerosols are present throughout the year in northern India over the Indo-Gangetic (IG) plains [*Reddy and Venkataraman*, 2002a, 2002b], which is a vast stretch of land in south Asia extending about 1600 km in length and 400 km in breadth cutting across Pakistan, India, Nepal and Bangladesh [*Abrol et al.*, 2002]. Such aerosols form thick layers of haze in winter, termed as Atmospheric Brown Clouds (ABC), which block the radiation from reaching the surface [*Ramanathan et al.*, 2005]. Over India, AODs derived from TOMS data from 1979 to 2000 increased by 11% per decade during winter with large values over IG plains [*Massie et al.*, 2004]. The stations New Delhi, Jodhpur and Varanasi are located in the IG plains. Over Peninsular India, the extensive measurements of AOD using a network of ground based Multi Wavelength radiometers covering distinct regions (remote coastal, urban coastal, remote continental and island locations) during the period 1986 to 2000, showed significant increase in AOD and also, climatologically, the AODs are found to be highest during pre-monsoon as compared to local winter [*Krishna Moorthy et al.*, 2002]. Thus, the observed reductions in S during winter and pre monsoon seasons are consistent with the variations in AOD values.

[8] Further, for each station monthly averages have been estimated for the two decades 1981–1990 and 1991–2000. Decadal monthly mean surface reaching solar radiation is shown in Figure 2. All stations show strong decline during the second decade, indicating higher AOD values as well as changes in cloud properties during the second decade as compared to the first decade. For two decades Visakhapatnam shows a maximum reduction of 17 W/m$^2$ and New Delhi, Kolkatta and Trivandrum show the next maximum reduction of $\sim$15 W/m$^2$, Ahmedabad (14 W/m$^2$), Jodhpur (13 W/m$^2$), Nagpur (10 W/m$^2$), Goa (10 W/m$^2$), Varanasi (9 W/m$^2$), Mumbai (8 W/m$^2$), Pune (5 W/m$^2$) and only Chennai shows an increase of 2.2 W/m$^2$ (i.e., 1%). Chennai situated on the east coast has climatic conditions quite different from that of the rest of the country; the northeast monsoon occurring during October and November is a special feature of this area. Hence, through out the year, Chennai is cloudy and receives relatively uniform diffused radiation [*Bhattacharya et al.*, 1996]. The average reduction over India is found to be 5% per two decades.

[9] Despite the decrease in S, the surface temperatures have increased. All India annual maximum (Tmax) and minimum (Tmin) air temperature changes (deviations from 1961–1980 mean) for two decades 1981–90 and 1991–2000 are shown in Figure 3. Both the temperatures show increasing trend. During the two decades 1981–90 and 1991–2000, the changes in Tmax and Tmin increased from $\sim$0.20°C to 0.24°C and $\sim$0.25°C to 0.56°C respectively. From the first decade to second decade the change in increase in Tmax is only marginal, whereas the increase in Tmin has doubled, indicating an increasing greenhouse forcing. The Indian greenhouse gas emissions increased from 988 to 1484 million tones from 1990–2000 and the compounded annual growth rate of the emissions between 1990 and 2000 has been 4.2% [*Sharma et al.*, 2006]. Also, the absorbing aerosols in atmospheric brown clouds over South Asia might have masked as much as 50% of the surface warming due to increase in greenhouse gases [*Ramanathan et al.*, 2005].

[10] The solar radiation affects the Tmax more than Tmin [*Wild et al.*, 2007]. Despite dimming, Tmax is found to be increasing, but the change in increase is only marginal from first decade to second decade in spite of drastic increase in greenhouse gas emissions. A lower change in increase in Tmax than Tmin may be a sign of the presence of solar dimming as stated by *Wild et al.* [2007]. It suggests that aerosol induced solar dimming is effective in masking the greenhouse warming because otherwise Tmax would have increased drastically. Hence, no clear evidence of global warming has been observed in the variability of monsoon rainfall during the period 1871–2001 over India [*Kriplani et al.*, 2003]. But, if the climate models include ABC in addition to GHG, then Indian monsoon rainfall is found to be $\sim$5% lower during 1960–1998 as compared to 1930–1960 mean [*Ramanathan et al.*, 2005].

## 4. Conclusions

[11] Monthly mean S under all sky conditions have been evaluated for 12 stations, which are widely distributed over the Indian region, for the period 1981–2004. All the stations showed decreasing trends. The average solar dim-

ming observed over India for the period 1981–2004 is found to be $\sim -0.86$ W/m$^2$ per year (or $-20.64$ W/m$^2$ for the entire period) while during winter, pre-monsoon and monsoon seasons it is $\sim -0.94$, $\sim -1.04$ and $\sim -0.74$ W/m$^2$ per year, respectively. AODs and clouds together contribute to the annual trend. Stations located to the north of 20° latitude showed more reduction during the winter, while stations south of 20° latitude showed more reduction during the pre-monsoon period. These trends are a function of the AOD values, viz. to the north of 20° the values are more during the winter, and while to the south of 20° the values are more in the pre-monsoon. It implies that AODs play a major role in reducing the solar radiation reaching the surface. Decadal monthly mean S for the two decades 1981–1990 and 1991–2000 showed strong decline during the second decade. Higher AOD values as well as changes in cloud properties contribute to this difference. Despite the drastic decrease in S, the surface Tmax and Tmin over India have been increasing. But, the change in increase in Tmax is only marginal from the first decade to the second decade under the present situation of drastic increase in greenhouse gas emissions. In the regional studies, aerosol induced solar dimming is effective in masking the greenhouse warming. On the other hand the increase in Tmin has doubled indicating an increasing greenhouse forcing.

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