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Recent trend in the global distribution of aerosol direct radiative forcing from satellite measurements

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Abstract

Global distribution of aerosol direct radiative forcing (DRF) is estimated using Clouds and Earth's Radiant Energy System (CERES) synoptic (SYN) 1° datasets. During 2001–2017, a statistically significant change of global DRFs is revealed with a general decreasing trend (i.e., a reduced cooling effect) at the top of the atmosphere (DRF_{TOA} ~ 0.017 $W{\cdot}m^{-2}{\cdot}year^{-1}$) and at the surface ($DRF_{SFC}$ ~ 0.033 $W{\cdot}m^{-2}{\cdot}year^{-1}$) with rapid change over the land compared to the global ocean. South Asia and Africa/Middle East regions depict significant increasing trend of atmospheric warming by 0.025 and 0.002 $W{\cdot}m^{-2}{\cdot}year^{-1}$ whereas, the rest of the regions show a decline. These regional variations significantly modulate the global mean DRF (-5.36 ± 0.04 $W{\cdot}m^{-2}$ at the TOA and -9.64 ± 0.07 $W{\cdot}m^{-2}$ at the surface during the study period). The observed DRF trends are coincident with the change in the underlying aerosol properties, for example, aerosol optical depth, Ångström exponent and partly due to the increasing columnar burden of SO_2 over some of the regions. This indicates that increasing industrialization and urbanization have caused prominent change in the DRF during recent decades.

KEYWORDS

aerosol optical depth, angstrom exponent, global aerosol radiative forcing, trend

1 | INTRODUCTION

Assessing global distribution of aerosol direct radiative forcing (DRF) and their long-term trends are vital to improve the state of understanding about the significance of aerosol climate forcing as well as the effectiveness of emission control policies (IPCC, 2013; Zhao *et al.*, 2017; Yang *et al.*, 2018; Aas *et al.*, 2019). Study of aerosol radiation interactions are also essential for understanding the changes of the photolysis rates which influences other (viz., O_3, NO_2, SO_2) air pollutants (e.g., Li *et al.*, 2014; Xing *et al.*, 2015. In this regard, extensive measurements and radiative transfer simulations are used to estimate DRFs. However, the global estimation of DRFs has always been challenging especially due to inhomogeneity in both land surface and aerosol properties, posing most uncertain component for the estimation of cumulative radiative forcing (IPCC, 2013; Myhre *et al.*, 2013; Murphy and Ravishankara, 2018). These uncertainties result from the uncertainty in (a) mixing state (including size and density) of aerosols (Seinfeld and Pandis, 2006; Kahn and Gaitley, 2015; Samset *et al.*, 2018), (b) vertical profile of

aerosols (Chung *et al.*, 2005), (c) consideration of inaccurate aerosol species contributing to the total forcing in the models (Forster *et al.*, 2007; Murphy, 2013; Myhre *et al.*, 2013; Stevens, 2015; Paulot *et al.*, 2018), their subsequent feedback to climate systems (Stocker *et al.*, 2013); in addition to measurement errors and errors in models itself (IPCC, 2013). Lack of appropriate quantification of anthropogenic fraction of aerosol composites is also accountable to the large fraction of total uncertainty (Su *et al.*, 2018; Myhre *et al.*, 2013). For example, best estimated radiative forcing for the change in the net aerosol radiation interaction between 1,750 and 2005 is associated with a large uncertainty range of −0.85 to +0.15 $W{\cdot}m^{-2}$ for the corresponding mean value of −0.35 $W{\cdot}m^{-2}$ (IPCC, 2013).

To reduce the uncertainties in radiative forcing estimation, numerous studies have been made employing the combinations of radiative transfer simulations (e.g., Penner *et al.*, 1994), models (Hansen *et al.*, 1997; Li *et al.*, 2014; Paulot *et al.*, 2018), in-situ measurements (Putaud *et al.*, 2014) and remote sensing observations (Loeb and Kato, 2002; Zhang *et al.*, 2005). In recent years, the global observations of the solar radiation (Christopher and Zhang, 2004; Contreras *et al.*, 2017) and aerosols (Kahn et al., 2005; Remer *et al.*, 2005, 2008; Levy *et al.*, 2009; Moorthy *et al.*, 2013; Babu *et al.*, 2013; Kahn and Gaitley, 2015; Zhao *et al.*, 2017) from space have been used for the accurate estimation of the radiative forcing (Christopher and Zhang, 2004; Bellouin *et al.*, 2005; Patadia *et al.*, 2008; Kahn, 2012). Using the Moderate Resolution Imaging Spectroradiometer (MODIS) and Clouds and the Earth's Radiant Energy System (CERES) data sets, Patadia *et al.* (2008) have found the global clear sky DRF over the land to be -5.1 ± 1.1 $W{\cdot}m^{-2}$. Similarly, Loeb and Kato (2002) used the collocated Visible Infrared Scanner (VIRS) and CERES data to estimate SW DRFs over the tropical oceans (−0.46 $W{\cdot}m^{-2}$). Zhang *et al.* (2005) used CERES and MODIS AODs and estimated SW-DRF over global ocean as -5.3 ± 1.7 $W{\cdot}m^{-2}$ (2000–2001).

The global average aerosol forcing due to both natural and anthropogenic aerosols was found to be −4.3 $W{\cdot}m^{-2}$ at the top of the atmosphere (TOA), + 5.5 $W{\cdot}m^{-2}$ in the atmosphere (ATM) and − 9.7 $W{\cdot}m^{-2}$ at the surface (SFC) (2001–2009, Chung, 2012). Paulot *et al.* (2018) have reported an increase in the DRFs over Western Europe and eastern America by 0.7–1 and 0.9–1.4 $W{\cdot}m^{-2}$ $decade^{-1}$ and decrease over India by −1 to −1.6 $W{\cdot}m^{-2}$ $decade^{-1}$ during the period 2001–2015. This is in line with the fact that even though concentration of aerosols is seen to be decreasing in eastern America, central South America, Europe and northeast of Oceania, it is increasing in the rest of the world (Mao *et al.*, 2014). Regionally, increase in aerosol burden and changes in their emission pattern is mostly attributed to anthropogenic activities (Dey and Girolamo, 2011; Babu *et al.*, 2013; Moorthy *et al.*, 2013; Kahn and Gaitley, 2015; Nair *et al.*, 2016; Srivastava, 2017; Zhao *et al.*, 2017). This is modulated further by the prevalent changes in meteorological parameters effectively enhancing the aerosol concentrations in the atmosphere (Yang *et al.*, 2016). Thus, the change in DRFs is highly dependent on the aerosol types in addition to columnar abundance. For example, black carbon (BC) imparts larger positive effect (Bond et al., 2013; Zarzycki and Bond, 2010; Chung, 2012; Gogoi *et al.*, 2017). Similarly, SO_4 and OC cause larger negative effect (Collins *et al.*, 2002; Myhre *et al.*, 2013; Paulot *et al.*, 2018). Hence, trend analysis of DRFs itself is vital to estimate the change in radiative impact of aerosols. However, the global estimation of DRFs at different levels of the atmosphere that is, SFC, ATM and TOA is complex.

In the present study, the global distribution of DRFs and trends are uniquely studied using Clouds and Earth's Radiant Energy System (CERES; Wielicki *et al.*, 1996) Synoptic (SYN) climate quality daily data sets. CERES_SYN1deg solar and longwave downwelling surface fluxes were evaluated against measurements at 85 land and ocean sites around the globe over the period from March 2000 to December 2007, revealing a monthly mean bias of 2.2 $W{\cdot}m^{-2}$ (1.1%) for the shortwave and −4.1 $W{\cdot}m^{-2}$ (−1.2%) for the longwave irradiances (Rutan *et al.*, 2015). Moreover, CERES Science Team has applied the table of scaling factors for both Terra and Aqua to the observed TOA SW fluxes for the tuning of the computed fluxes. Thus, the synoptic data quality used in the present study is highly accurate and estimation of DRF over both regional and global scale at distinct atmospheric levels (i.e., SFC, ATM and TOA) adheres to improved estimation due to applications of updated CERES data sets. Based on this, the estimation of DRF and its trend in distinct geographical regions of the globe are themselves unique. The methodology adopted in the present study also serves as a primary proxy to accurately estimate global change in DRFs which is otherwise difficult to obtain from the limited in-situ measurements and high-computation modeling. Another important aspect in the present study is the long-term data base (2002–2017) chosen to examine the regional changes in aerosol loading in recent years over different parts of the globe. Thus, the estimation of DRF trends in the global scale in our study gives insight in to the identification of regional impact of aerosols on the Earth's energy budget associating distinct regional changes (increase/decrease).

2 | DATA AND METHODOLOGY

Daily global radiation data (CERES_SYN1deg-Day_Terra-Aqua-MODIS_Ed3A; Doelling *et al.*, 2013) measured by

CERES operating on-board Terra and Aqua satellite have been used to estimate the clear sky DRF at the TOA, ATM and SFC. The surface net radiations are estimated using the radiative transfer model with the atmospheric and surface properties obtained from MODIS, 3-hr geostationary (GEO) data and meteorological assimilation data from Goddard Earth Observation System (GEOS), while constraining both solar reflected and earth-emitted radiation for the TOA for all-sky and clear-sky conditions. Here, the radiative transfer calculation is made using the NASA Langley Research Center-Modified (LaRC) Fu-Liou radiative transfer model (Fu and Liou, 1993; Randles *et al.*, 2013; Rose *et al.*, 2013). The model is based on Fu-Liou scheme (Fu and Liou, 1992, 1993). This code is a modified version of the original Fu-Liou code to improve treatment of Rayleigh scattering and updated shortwave (SW) and longwave (LW) gaseous absorption (Kato *et al.*, 1999; Kratz and Rose, 1999). These computations use MODIS and geostationary cloud properties along with the atmospheric profiles of pressure, specific humidity and air temperature provided by NASA Global Modeling and Assimilation Office (GMAO; Reichle *et al.*, 2009) reanalyzes as inputs. Furthermore, the absorption by water vapor, carbon dioxide, methane and oxygen are treated using the methodology followed by Kato *et al.* (1999). The computations are constrained by the observed CERES TOA fluxes (Rutan *et al.*, 2015; Wang et al., 2017). The model is further constrained by the aerosol optical depth and scattering properties for the vertical column from the Model for Atmospheric Transport and Chemistry (MATCH; Gidhagen *et al.*, 2005). The MATCH simulated aerosol properties are constrained by the observations from MODIS (Collins *et al.*, 2001; Levy et al., 2013). The four modes of fluxes are used: pristine (clear, no-aerosols) and clear sky (clear, with aerosols) conditions at SFC and TOA. Here, 'clear' indicates 'cloud free aerosol skies'. The aerosol forcing at TOA (DRF_{TOA}) and surface (DRF_{SFC}) is estimated by differencing net clear sky from net pristine sky fluxes and in the atmosphere (DRF_{ATM}) by subtracting the two DRFs as follows:

$$DRF_{TOA,SFC} = (F\downarrow\uparrow_{clear})_{TOA,SFC} - (F\downarrow\uparrow_{pristine})_{TOA,SFC} \quad (1)$$

$$DRF_{ATM} = DRF_{TOA} - DRF_{SFC} \quad (2)$$

Using long-term values of DRF at TOA, ATM and SFC, trends have been estimated. The Mann–Kendall test (Kendall, 1975, Li *et al.*, 2014; Mann, 1945) has been used to identify significance of the changes at the 95% confidence level.

The MODIS on-board Terra and Aqua satellites provides aerosol retrievals over both land and ocean that are suitable for studying regional distribution of aerosol sources and trends. In this study, MODIS derived Aerosol optical depth (AOD, τ_λ), and Angstrom exponent (α) are used to understand aerosol loading and information on aerosol size distribution in the atmosphere. While AOD is the integrated extinction coefficient over columns of unit cross section measured at a particular wavelength (λ), values of given information on aerosol size distribution in the atmosphere. Following Angstrom (1929), α is estimated as:

$$\alpha = \frac{\log\frac{\tau_{\lambda1}}{\tau_{\lambda2}}}{\log\frac{\lambda2}{\lambda1}} \quad (3)$$

where, $\tau_{\lambda1}$ and $\tau_{\lambda2}$ are AOD at wavelength λ_1 and λ_2, respectively.

α is inversely related with the particle size, that is, $\alpha \leq 1$ indicates size distribution dominated by coarse mode aerosols and $\alpha \geq 1$ by fine mode aerosols.

In addition, present study uses columnar SO_2 retrieved from OMI onboard Aqua satellite (Fioletov *et al.*, 2013; Krotkov *et al.*, 2016) for the period 2004–2017. OMI is the result of a partnership between NASA and the Dutch and Finnish meteorological institutes and space agencies flying on the NASA EOS Aura satellite (Levelt *et al.*, 2006; Schoeberl *et al.*, 2006). The OMI SO_2 product uses spectral measurements between 310.5 and 340.0 nm in the UV-2 (Li *et al.*, 2013).

3 | RESULTS AND DISCUSSIONS

3.1 | Global distribution of aerosol DRF

The global distribution of aerosol DRF shows (Figure 1) highly heterogeneous properties, having significant region-specific temporal change in absolute magnitude from 2001 to 2017. The global average DRF_{TOA} and DRF_{SFC} during the observational period (2001–2017) are -5.36 ± 0.04 W·m^{-2} and -9.64 ± 0.07 W·m^{-2}, respectively, along with an atmospheric warming of 4.27 ± 0.04 W·m^{-2}. Magnitudes of temporal changes in DRFs are found to be higher over most of the continental hotspots of the Northern Hemisphere, where the source of strong aerosol emission exists. Average (during 2001–2017) DRF_{TOA}/DRF_{SFC} over the land alone is -5.72 ± 0.04 W·m^{-2}/-13.71 ± 0.11 W·m^{-2} which translates to atmospheric warming of 7.99 ± 0.07 W·m^{-2}. During 2001, average values of the global DRF_{TOA} and DRF_{SFC} over land are -5.93 and -13.8 W·m^{-2}, resulting to atmospheric warming of 7.87 W·m^{-2}. This is close to that reported earlier by Patadia *et al.* (2008), where, the

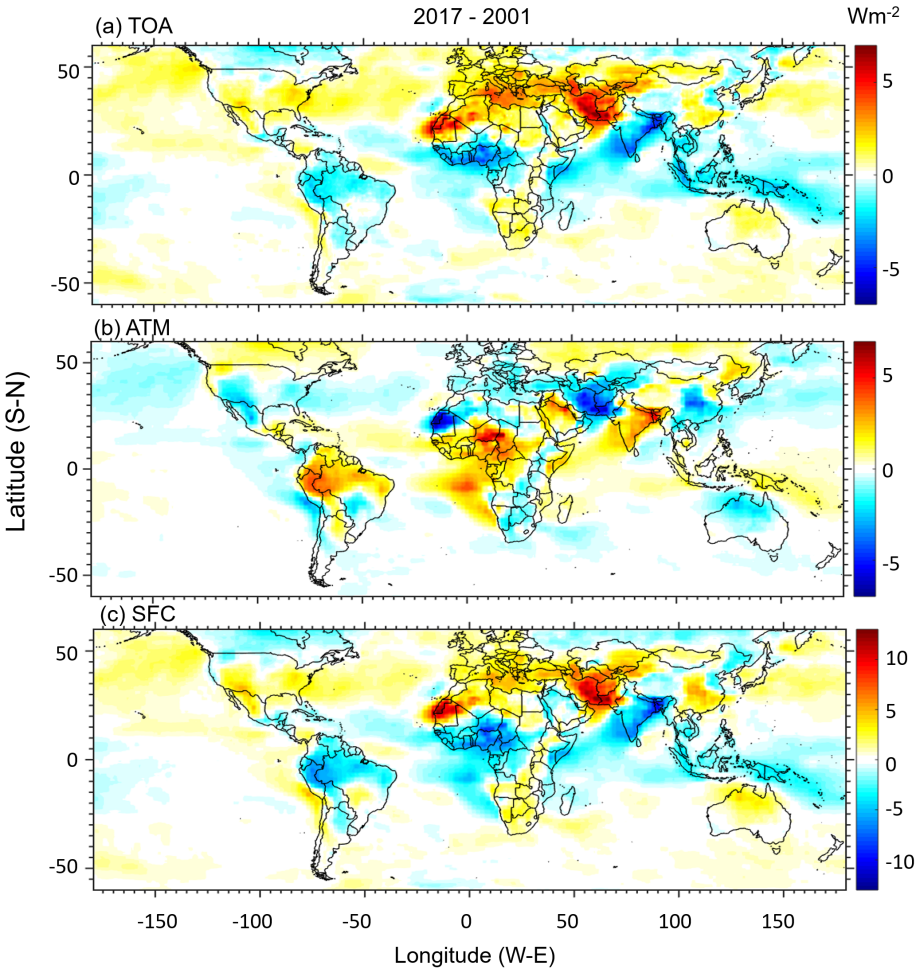

FIGURE 1 The difference in aerosol direct radiative forcing between 2017 and 2001 at the top of the atmosphere (a, TOA), in the atmosphere (b, ATM) and at the surface (c, SFC) as obtained from CERES synoptic (SYN) 1° datasets over the globe. Global distribution of aerosol direct radiative forcing during the respective years of 2001 and 2017 are shown in Figure S1

DRF_{TOA} was found to be -5.1 W·m^{-2} (2000–2001) over the land. Compared to 2001, global land DRF_{TOA} is altered by ~3.6% in 2017, where, the magnitudes of DRF_{TOA}, DRF_{SFC} and DRF_{ATM} reach -5.72, $-$ 13.77 and 8.05 W·m^{-2} during the later year. It is interesting to note that the geographic regions of Africa, south and east Asia consistently show higher values of DRFs during both the years: 2001 and 2017 (Figure S1). Collins *et al.* (2002) have reported that the surface insolation (under cloud free skies) over the Indian sub-continent is reduced by 40 W·m^{-2} during spring (1999) due to the impact of natural and anthropogenic aerosols, accompanied by warming (25 W·m^{-2}) in the atmosphere. In the present study, the values of DRF_{ATM} over the highly polluted Indo-Gangetic Plains (IGP) is as high as ~30 W·m^{-2} during 2017, along with a reduction in the surface reaching flux by about 45 W·m^{-2}. East China shows higher surface dimming in the beginning of the study period which reduces during the later years. DRF_{TOA} over Africa is comparatively low (~−12 W·m^{-2}) during both the years, but the DRF_{SFC} and DRF_{ATM} extend to -40 and 30 W·m^{-2}, respectively. Rest of the land area experiences much lower values of DRF.

On the other hand, oceanic regions exhibit lower perturbation of the solar radiation due to lower aerosol loading, inferring an average value of 2.99 ± 0.04 W·m^{-2} in the atmosphere associated with the cooling at the TOA by -5.24 ± 0.04 W·m^{-2} and surface dimming of -8.23 ± 0.07 W·m^{-2} (averaged from 2001 to 2017). Values of DRFs are higher near the west coast of Africa and east coast of Asia, similar to that reported by Zhang *et al.* (2005) where DRF (-5.3 W·m^{-2}) was estimated over cloud-free global oceans using the collocated MODIS and CERES data for the period November 2000–August 2001. Oceanic DRF_{TOA}, DRF_{ATM} and DRF_{SFC} (-5.25, 2.94 and $-$ 8.19 W·m^{-2}, respectively) in 2001 was changed by 1.9, 1.4 and 1.7% (-5.15, 2.90 and $-$ 8.05 W·m^{-2}), respectively in 2017. These changes are much lower compared to that of the land. Anthropogenic aerosols are found to contribute significantly on the total aerosol loading over the oceanic region predominantly over the regions where the values of DRFs are found higher (Boucher and Haywood, 2001; Bellouin *et al.*, 2005; Li *et al.*, 2014). Strong dust plumes originating from Asia reaches northern Pacific Ocean and west coast of North America. These regions exhibit annual DRF_{SFC} of ~ $-$ 14 W·m^{-2} and DRF_{ATM} of

~8 W·m^{-2} during 2001 (similar to Zhang *et al.*, 2005). Fire activities are persistent near the west and east coast of South America resulting to atmospheric forcing of ~12 W·m^{-2}. The aerosol forcing has a strong seasonal and regional dependence which are addressed in various studies in the past (Hatzianastassiou *et al.*, 2004; Quaas *et al.*, 2008; Randles and Ramaswamy, 2008; Pathak *et al.*, 2016; Nair *et al.*, 2016; Paulot *et al.*, 2018; Subba *et al.*, 2018; Yang *et al.*, 2018) and is not the primary focus of this study.

3.2 | Trends in global aerosol direct radiative forcing

The above results clearly indicate that in recent years, there has been potential change of the radiative balance of the atmosphere due to the impact of aerosols. Considering 2001 as base year, the DRF_{TOA}, DRF_{ATM} and DRF_{SFC} trend over the globe are found to be 0.02, −0.02, and 0.03 W·m^{-2}·year^{-1}, respectively (Figure 2). The global land area exhibits rapid change of atmospheric forcing by −0.03 W·m^{-2}·year^{-1} associated with an increase in DRF_{TOA} and DRF_{SFC} by 0.02 and 0.05 W·m^{-2}·year^{-1}. However, oceanic region shows relatively weaker change in the DRF trend which is consistent with the comparatively lower change in the underlying oceanic surface and aerosol loading over majority of oceanic region. General trend in atmospheric forcing and surface dimming over oceanic regions is −0.01 and 0.03 W·m^{-2}·year^{-1}, respectively, almost half of the values over land regions.

Over land regions, trend of DRF_{TOA} are decreasing mostly over eastern and western of Africa, and south Asia, as against slightly increasing trend seen over North America and Europe (Figure 3). There cannot be one to one correlation between the radiative effect and the aerosols over every region. Especially over India, east and central China, South America, Africa due to the heterogeneity in the aerosol type (Paulot *et al.*, 2018). Anthropogenic emissions over India and China are expected to be more uncertain than those over America and Europe (Pan *et al.*, 2015; Saikawa *et al.*, 2017). For example, India has been experiencing changes in surface albedo due to underlying surface properties (Paulot *et al.*, 2018). Increase in rainfall and decrease in dust emissions (Pandey *et al.*, 2017) have caused more greening over the north-western regions (Jin and Wang, 2018). The decrease in surface albedo over India masks the effect of the increasing anthropogenic emissions on the outgoing radiation (Paulot *et al.*, 2018). This can change the signs of TOA forcing (Satheesh, 2002).

Since, aerosol forcing is dependent on the regional heterogeneity of land surface and aerosol loading, we have selected six distinct regions (R1-R6; R1- North-East America,

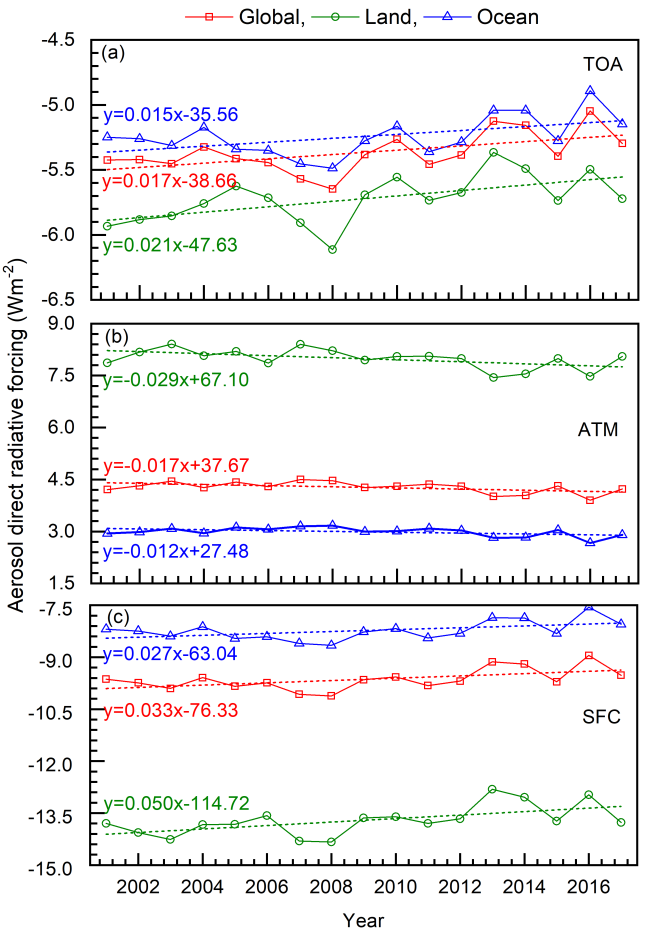

FIGURE 2 The trend in clear-sky shortwave aerosol direct radiative forcing (a) at the top of the atmosphere (TOA), (b) in the atmosphere (ATM) and (c) at the surface (SFC), averaged over the entire globe, global land and oceanic regions

R2- South America, R3-Europe, R4-Africa and Middle East countries, R5-south Asia and R6- eastern China) having significant trends and greater influence in overall DRFs. The trend of DRFs over each of these regions reveals substantial changes (Figure 3, Table 1). These changes are much greater than that of the global averaged changes, indicating the heterogeneous spread of aerosols. Trend over R2 and R4 are least (DRF_{TOA} < 0.012 W·m^{-2} ·year^{-1}), while showing weak increasing trends over R1, R3 and R6 (0.074, 0.114 and 0.038 W·m^{-2} ·year^{-1}). However, DRF trend over R5 is unique indicating decreasing trend of TOA cooling (−0.076 W·m^{-2} ·year^{-1}) and increasing trend of ATM warming (0.025 W·m^{-2} ·year^{-1}). These changes can be attributed to change in both mass loading and type of aerosols over these regions. Decreasing trend of cooling at TOA is attributed to increase in the fraction of absorbing AOD and decrease in aerosol single scattering albedo, respectively. Growth in the small sized particles, mostly of anthropogenic origin enhancing the cooling at the TOA. These properties are discussed in the following section.

3.3 | Regional variability of DRF

The long-term change in DRFs indicate that there has been profound change in aerosol burden across the globe in recent decades. We find potential enhancement of atmospheric warming (>0.04 $W \cdot m^{-2} \cdot year^{-1}$) over central, eastern IGP and southern India, southern and central part of Africa and Middle East countries and their adjacent water bodies. Rest of the globe shows the opposite. To understand the behavior of aerosols, we have investigated the spatio-temporal distributions of aerosol optical depth (AOD) and Ångström exponent (α) obtained from MODIS onboard Terra and Aqua satellites. Since the change in the DRFs in the recent decade is mostly attributed to the anthropogenic emissions, we have also studied the change in columnar SO_2 retrieved from OMI onboard Aqua satellite (Fioletov *et al.*, 2013; Krotkov *et al.*, 2016). Although SO_2 is just one of the precursor gases of the sulfate aerosol and not always the representative of the anthropogenic aerosols, we have examined its global distribution and trends to understand the widespread emissions by fossil fuel combustion, which is a major source of anthropogenic aerosols. We see that there have been significant positive trends of AOD over the continental regions, such as central and eastern parts of the IGP (R5), Middle East countries and the central part of Africa (R4), along with their adjacent water bodies such as the Arabian Sea, the northern Bay-of-Bengal and the east coast of Africa (Figure 4a). Whereas, continental regions such as eastern parts of the United States, South America, European countries, eastern China and their adjacent water bodies show negative trends in AOD (−0.01 to −0.04 AOD $\cdot year^{-1}$). In line with this, the values of α (a qualitative indicator of the size of aerosol particles following the inverse relationship [Angstrom, 1929]; higher values indicate fine mode particles and vice versa) also exhibits significant changes over the period 2003–2017; especially over eastern China, India, Europe, the Middle East countries and Africa (Figure 4b).

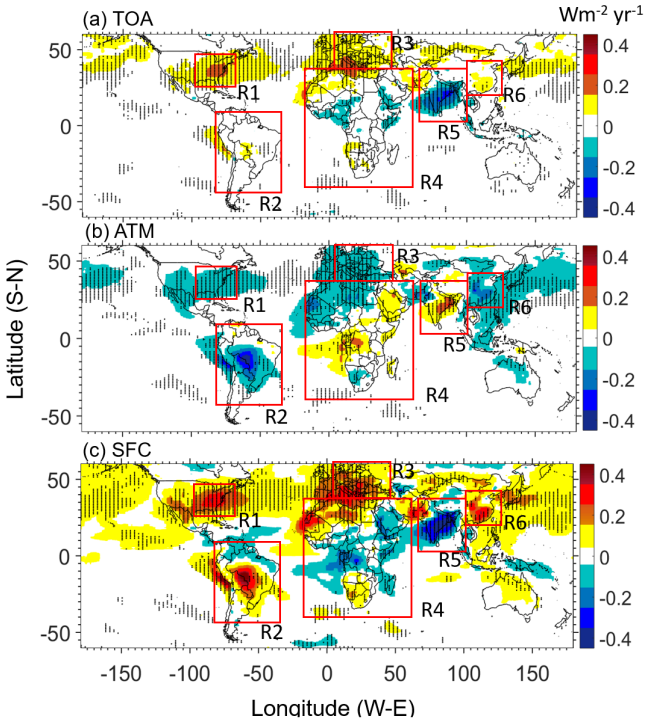

FIGURE 3 The global distribution of trend in clear-sky shortwave aerosol direct radiative forcing (a) at the top of the atmosphere (TOA), (b) in the atmosphere (ATM) and (c) at the surface (SFC). The red boxes represent distinct geographic regions denoted by R1-R6. Dotted areas are regions having significant trend above the 95% confidence level

TABLE 1 The values of DRFs at top of the atmosphere (TOA), surface (SFC) and in the atmosphere (ATM) in 2001, 2017 and their respective trends during the period 2001–2017 over the globe, land, ocean, region R1–R6

	DRF in 2001 ($W \cdot m^{-2}$)			DRF in 2017 ($W \cdot m^{-2}$)			DRF trend ($W \cdot m^{-2} \cdot year^{-1}$)		
Regions	**TOA**	**ATM**	**SFC**	**TOA**	**ATM**	**SFC**	**TOA**	**ATM**	**SFC**
GLOBE	−5.4	4.2	−9.6	−5.3	4.2	−9.5	0.017	−0.017	0.033
LAND	−5.9	7.9	−13.8	−5.7	8.1	−13.8	0.021	−0.029	0.050
OCEAN	−5.2	2.9	−8.2	−5.1	2.9	−8.0	0.015	−0.012	0.027
R1 (Northeast America)	−6.4	5.2	−11.6	−5.9	5.0	−10.9	0.074	−0.053	0.127
R2 (South America)	−4.7	6.8	−11.5	−5.2	7.4	−12.6	0.012	−0.065	0.077
R3 (Europe)	−8.7	7.5	−16.3	−7.0	7.1	−14.1	0.114	−0.076	0.191
R4 (Africa and Middle East countries)	−7.1	8.5	−15.6	−7.0	8.9	−15.9	0.001	0.002	−0.001
R5 (South Asia)	−9.7	9.7	−19.4	−10.7	10.4	−21.0	−0.076	0.025	−0.102
R6 (Eastern China)	−8.8	8.3	−17.2	−8.7	8.0	−16.7	0.038	−0.060	0.102

Note: The statistical significance of the trends is determined by the Mann–Kendall test.

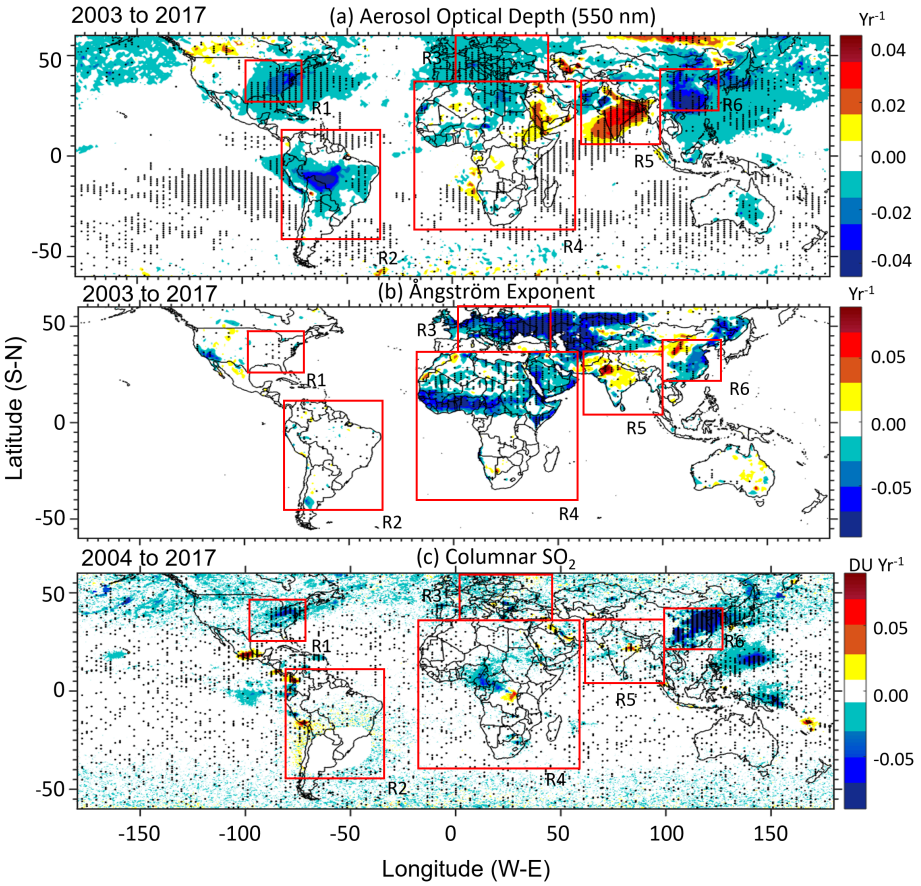

FIGURE 4 The trends of (a) aerosol optical depth (AOD) at 550 nm, (b) angstrom exponent and (c) columnar sulfur dioxide (SO_2). Dotted areas are the regions having significant trend above the 95% confidence level. The red box represents different regions R1–R6

This reveals that not only the amount of global aerosol loading has changed; simultaneously the physico-chemical properties of aerosols have also been changed. However, change in total columnar AOD is not just caused evenly by the change in the amounts of all types of aerosols, but is rather driven by the predominant contributors of the composite aerosols. This can be observed in terms of the change of α, which especially increase over the Indian subcontinent and central China. This is attributed to increasing anthropogenic activities in response to growing population and urbanization resulting in higher emission of small sized particles. Various studies in the past have shown that the aerosol loading over the Indian subcontinent is highly influenced by the anthropogenic aerosol loading/activities over the region (Babu *et al*., 2013; Moorthy *et al*., 2013; Srivastava et al., 2017; Pathak *et al*., 2016). SO_2 is one of the major precursors of the anthropogenic aerosols (Smith *et al*., 2011) and falls within the sub-micron range. Investigation of long-term SO_2 indicates that the increase in α coincides with the increase in SO_2 loadings (Figure 4c) over eastern IGP, whereas other parts of the Indian subcontinent (region R5) do not show similar variation of SO_2 and α. Similarly, the positive trend of SO_2 over the boundary of Peru and Chile (region R2) and central Africa (Republic of Congo; region R4) is not consistent with the collocated positive trend of α. In contrast, eastern China (R6) shows decline in aerosol loading and corresponding decline in columnar SO_2 (~0.08 DU ·year^{-1}). Recently, reported similar decline in SO_2 values (2004–2016). Similarly, a small region of Africa, middle east and south America (Figure 4c) show increase in SO_2, where α also shows an increasing trend. Thus, the increasing/decreasing trend of AOD (Figure 4a) seen over distinct regions of the globe can be attributed to various factors (e.g., varying source processes and transport pathways, etc.). Over the Indian region, very good association between the increasing trends of AOD and SO_2 over the eastern IGP indicates the growing role of anthropogenic activities over this region, while the rest of country experiences the influence of the aerosol loading which are driven by various other sources. These include the emissions from thermal power plants, industrial, residential, transportation and commercial divisions, constructional areas, livestock farming and fertilizer applications, biomass burning, wild forest fires, desert dust plumes, marine aerosols and biogenic emissions, etc. (IPCC, 2007; IPCC, 2013; Dey and Girolamo, 2011; Streets et al., 2013; Benedetti *et al*., 2014; Matthias *et al*., 2018). Among these, emissions of dust, sulfate and organic carbon enhancing their abundance in

the troposphere is significant (Fadnavis *et al*., 2019) in altering the incoming solar radiation. The western part of India, where dust is the primary contributor of aerosol loading, exhibits decreasing trend of DRF_{SFC} driven by decreasing trend of dust aerosols in the last decade (Pandey *et al*., 2017). Similarly, contributions of carbonaceous components to the long-term trend of DRF over the Indian region cannot be ignored. From the study of BC trend over the Indian region, Manoj *et al*. (2019) have indicated the presence of carbonaceous aerosols in the elevated lower free-tropospheric regions, even though a general decreasing trend of BC near the surface was revealed from the study.

In addition to distinct source processes, influence of regional climate variables (e.g., seasonal and regional rainfall) on the variability of aerosol loading is important. Babu *et al*. (2013) have shown that increasing trend in AOD over the IGP can be attributed to the competing effects of aerosol influx and reduced wet removal impact of aerosols. Thus, the sharp increase in atmospheric warming over the Indian sub-continent can be attributed to the complex interaction between natural and anthropogenic forcing at different spatio-temporal scales, modulated by regional climate variables.

Based on the above observations, increasing trend in TOA cooling can be synchronous with the change in anthropogenic aerosol loading, where the emission of SO_2 hold significance over eastern America, parts of Africa and eastern China and the adjoining oceanic region. Zhao *et al*. (2017) attributed the decreasing trend of DRFs over eastern United States and Europe to decrease in SO_2 and NO_x which are the precursors for the secondary aerosol formations, except for mineral dust and ammonia especially after 2011. Similarly, 25–50% of organic carbon (30% of PM) over US was found to decline between 1990 and 2012, with no significant change in biogenic aerosols (Ridley 2018; Blanchard *et al*., 2013, 2016; Attwood *et al*., 2014). This is attributed to decline in the anthropogenic emissions predominantly from vehicular and residential fuel burning related to series of control measurements under the Clean Air Act (Xing et al., 2013).

Interestingly, R1 exhibits increasing trend until 2007 (DRF_{ATM} trend: 0.13 $W{\cdot}m^{-2}$ $\cdot year^{-1}$) and a decreasing trend after 2007 (DRF_{ATM} trend: −0.15 $W{\cdot}m^{-2}$ $\cdot year^{-1}$). Similar bimodal trend was observed by Paulot *et al*. (2018) over the same region. Decrease in DRFs is indicative of the positive result of the implementation of various air pollution acts (Wang et al., 2014). However, it is important to note that though there has been decrease in DRFs over East China (Figure 2), their magnitudes in the recent years are still higher over some of the locations compared to the rest of the world (Figure 1 and Figure 2). Hence, continuous mitigation of air quality is still important.

4 | CONCLUSIONS

Present study demonstrates an extensive utilization of the combination of space-borne radiation flux measurements and radiative transfer modeling for improved quantitative estimation of global aerosol DRF trend over the period from 2001 to 2017. Since there exist noticeable discrepancies in the estimation of aerosol trends from various satellite retrievals (e.g., MODIS, MISR, OMI), most likely due to the difference in spatio-temporal sampling, observing strategy and retrieval algorithms (Kahn et al., 2009; Zhao et al., 2017), consideration of direct radiation measurements by satellite sensor is unique and suitable for global radiation budget studies. Thus, utilization of highly accurate synoptic (SYN) datasets from Clouds and Earth's Radiant Energy System (CERES) provides updated information on the global distribution of DRF trend, which is otherwise difficult to obtain from the limited in-situ measurements and high-computation modeling. The major outcomes of this study include:

1. In the recent decades, there have been substantial changes in the regional and global distribution of DRFs due to aerosols. The global (−60°S to 60°N) values indicate a decreasing trend of TOA forcing (i.e., a reduced cooling effect) by 0.017 $W{\cdot}m^{-2}$ $\cdot year^{-1}$, along with a decreasing trend of atmospheric forcing (i.e., a reduced warming effect) by −0.017 $W{\cdot}m^{-2}$ $\cdot year^{-1}$ having rapid change over the land (− 0.029 $W{\cdot}m^{-2}$ $\cdot year^{-1}$) compared to that over the ocean (−0.012 $W{\cdot}m^{-2}$ $\cdot year^{-1}$). While many distinct geographic regions (over land) of the globe depicted a general decreasing trend of the atmospheric forcing (warming) ranging from −0.053 $W{\cdot}m^{-2}$ $\cdot year^{-1}$ in North-east America to −0.076 $W{\cdot}m^{-2}$ $\cdot year^{-1}$ in Western Europe, Africa and South Asia showed increasing trend (i.e., an enhanced warming effect in the atmosphere) by 0.002 $W{\cdot}m^{-2}$ $\cdot year^{-1}$ and 0.025 $W{\cdot}m^{-2}$ $\cdot year^{-1}$ respectively.

2. Global map of AOD reveal significant positive trend over the continental regions, such as central and east Indo-Gangetic basins of India, Middle East countries and Africa, along with their adjacent water bodies such as Arabian Sea, North Bay of Bengal and east coast of Africa.

3. The global trend of DRF can be attributed largely to the anthropogenic aerosols. The increasing trend of SO_2 over eastern IGP, a small region of Africa, Middle East, and South America indicates increase in anthropogenic activities over these regions and may be a dominant factor in governing the DRF trend over these regions.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of this article.

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