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RESEARCH ARTICLE

Spectral and seasonal variations of aerosol radiative forcing with special reference to Kanpur, Indo-Gangetic Basin

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Abstract

Objective: To find the influence of aerosols on the sun rays arriving at the surface and to measure aerosol radiative forcing over Kanpur, Indo-gangetic basin. The study was performed during period 2001-2015. **Methodology**: The present work is credited to the availability of data through the network relying on the ground based optical observations obtained with the help of ground based instrument called Cimel sun photometer using AERONET (Aerosol Robotic Network) radiative transfer model with particular focus on Indo-Gangetic plain over Kanpur. The aerosol radiative forcing at the surface, atmosphere and top of atmosphere has been computed with the help of radiative transfer approach depending on AERONET aerosol retrievals. **Findings**: Our study investigated the seasonal and spectral variations of ARF along with aerosol radiative forcing with special reference to Kanpur region (IGP) by using AERONET data. The monthly average ($\pm\sigma$) ARF during the entire observational period (2001-2015), at three levels i.e., surface (ARFSFC), atmosphere (ARFATM) and the atmospheric top (ARFTOA) are recorded as –89.6 $\pm$ 18.6 Wm–2, +64.4 $\pm$ 16.5 Wm–2 and –25.2 $\pm$ 6.8 Wm–2 respectively. From the ARF measurements, it is found that there is a large reduction in surface arriving solar rays due to presence of absorbing and scattering types of aerosols. **Novelty**: Since this study provides an overview of the present state of prevailing aerosols and their climatic effects. So, findings may be used to create an aerosol climate map for the region under study.

Keywords: Aerosol robotic network; aerosol radiative forcing; global atmospheric model; sun photometer

1 Introduction

Aerosols engender disturbances in earth's energy system thereby changing earth's energy balance changes completely, it is referred to as radiative forcing. The imposed perturbations are brought by atmospheric species e.g., CO_2, aerosols etc. Generally, atmospheric models are used to find the atmospheric results affected by a single factor. However, during investigation of the atmospheric result affected by a single factor, it is not found appropriate to know cause and effect and hence such models are avoided to replicate the result related to each area of interest. Earth's atmosphere is affected mostly by energy of the sun. This energy falls at the atmospheric top, crosses through atmosphere and arrives at the surface of earth. A major quantum of energy is returned back into the atmosphere, named scattering whereas a part is absorbed by aerosols, named absorption [(1–4)]. These phenomena have explicit impact on Earth's energy [(2,4,5)]. Atmospheric radiation budget comprises solar rays released from the sun as well as thermal rays emitted from the Earth's surface. As a result of this, smaller amount of sunlight arrives at the surface of earth and thus gives rise to cooling effect at regional level. Whereas aerosol absorption has reverse impact and leads to warming effect on the environment. Thus, aerosols affect the atmosphere in several ways. There is a strong interaction between aerosols and solar radiations and hence aerosols have a significant repercussion on environmental change. The consequence of this interaction is that the earth's radiative balance is strongly affected. It is noted that the transport of atmospheric dust has a great repercussion and the amount of solar radiations arriving at the surface are greatly reduced. The transported aerosols mixed with carbonaceous aerosols emitted from industries and urban sites develop a tropospheric temperature abnormality.

The deposition of black carbon on the snow-covered area increases its absorption and thus the albedo power of snow surface decreases. As a result, its efficiency for absorption of solar radiation increases, thereby warming the surface and leads to glacier retreat. Its example is retreat of the Tibetan Plateau [(6,7)]. This process gives a momentum to melting of Tibetan glaciers [(8)]. These types of effects were also observed 2 km around the northern Indian Ocean and approximately 4km in mid parts of India. Due to this mechanism, the temperature gradient of 4 K°/km is created which is enough to change the water cyclic process and thus the monsoon in the Indian sub-continent [(4,9,10)]. High magnitude of combining black carbon aerosols on bright clouds causes the increase in the absorption efficiency. Due this fact the shrinking of glaciers has been reported in Indian Himalayan region [(11,12)]. A small proportion of the soot aerosols in the optical depth of aerosol can accelerate the melting of glaciers. This may cause the alarming effect on the earth's environment especially related to the existence of Glaciers [(13–15)]. The black carbon has a main contribution in the attenuation of the reflectance of snow in the aggregation regions of glaciers in the Baspa Valley of Himachal Pradesh [(16)].

The particle size distribution and chemistry are very different. The transported aerosol is mixed with carbon aerosols (emitted by industry and urban areas) to increase the efficiency of the absorption of solar radiation which can lead to anomalies in the tropospheric temperature. In addition, the Indian subcontinent has a very complex meteorology with enormous potential currents, different sea surface temperatures, strong medium-sized circulation and vast topography. These factors make remote sensing and modeling difficult in the Indian region. In addition, the India region is one of the regions in the world where the assumptions and algorithms of aerosols can be fully highlighted. The average description of the aerosol is mainly divided into two types of layers; one is the surface layer (SL), which extends to 1.5 km and the second is the high aerosol layer (EAL) which extends between 1.5 and 5.5 km. The improvement in the net column aerosol load compared to Kanpur is related to a relatively larger increase in contributions due to the EAL load compared to SL [(17)].

The measurements of aerosol optical properties and radiative forcing have been done by using remote sensing devices such as ground – based sensor: CIMEL sun photometer and satellite- based sensors: Moderate Resolution Imaging Spectroradiometer-MODIS & Cloud-Aerosol Lidar with Orthogonal Polarization- CALIOP over Indian region with particular focus on Indo-Gangetic Plain. The study from this part of India is important of Aerosol from this part of India is important because the accumulation of the aerosol particularly mixing state of aerosols has impact on atmospheric thermodynamics [(15)]. The AERONET is a broad remote sensing aerosol network based on ground-based observations obtained from the device called CIMEL sun photometer. Everyday observations of the optical depth of the aerosol recorded by MODIS Terra satellite in the region of the Indo- Gangetic Basin are also in good agreement with the measurements by AERONET [(18)]. Regionally, there are various aerosols networks. India started the systematic study of aerosols in the year 1988 under Indian Middle Atmospheric characterization Programme (IMAP) and another programme named Aerosol Climatology and Effects was commenced in 1991. ARFI (Aerosol Radiative Forcing over India) network programme is currently doing excellent work in this area. This is one of the biggest programmes implemented in India having greater than 40 ARFI network stations. [(19)].

Earlier, the radiative forcing estimates were provided for three aerosol effects [(20)]: (i) aerosol having direct effect. It is the interaction of the aerosols with radiations. (ii) cloud albedo effect- radiative forcing of the aerosols. It is the interaction of the aerosols with radiations. (iii)surface albedo- black carbon effect on ice and snow. Nowadays (terminology change), the radiative forcing because of interaction between aerosol and solar rays causes both scattering as well as absorption. The estimate of radiative forcing because of the interaction between radiation and aerosol has so far been more uncertain than the present estimate of radiative forcing. The significant advancement in the aerosol observation system with little uncertainty is an instance of recent development. This is due to availability of data via the network based on the ground-based optical observations -AERONET, satellite-based instruments like MODIS and MISR, and others which bestowed to constrain present radiative forcing with the help aerosol observations. The properties obtained from sun-photometer in the course of pre-monsoon period are used to reckon radiative forcing at the upper atmosphere and at the facet of the Indio- Gangetic region [21].

Aerosol radiation interaction greatly impacts the adscription of $PM_{2.5}$ air pollution changeability to emission variations and meteorology [22]. The diffuse part of global radiation related with the aerosols direct effect, which is precluding clouds effect, increases with the increase of aerosol loading [23]. During past decades, rapid boost of air pollution was noticed in China, giving rise to tremendously high value of aerosol radiative forcing, about ten times large in comparison to the global means [24]. Whether aerosols are functioning as CCN or IN or commonly modifying the stability of the atmosphere due to the absorption of solar radiation, yet there is large uncertainty related to their impacts on the lifetime of cloud [25]. This study provides an overview of the present state of prevailing aerosols and their climatic effects. The findings may be used to create an aerosol climate map for the Kanpur region and encourage the researcher to carry on the monitoring of aerosol from various parts of the world. This work aimed to find the influence of aerosols on the sun rays arriving on the surface and aerosol radiative forcing' during 2001 to 2015 over Kanpur.

2 Study Area

The aerosol radiative forcing at the surface, atmosphere and top of atmosphere has been computed with the help of radiation model based on AERONET (Aerosol Robotic Network) aerosol retrievals. The AERONET is a comprehensive remote sensing aerosol network using application of ground based observations obtained from the device called CIMEL sun photometer. Under this world-wide network, the data has been obtained from CIMEL sun photometer situated at Kanpur (26.51ºN, 80.23ºE; 123m amsl; period:2001-2015) under AERONET programme (Source: http://aeronet.gsfc.nasa.gov).

AERONET site Kanpur is located on the basin of Indo-Gangetic plain which is considered as an urban industrialized region [26]. Thus this region is the main source of anthropogenic aerosols which introduce a significant impact for the spectral and seasonal variations of aerosol forcing. ARFI network programme is doing tremendous job in the field of aerosol study

3 Methodology

AERONET radiative transfer approach has been used to find aerosol radiative forcing. Radiative transfer means the process in which energy transmission takes place as electromagnetic waves. The transmission of sun rays in the atmosphere is influenced by absorption, emission as well as scattering mechanisms. In present study, the evaluations of clear-sky direct aerosol radiative forcing (ARF) has been executed by applying transfer module which is desegregated into operational AERONET inversion code. This module uses several characteristics of columnar aerosols recovered by AERONET. The important characteristics are complex refractive index, aerosol optical depth, phase function, aerosol size distribution, single scattering albedo and a small amount of spherical particles.

It is a four stream plane in the form of delta in parallel with broadband radiative transfer code. In the region of shortwave having range from 0.2-4.0 μm with over 200 size sub-intervals, the ARF clear-sky calculations depends on Discrete Ordinate Radiative Transfer (DISORT) module [27]. The, extinction coefficient, phase function and single scattering albedo are computed with the help of obtained size distribution corresponding to every one size sub-intervals after a same process as in the case of AERONET collection scheme. The spectral complex refractive index ($\mu(\lambda)$ and k(λ)) are extrapolated and interpolated linearly with respect to the values $\mu(\lambda)$ and k(λ) obtained at the AERONET wavelengths. The same process is used to find the values of surface reflection. Radiative fluxes are calculated by taking into account a plane-parallel atmosphere in an angular range of solar zenith angles i.e., 50º-80º. It is considered that the solar geometry conditions in this range are most suitable for retrieving the properties of aerosol. The correlated k-distribution method is applied to treat the absorption of non-gray gaseous caused by H_2O, CO_2, O_3, N_2O, and CH_4 [28–30].

Global Atmospheric Model (GAME) code is utilized to obtain the desegregation of absorption as well as scattering of atmospheric aerosol, molecular scattering by molecules, absorption by gas and impacts of surface reflection. The correlated k-distribution permits to consider the interactions between absorption by the gas and multiple scattering with possible calculated time. The correlated k-distribution coefficients are assessed from reference calculations with the help of line by line code [31]. The model considers a spectral absorption of ozone within the wavelength ranging from 0.2-0.35 μm (ultra violet spectrum) and 0.5-0.7 μm (visible spectrum) whereas the water vapour gives rise to spectral absorption of ozone with range of wavelength from 0.8-3 μm (infrared spectrum). The code incorporates the amount of total ozone obtained from total ozone mapping Spectrometer (TOMS) measurements. AERONET GAME code applies a constant spectral resolution of value 100 cm^{-1} within range 2500 to 17700 cm^{-1} (4 to 0.6 μm) and also 400 cm^{-1} within range 17700 cm^{-1} to 50000 cm^{-1} (0.6 to 0.2 μm). The more detailed approach is also given in various literatures [28,32,33].

The radiative properties of aerosol can also be obtained from OPAC (Optical Properties of Aerosol and Clouds) model [34]. The results taken from this model contain shortwave direct, diffuse, and total irradiance of shortwave at the atmospheric top, earth's surface and also in every atmospheric layer. The influence of aerosols on surface radiative flux is called as surface (SFC) radiative forcing whereas on the top of the atmosphere radiative flux, it is called radiative force at the top of atmosphere (TOA). The net fluxes difference with and without aerosol at the TOA and at the SFC results in aerosol radiation forcing at TOA and SFC respectively [35].

The equation for Aerosol radiative forcing at TOA and SFC is given by,

$$ARF_{TOA,\,SFC} = \frac{\int_0^{24}\left[Flux\,(net)_{with\,aerosol\ \ TOA,\,SFC} - Flux\,(net)_{without\ \ aerosol\ \ TOA,\,SFC}\right] dh}{\int_0^{24} dh}$$

The expression for the change in aerosol radiative forcing (ΔF) is,

$$\Delta \mathrm{F}_{\mathrm{TOA},\,SFC} = \mathrm{flux}\left(\mathrm{F}^{\downarrow} - \mathrm{F}^{\uparrow}\right)_{\mathrm{with\ \ aerosol\ \ TOA,SFC}} - \mathrm{flux}\left(\mathrm{F}^{\downarrow} - \mathrm{F}^{\uparrow}\right)_{\mathrm{without\ \ aerosol\ \ TOA,SFC}}$$

where $F^{\downarrow}$ represents downward flux whereas $F^{\uparrow}$ upward flux.

The atmospheric forcing is given by,

$$ARF_{ATM} = ARF_{TOA} - ARF_{SFC}$$

The ΔF_{ATM} is the energy retained through the atmosphere by the aerosol presence and is used to obtain the influence of aerosols on climate taking into consideration hydrostatic equilibrium and the First Law of Thermodynamics [36]:

$$\frac{\partial T}{\partial t} = \frac{g_e}{C_p}\frac{\Delta ARF_{ATM}}{\Delta P}$$

where $\partial T/\partial t$ is the rate at which atmosphere is heated in K° per day, g_e is the acceleration value due to gravity of earth, C_p is the specific heat capacity at a constant value of pressure due to air = 1006 J kg^{-1} K^{-1} and ΔARF_{ATM} represents the atmospheric forcing. ΔP represents the atmospheric pressure difference (300 hPa) which corresponds to difference in pressure between surface and 3 km height. A flow chart illustrating the entire AERONET scheme, incorporating inversion process with simulation of solar fluxes is shown in Figure 1.

Although ARF estimate gives the net radiative effect of aerosols present in atmosphere, but for a consistent distinction the aerosol radiative forcing efficiency is more suitable and is given by

$$\Delta\, F_{SFC,\,TOA}^{Eff} = \frac{\Delta\, F_{SFC,\,TOA}}{AOD_{500\,nm}}$$

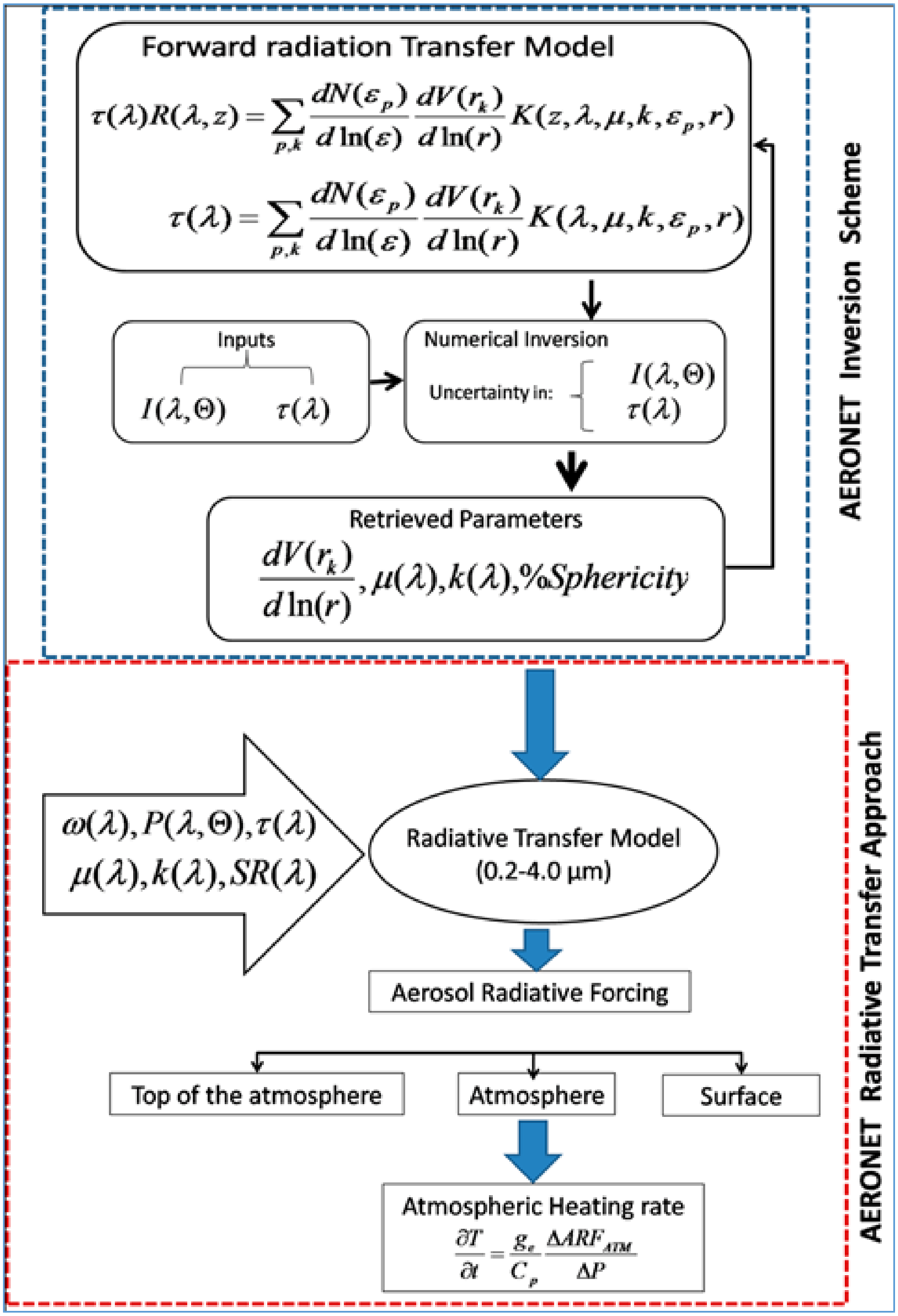

Fig 1. Flow chart describing the methodology adopted toestimate shortwave aerosol radiative forcing, using measured aerosol characteristics (aerosol optical depths, single scattering albedo, asymmetry factor, Phase function, size parameters, complex refractive index and others.

4 Result and Discussion

4.1 Seasonal variations in aerosol radiative forcing

The monthly average($\pm\sigma$) ARF during the entire observational period (2001-2015), at three levels i.e., surface (ARF_{SFC}), atmosphere (ARF_{ATM}) and the atmospheric top (ARF_{TOA}) are recorded as –89.6 $\pm$ 18.6 Wm^{-2}, +64.4 $\pm$ 16.5 $Wm^{-2}$and –25.2 $\pm$ 6.8 Wm^{-2}respectively. The values of ARF changes–7 to –43 Wm^{-2},–41 to 138 $Wm^{-2}$and +24to +106 Wm^{-2}at the surface (SFC), top of the atmosphere (TOA)and atmosphere (ATM) respectively. Figure 2 shows the estimated values of seasonal variation in ARF at the TOA, SFC, and ATM.

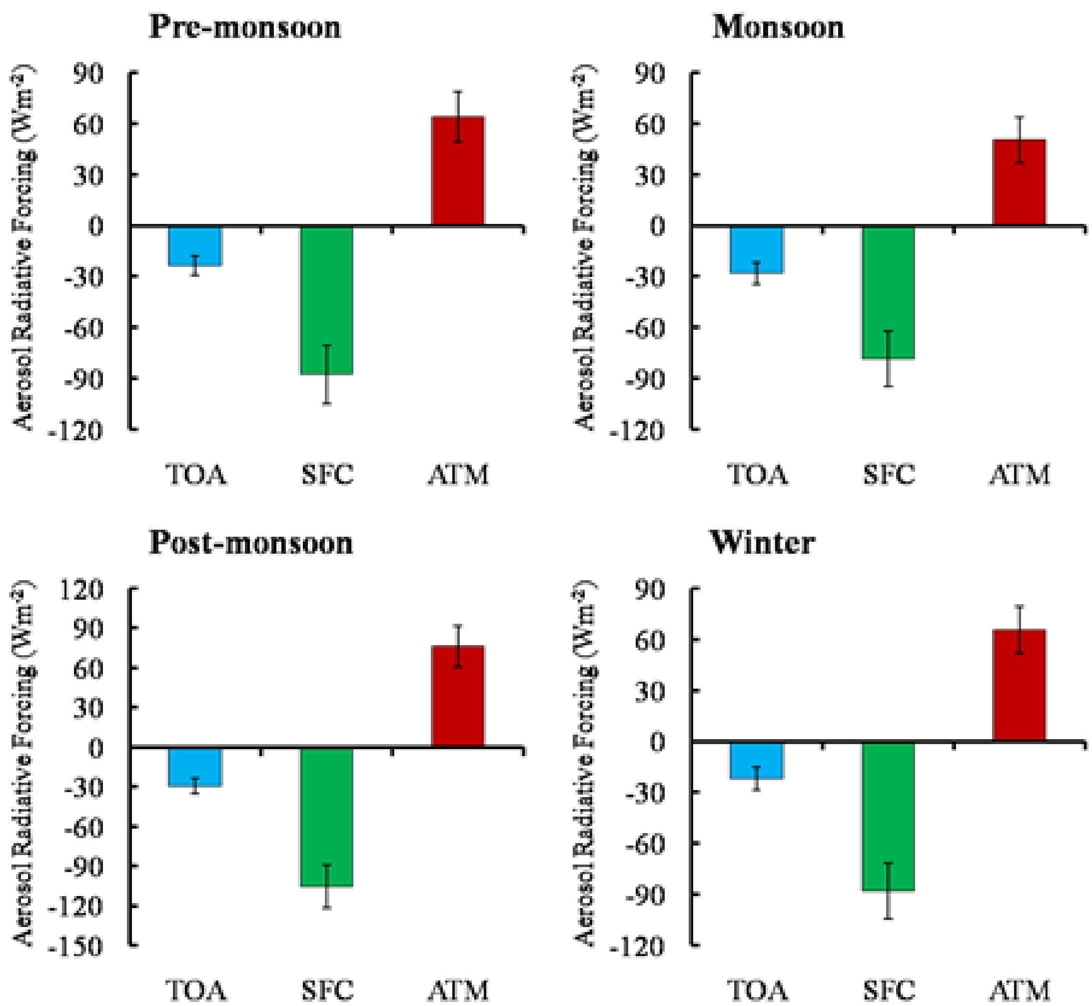

Fig 2. Seasonal variations of ARF for 15-years dataset(2001–2015) over Kanpur

The lowest value of ARF is found during monsoon period. The highest value of atmospheric forcing is found during the post-monsoon period which is due to the aerosols absorptive properties (SSA at 675 nm = 0.91). Monsoon is the period with the least absorptive aerosols while maximum value of SSA is observed. The aerosol forcing during the pre-monsoon is attributed to desert dust while in post-monsoon, it is due to polluted dust. We do not estimate large change in surface ARF in comparison with AOD since SSA is maximum (minimum)while AOD is maximum (minimum). Our study shows that large solar rays are attenuated for a given value of AOD. The AOD at 340 nm and 500 nm consistently increased with effect from pre-monsoon (March-May) to post-monsoon (October-November) with values 41% and 33% respectively because mostly the weather remains raining and cloudy in this period and effects the measurements [37].

4.2 Spectral variation in monthly average aerosol radiative forcing

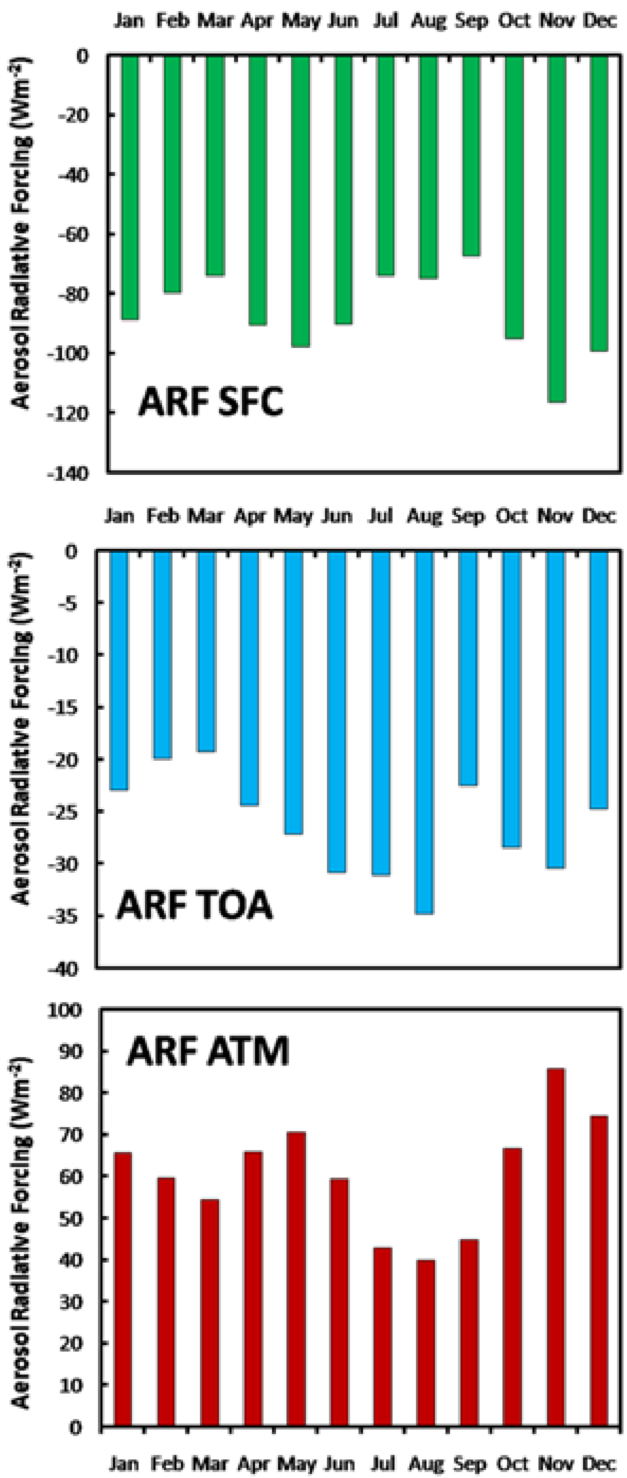

Fig 3. Monthly average (period: 2001-2015) ARFestimated over Kanpur at surface (SFC),atmosphere (ATM) and at the top ofatmosphere (TOA).

The monthly mean ARF estimated during the period 2001-2015 over Kanpur is shown in Figure 3. During the months October to December, the surface ARF measurements are large in value. Contrary to this, the moderate values observed in the measurements of TOA forcing means that during this duration, the large attenuation in surface arriving solar radiation is mainly due to the presence of anthropogenic aerosols. The small values observed in the measurements of ARF at TOA imply the influence of absorbing aerosols present during the months of February and March. The large negative ARF values at TOA shows the influence of scattering aerosols that modifies the ARF from less negative value to more negative value, especially during the months from Jun to Aug. The simultaneous decrease in incoming solar rays leads to intensive solar heating as noted from the magnitudes of bars obtained for SFC and ATM forcing.

ISRO has conducted Aerosol Radiative Forcing programme over India (ARFI) for estimating radiative forcing in Vikram Sharabhai Space Centre Trivandrum. The researchers from different part of the country presented significant results during last two decades. The estimated values of ARF across the Bay of Bengal, at the SFC, ATM and TOA are found about −15 to −24 Wm^{-2}, +13 to +20 Wm^{-2} and −2 to −4 Wm^{-2} respectively[38].INDOEX (Indian Ocean experiment)[39]has conducted a study over the Indian Ocean to know the impacts of anthropogenic aerosols and found that anthropogenic aerosols attenuate the incoming solarray by an amount of–50 Wm^{-2}. The ARF values obtained from the Visakhapatnam ARFI network station[40], at the SFC, ATM and TOA are found to about −16.33 Wm^{-2}, +20.19 Wm^{-2} and+3.86 Wm^{-2} respectively. Pandithurai et al., 2004[41] recorded outcomes over Pune urban region and found a significant attenuation in incident solar radiation by an amount of 33 Wm^{-2} with approximately zero value of forcing at the TOA.Srivastava et al., 2012 reported results with location having high altitude such as at Nainital[42] and found that the mean ARF at the ATM and SFC estimated to about +14 $Wm^{-2}$and −14 Wm^{-2} respectively having approximately zero forcing at the TOA. Dibrugarh is a rural area, the ARF values reported at the SFC, TOA and ATM are found with values –29 Wm^{-2}, –0.9 and+28 Wm^{-2} respectively[43]. Results also reported from national capital Delhi, the ARF at the SFC, TOA and ATM recorded to about–77 Wm^{-2}, +3.3Wm^{-2} and +80.3Wm^{-2} respectively. In another study, the mean ARF at the SFC, TOA and ATM are recorded with values –67Wm^{-2}, 4 Wm^{-2} and +71Wm^{-2} respectively[44]. The seasonal ARF results over various Indian regions are presented in Table 1.

Table 1. Seasonal clear-sky ARF over India

Locations	Surface forcing (Wm−2)		Atmospheric forcing (Wm−2)		Reference
	Pre-monsoon	Winter	Pre-monsoon	Winter	
Kanpur (23.43°N/80.33°E)	-87.67	-87.98	63.99	65.76	Present study
Nagpur (21.1°N/79.3°E)	-38.1	-37.3	5.3	24.3	Sarkar et al., 2006
Trivandrum (8.55°N/77.0°E)	-18.7	-16.0	12.0	15.4	Sarkar et al., 2006
Varanasi (25.3°N/82.9°E)	-46.4	-29.5	3.2	14.8	Sarkar et al., 2006
Kanpur (23.43°N/80.33°E)	-71.0	-44.4	38.3	39.8	Sarkar et al., 2006
Kolkata (22.5°N/88.4°E)	-56.3	-42.6	23.5	28.1	Sarkar et al., 2006
Visakhapatnam (17.7°N/83.8°E)	-16.8	-35.8	20.8	44.2	Sreekanth et al., 2007
Dibrugarh (27.3°N/94.6°E)	-37.1	-34.2	35.7	33.2	Pathak et al., 2010
Ahmadabad (23.03°N/72.55°E)	-41.4	-54.0	48.0	28.0	Ganguly & Jayaraman, 2006

4.3 Aerosol radiative forcing efficiency

It is the rate of forcing the atmosphere per unit AOD at wavelength at 500 nm. In present study, the radiative forcing efficiency (ΔF^{Eff}) of aerosols at TOA and SFC has been analyzed by taking into account AERONET radiative transfer model. The forcing efficiency is much responsive to aerosol-solar interaction particularly for absorbing aerosols and greatly responded to the aerosol optical model. Therefore, radiative forcing efficiency is a good approach to distinguish the kinds of aerosols as it has greatly influenced by absorbing and scattering nature of particles. Moreover, it may also greatly have influenced by SSA and surface albedo. The low SSA means more absorbing types of aerosols where a large value of aerosol radiative efficiency forcing has been observed as shown in Figure 4 (a). On the other hand, aerosol shows a lower efficiency per unit of AOD increase at 500 nm at the TOA as shown in Figure 4(b).

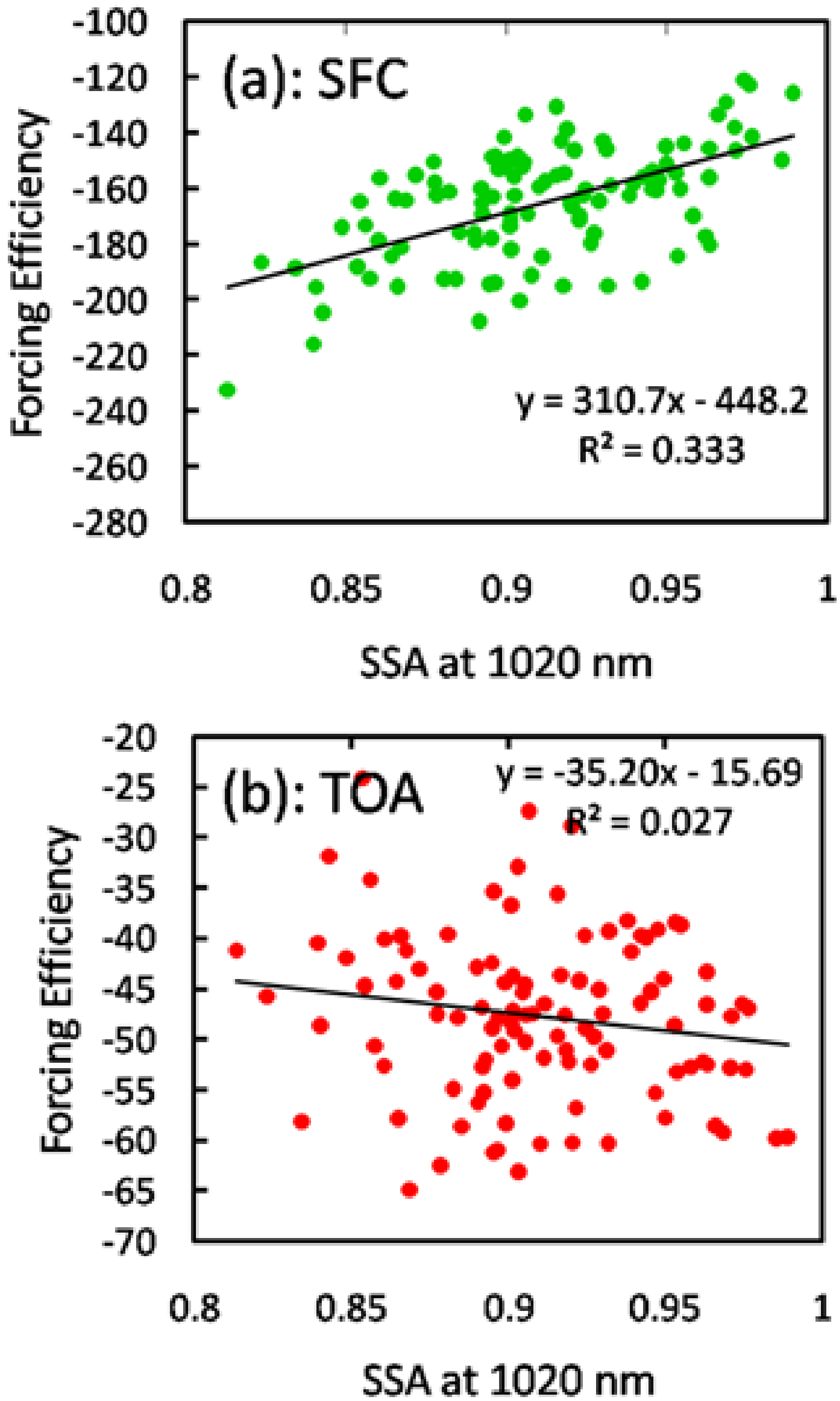

Fig 4. Aerosol radiative forcing efficiency ($Wm^{-2}AOD^{-1}$) of daily average response to SSA at 1020 nm

This indicates that absorption process of aerosol has reduced a significant fraction of energy as that energy is back scattered towards the space and thus responsible to maintain the large percentage of sun energy in the atmosphere. The average monthly values of aerosol radiative forcing efficiency of daily average are -165±26 Wm^{-2} AOD^{-1} and -47±10 Wm^{-2} AOD^{-1} at the SFC and TOA respectively. This indicates a significant effect of aerosol-solar absorption at surface thereby give rise to more cooling. There is a loss in solar rays arriving at the surface because of the scattering of radiation back towards the space which gives rise to cooling of climate system [45]. The small TOA forcing efficiency associated with the high surface forcing indicates a strong absorption due to high aerosol loading as shown in Figure 5 . It is found that there is an increase in backscattered energy towards TOA when SSA increases. The aerosols of absorbing nature are found very powerful at the SFC in comparison to at the TOA, where they scatter little energy back into the atmosphere. These characteristics are examined after Figure 4.

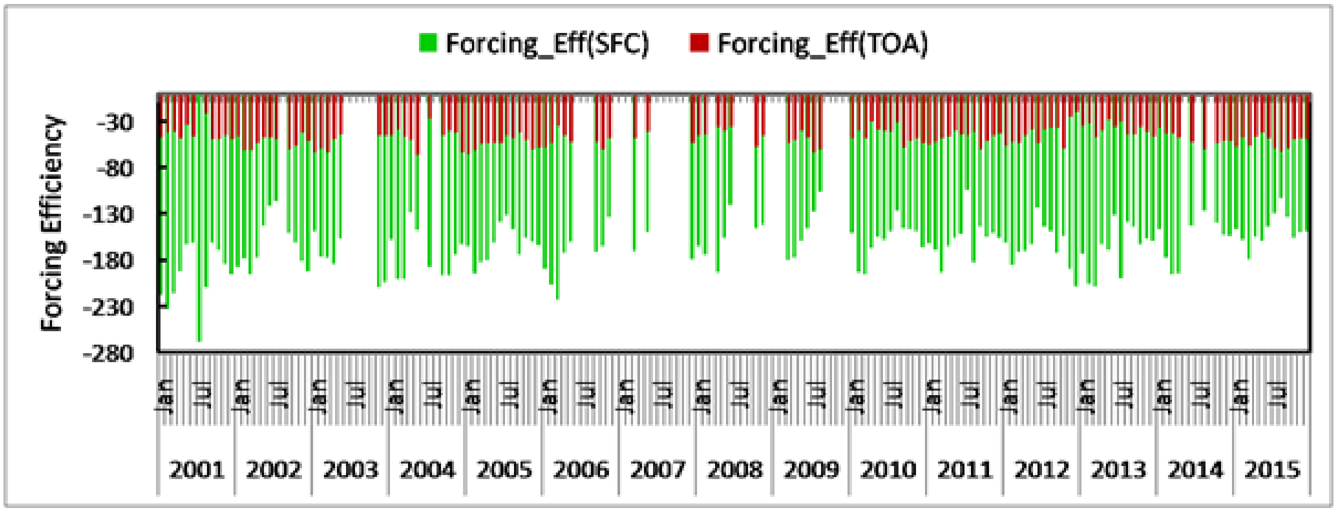

Fig 5. Monthly variation in aerosol radiative forcing efficiency (Wm^{-2} AOD^{-1}) of daily average at surface (SFC) and top of the atmosphere (TOA)

5 Conclusions

AERONET radiative transfer approach is used to find aerosol radiative forcing. This study investigated the seasonal and spectral variations of ARF along with aerosol radiative frequency with special reference to Kanpur region (IGP) by using AERONET data for the period 2001 -2015. The main concluding points of this study are:

1. The seasonal variation of ARF implies that the values of top of atmosphere ARF have been found more negative during monsoon and post-monsoon seasons while less negative during pre-monsoon and winter seasons. The seasonal largest atmospheric ARF estimated during post-monsoon while the smallest during monsoon. During monsoon to post-monsoon period, a quick variation in seasonal shift in ARF has been observed. The value of surface ARF in post-monsoon period occurred approximately 1.3 times greater than monsoon period.
2. Spectral variation in monthly average ARF implies that large values of surface ARF and moderate values of top of atmosphere ARF have been found during the months of October to December. Small values of top of atmosphere ARF have been observed during the months February and March which indicates a large fraction of absorbing types of aerosols present in the atmosphere. Large negative values of top of atmosphere ARF have been found during the months of June to August which indicates a significant fraction of scattering types of aerosols present in the atmosphere.
3. It is concluded that the values of ARF over IGP, northwestern and northeastern parts of India during pre-monsoon period are higher in comparison to other seasons because here the particles of large size are dominant with significant proportion of desert dust. In winter, the ARF values are found higher over the coastal regions of eastern and southern parts of India because of the predominance of large amount of anthropogenic aerosols. In post-monsoon period, the ARF values are higher over western India because of the dominance nature of continental aerosols present there along with a considerable proportion of anthropogenic aerosols. This implies that in eastern and northern parts of India, there is attenuation in surface arriving solar rays due to desert dust in significant amount. On the other hand, in southern and western parts of India, the more attenuation in surface arriving sun ray is because of anthropogenic aerosols present in considerable amount.

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