Since January 2020 Elsevier has created a COVID-19 resource centre with free information in English and Mandarin on the novel coronavirus COVID-19. The COVID-19 resource centre is hosted on Elsevier Connect, the company's public news and information website.

Elsevier hereby grants permission to make all its COVID-19-related research that is available on the COVID-19 resource centre - including this research content - immediately available in PubMed Central and other publicly funded repositories, such as the WHO COVID database with rights for unrestricted research re-use and analyses in any form or by any means with acknowledgement of the original source. These permissions are granted for free by Elsevier for as long as the COVID-19 resource centre remains active.
Global and regional variations in aerosol loading during COVID-19 imposed lockdown

S.D. Sanap

Climate Research and Services, India Meteorological Department, Ministry of Earth Sciences, Shivajinagar, Pune, 411005, India

HIGHLIGHTS

- Global reduction in aerosol loading due to lockdown.
- High aerosol anomalies over Mexico and Amazon river basin.
- Positive Surface aerosol radiative forcing during lockdown.
- Wildfire emission contributed significantly to global aerosol burden during lockdown.

ARTICLE INFO

Keywords:
Aerosol optical depth
COVID-19
Lockdown
Aerosol radiative forcing
Wildfire
Regional variation

ABSTRACT

In the backdrop of upward trend in anthropogenic aerosols over global hotspot regions, the air quality had improved worldwide post declaration of the Corona virus disease-2019 (COVID-19) as a global pandemic in mid-March-2020. Present study using Moderate Resolution Imaging Spectroradiometer (MODIS) satellite derived aerosol optical depth (AOD) and the Modern-Era Retrospective analysis for Research and Applications (MERRA) version-2 datasets however, demonstrates the regional variation in aerosol loading during peak of the lockdown period. Reduction in aerosol loading over majority of the aerosol hotspots is observed from mid-March/April-2020 with highest percentage reduction in the month of May. Reduction in aerosol loading over global hotspots resulted in positive surface aerosol radiative forcing (ARF, up to 6 Wm$^{-2}$). Albeit reduction in aerosol loading observed worldwide, the considerable above normal aerosol burden was identified during April–May 2020 over the Amazon river basin, northern parts of the South America, Mexico region, South-West parts of the Africa and South East Asian region. Analysis revealed that the wildfire emission contributed significantly in anomalous aerosol burden over these regions during the lockdown period. An appropriate mitigation measures to reduce wildfire emissions is essential in addition to controlled anthropogenic emissions as far as air quality, deforestation and ecosystem is concerned.

1. Introduction

World Health Organisation (WHO) declared, Corona virus disease-2019 (COVID-19) as a global pandemic on 11th March 2020. The COVID-19 was first reported in Wuhan province of the China in December 2019. It was initially confined to China and has become the global pandemic by the end of February 2020. In order to restrict the mass transmission and to isolate the cases of the COVID-19, world governments had implemented the stringent measures mainly from mid-March-2020. Major population internment has resulted into reduction in functioning of the major industries, energy use, global and local air, road and rail traffic etc. Numerous studies have now started emerging in this direction and stressing on how global lockdown activity due to COVID-19 has improved the state of the Earth’s Atmosphere. Study by Le Quéré et al. (2020) demonstrated that daily global CO2 emissions decreased by 17% in early April 2020 as compared to its mean 2019 levels. Improved water quality due to lockdown is highlighted by Yunus et al. (2020) and Paital (2020). Substantial reduction in the pollutants like, NO$_2$, CO, PM2.5, PM10 and aerosol optical depths (AOD) at major COVID-19 hotspots is attributed to the imposed lockdown and controlled anthropogenic activities (Lal et al., 2020; Muhammad et al., 2020). Reduction in NO$_2$ levels up to 25% during lockdown period compared to historical records were reported by Berman and Ebisu (2020), Shi and Brasseur (2020) by utilising ground-based measurements, demonstrated that the...
levels of surface PM2.5 and NO2 have decreased by approximately 35% and 60%, respectively during 1st to 22nd January 2020 and the period 23rd January to 29th February 2020 over Northern China. Various studies have documented the significant reduction in aerosols and other pollutants over Indian region during lockdown period (Gautam, 2020; Jain and Sharma, 2020; Sharma et al., 2020; Mahato et al., 2020).

Atmospheric aerosols are the complex mixture of organic and inorganic substances in both liquid and solid form, and their size varies from few nm in diameter to greater than 100 μm. They have different shape, chemical composition and optical properties. Atmospheric aerosols have direct impact on earth’s radiation balance, fog formation, cloud microphysics, visibility degradation as well as on human health. Based on the satellite data and climate model simulations, global aerosol hot spots were identified by Ramanathan et al. (2007) viz. East Asia, Indo-Gangetic plains, Indonesian region, South Africa and Amazon basin in South America. Impact of aerosols on regional circulation and monsoon rainfall at different regions have been studied extensively (Sanap and Pandithurai, 2014; Sanap et al., 2015; Sanap and Pandithurai, 2015; Menon et al., 2002; Chung and Ramanathan. 2006; Sanap et al., 2014; Manoj et al., 2011; Ganguly et al., 2012 and many more). Level of Scientific understanding of the aerosols have improved from low to medium-high in fifth assessment report (AR-5) of the Intergovernmental Panel on Climate Change (IPCC). By considering the impact of atmospheric aerosols on regional climate, here we revisit the global aerosol hotspots and study impact of the COVID-19 imposed global lockdown on its spatio-temporal variation, causes and radiative forcing estimates using satellite observations and reanalysis data products. Numerous studies on reduction in air pollution due to COVID-19 imposed lockdown has been published in recent past. However, majority of them are city or country specific and emphasis is mainly on the reduction of the pollutants due to lockdown. In present study we discuss the regional as well as global variation in aerosol loadings due to COVID-19 imposed lockdown, its regional reduction (enhancement) and causes for its variability. Details of the dataset used and methodology adopted for carrying out the analysis is described in section 2. Major findings of the study are discussed in Section 3 followed by summary and conclusion in section 4.

2. Data and methodology

The MODIS instrument flies on the Earth Observation System’s (EOS) Terra and Aqua satellites. These are polar orbiting satellites, with Terra (aqua) on a descending (ascending) orbit over the equator. It is in orbit at 700 km above the surface, with a ±55° view scan, each MODIS scan views the Earth with a swath about 2330 km, implies it observes nearly the entire globe on daily basis. The Earth Atmospheric measurements are being taken in solar to thermal infrared spectrum region from 0.41 to 14.235 μm (Salomonson et al., 1989). Details of the instrumentation and components can be seen at http://modis.gsfc.nasa.gov. The daily and monthly mean of the Combined Dark Target and Deep Blue AOD at 0.55 μm for land and ocean is utilised at 1° x 1° resolution. MERRA-2 derived radiation flux products, dust and BC AOD at 0.5–0.625 spatial resolution are used. It utilises the Goddard Earth Observing System (GEOS-5) atmospheric general circulation model, wherein various satellite and ground based atmospheric observations are assimilated to generate the various products (Gelaro et al., 2017). Empirical orthogonal function (EOF, Lorenz, 1956; Bjornsson and Venegas, 1997) analysis is performed on the AOD data to identify the dominant modes in aerosol and their time evolution. It basically decomposes the multivariate data matrix into a set of independent orthogonal eigenvectors. Li et al. (2013) suggested that the EOF analysis can be utilised for identifying the aerosol sources and their variability. Time evolution of the anomalies in aerosol loading over different regions is based on the climatology for the period 2000–2020. Aerosol radiative forcing (ARF) estimates are calculated using the MERRA derived radiation variables (Pls see section 3.3). MERRA2 reanalysis aerosol products are widely used by climate researchers. MERRA2 reanalysis well compares with the satellite observed aerosol loadings (Buchard et al., 2017; Randles et al., 2017). Shi et al., 2019 demonstrated that MERRA-2 AOD dataset has a comparable accuracy (RMSE = 0.119, MBE = −0.008) with the satellite MODIS AOD datasets (RMSE = 0.110, MBE = 0.011). It further confirms that it has analogous spatial distributions with MODIS data and mentioned that it can capture the dynamical changes of AOD temporally. Monthly fire data is obtained from the National Aeronautics and Space Administration’s (NASA), Fire Information for Resource Management System (FIRMS) data portal. It provides the real time active fire data within 3 h
of the satellite observations at 500 m resolution from MODIS, Visible Infrared Imaging Radiometer Suite (VIIRS) and NOAA-20 satellites (Giglio et al., 2015). Monthly emissions and burned areas with small fires are obtained from Global Fire Emission Database (GFEDs) version 4 with spatial resolution of 0.25°. It provides the fractional contribution of the different fire types. In present study, the fractional contribution of the tropical forest fire and fire counts is exclusively used to identify relative contribution of fire emission in aerosol anomalies over the region.

3. Results

3.1. Global aerosol distribution and variability

The MODIS satellite derived global AOD climatology for the period
Fig. 4. Monthly aerosol optical depth (AOD) anomalies for (a) January (b) February and (c) March 2020.
2000–2020 is depicted in Fig. 1. The high aerosol loading regions are identified and marked with boxes. These includes, East Asia, Indo Gangetic plains (IGP), Middle-East region, North and South Africa. Type of aerosol emission (natural or anthropogenic) in these regions is dissimilar. For e.g Aerosol emission from Saharan region of the Africa, parts of Middle East and north-west Indian region is of natural type (wind-blown dust from desert), however majority of the regions from IGP, China and South Africa is mainly of anthropogenic in origin. The EOF analysis (Lorenz, 1956; Bjornsson and Venegas, 1997) is performed on the monthly mean anomalies of the AOD data for January–May (Fig. 2) to understand the global spatio-temporal variation of the aerosol loading. The EOF technique is helpful in identifying the dominant modes (spatial) of aerosols and its temporal variability (Li et al., 2013). As aerosols have diverse physical, optical and chemical characteristics, EOF method is convenient for isolating the dominant modes in aerosol loading over a region (Sanap and Pandithurai., 2014). The spatial pattern of the first two leading modes of EOF are presented in Fig. 2(a–b). Variance explained by EOF1 is 18.8% followed by EOF2 (10.4%). Spatial pattern of the EOF1 indicate the maximum loading is confined to NW Indian region, China, Europe, Parts of South America and United States of America (USA). These regions are highly dominated by the anthropogenic emissions. Therefore, EOF1 (Fig. 2a) may be attributed to aerosol emission due to anthropogenic activities. EOF2 pattern shows the high loading over West-Central part of the Africa, south of the Sahara Desert (Fig. 2b), Middle East region, which apparently suggest the region of natural source of aerosol emission (dust). Time evolution of the aerosol loading corresponding to EOF1 and EOF2 (principle component (PC) analysis) is shown in Fig. 3. It is interesting to note from the time series that the anthropogenic activities corresponding to the EOF1 show an upward trend (PC1). However, interannual variation indicated by PC2 show upward trend till 2012 and reduction thereafter. It might be due to the decadal variability of the dust emissions. However, in present study, it cannot be concluded with merely two decades of satellite observations.
3.2. Reduction in global aerosol loading due to COVID-19 pandemic

The COVID-19 was initially reported in Wuhan region of the China in December 2019. It rapidly spread all over the world and declared the world pandemic by WHO in March-2020. Economic activity has come to halt in many countries due to the government enforced lockdown to control the rapid spread of COVID-19. Most of the countries enforced the lockdown due to COVID-19 in second half of the March-2020. As the anthropogenic activities became limited, global as well as regional air quality improved significantly. Fig. 4(a–c) illustrate the global AOD anomalies for January, February and March months of year-2020. It is interesting to note from the analysis that the high positive AOD anomalies are confined to the Indian region, part of the SE Asia (Myanmar, Thailand, Laos, Vietnam and Cambodia), Australia and West Central African region. Positive AOD anomalies are also observed over the Southern hemispheric oceanic region and Australia. Positive AOD anomalies over Australian region in January-2020 is mainly due to the widespread forest fire over the region. Due to prevailing low level mid-latitude westerly winds over the region, transport of the forest fire induced aerosol emission up to central/southern parts of the west coast of the South America is clearly noticeable from the analysis (Fig. 4a and Fig. 5a). Due to initiation of lockdown in the beginning of year 2020, aerosol loading has reduced significantly over major parts of the China, in the backdrop of high aerosol loading over other global aerosol hotspots.

Reduction in aerosol loading is noted in the month of March compare to January and February over India and west-central Africa. However, parts of SE Asia, Amazon basin of the South America showed positive anomalies in AOD (Fig. 4c). Initiation of the lockdown by most of countries have resulted in significant reduction in aerosol loading over majority of the region in the month of April (Fig. 5a). On the other hand, parts of SE Asia, eastern part of the central Indian region, Northern region of the South America, some pockets of Africa, Mexico and adjoining regions shown anomalously higher positive AOD loading. Further reduction in aerosol loadings over majority of the global aerosol hotspots are observed in May-2020 (Fig. 5b). While world aerosol hotspots were indicating the reduction, the regions of SE Asia (Myanmar, Thailand, Laos, Vietnam and Cambodia), central Indian region, North-West African region, Mexico and parts of the Amazon river basin witnessed the positive anomalies in AOD.

Daily variation of the AOD averaged over different regions during January to May-2020 over various anomalously high aerosol regions is plotted in Figs. 6–8. The area averaged AOD for the period 01 January to 31 May 2020. Daily climatological variation is shown with black curve.

Fig. 6. Daily variation in the aerosol optical depth averaged over (a) North Indian region (68–92 E, 22–33 N) (b) China (103–125 E, 22–40 E) (c) South East Asia (98–110 E, 14–23 N) and (d) Middle East region (38–60 E, 13–32 N) for the period 01 January to 31 May 2020. Daily climatological variation is shown with black curve.

Fig. 7. Same as Fig. 6 but for the regions (a) North Africa (22 W–25 E, 5–25 N) (b) South Africa (3 W–27 E, 14 S–4 N) (c) South America (65–80 W, 0–12 N) and (d) Mexico and adjoining region (83–98 W, 12–28 N) for the period 01 January to 31 May 2020. Daily climatological variation is shown with black curve.

Reduction in aerosol loading is noted in the month of March as compare to January and February over India and west-central Africa. However, parts of SE Asia, Amazon basin of the South America showed positive anomalies in AOD (Fig. 4c). Initiation of the lockdown by most of countries have resulted in significant reduction in aerosol loading over majority of the region in the month of April (Fig. 5a). On the other hand, parts of SE Asia, eastern part of the central Indian region, Northern region of the South America, some pockets of Africa, Mexico and adjoining regions shown anomalously higher positive AOD loading. Further reduction in aerosol loadings over majority of the global aerosol hotspots are observed in May-2020 (Fig. 5b). While world aerosol hotspots were indicating the reduction, the regions of SE Asia (Myanmar, Thailand, Laos, Vietnam and Cambodia), central Indian region, North-West African region, Mexico and parts of the Amazon river basin witnessed the positive anomalies in AOD.

Daily variation of the AOD averaged over different regions during January to May-2020 over various anomalously high aerosol regions is plotted in Figs. 6–8. The area averaged AOD for different regions is shown with the boxes on the AOD climatology map in Fig. S1. Over Indian region, reduction in AOD loading is seen from mid-March-2020 over North Indian (Fig. 6a and South African region (Fig. 7b), first half of February over China (Fig. 6b), mid-April over SE Asia (Fig. 6c) and Middle East (Fig. 6d). It is very intriguing to note that higher than normal aerosol loading is observed over amazon river basin of the South America and Mexico region (Fig. 7c–d). Systematic increase (decrease)
in aerosol loadings over North African region (Sahara Desert) is also seen (Fig. 7a). It might be due the natural variation in the dust loading over the region due to seasonal (sub-seasonal) changes in meteorological conditions (discussed in details in sub section 3.3). Declaration of COVID-19 as a global pandemic by WHO in mid-march has reflected in the reduction of aerosol loading (Fig. 8) worldwide (except positive anomalies over some region as mentioned earlier).

The average month wise percentage reduction (increase) in aerosol loading over global aerosol hotspots is shown in Table 1. Reduction in aerosol loading seen in the anomaly maps and time series is reflected in calculated percentage changes. It is interesting to note that maximum reduction in aerosol loading is observed over China. Consistent more than 20% reduction in aerosol loading compared to its climatological value from February to May-2020 is observed. North Indian region, Middle East, North and South Africa and global aerosol loading indicate the reduction from the month of March/April with highest reduction over Indian region in April and May (−16% and −27%). It is quite contradictory to note that while whole world was experiencing the reduction in aerosol loading, Mexico and adjoining region indicated the higher than normal loadings of aerosols, especially during April-2020. However, there was reduction in aerosol loading over the region in February and March-2020. Similarly, in another case, parts of Amazon basin in South America shown reduction in aerosol loading in the beginning of year-2020 (Jan–Feb), however consistent greater than 25% enhancement in aerosol loading has been noted over the region. Consistent higher than normal aerosol loading was observed for the period January to April-2020 over south east Asian region.

3.3. Regional anomalies in AOD: role of wildfire and dust

We identified that the Northern parts of South America, Amazon river basin, Mexico and adjoining areas, parts of Africa and SE Asian region witnessed the high aerosol loading during April-May-2020. Here we attempt to understand the causes of these high loading using dust and black carbon (BC) AOD from MERRA reanalysis and wildfire information from FIRM and GFED4 datasets respectively. Dust aerosols are one of the largest sources of the natural aerosols. It mainly originated from the soil ablation in arid areas and released to higher altitudes due to atmospheric turbulence. They are also subjected to long range transport (Nicolae et al., 2019; Papayannis et al., 2008). Dust particles from Sahara and adjoining region of the Northern Africa responsible for more than 50% of the global mineral dust loadings (Salvador et al., 2016). Around 800 million tonnes of dust being transported from these regions every year (Querol et al., 2009). Studies have indicated that the transport is mainly during April–June months (Lamancusa and Wagstrom, 2019). Fig. 5 indicates the high aerosol loading over some pockets over North Africa during April and North Western region of the Africa in May. High AOD anomalies were also identified over parts of Taklamakan desert. In order to find the origin of this loadings, we plotted the MERRA reanalysis derived dust AOD for the month of the April and May (Pls see Fig. 9a–b). The analysis confirms that the regions of high AOD anomalies (Fig. 5a–b) and regions of dominant dust AOD over North African and Taklamakan desert region are co-located (Fig. 9a–b). Therefore, the anomalously high AOD over these regions during April–May is mainly from desert dust. Similarly, the region of the high AOD over SE Asian countries, central and South-West Africa, Mexico region, northern region of the south America and Amazon river basin are co-located with high BC AOD anomalies (Fig. 10a–b). Thus, it is understood from the analysis that high aerosol loading amidst of the COVID-19 imposed lockdown is mainly from the dust and BC.

Wildfires initiated generally by lightning or accidentally/intentionally by the people. These fires produce huge amounts of smoke pollutants, release greenhouse gases and degrade the ecosystem. Climatologically, the regions of the high BC anomalies during April-May-2020 are mainly from forest fire and agricultural emissions during boreal spring/summer. It is further verified by analysing the fire counts and contribution of the tropical forest fire in Fig. 11a–b. It is worth mentioning that the regions of high BC loading anomalies corroborates the regions of high fire counts. Hence, it is concluded that the fire emissions from these regions contributed significantly for high aerosol anomalies during lockdown period. Fig. 11 and Figs. S3 and S4 clearly demonstrates that hundreds of fires burning across Laos,

Table 1
The region wise averaged percentage changes in AOD concentration during January-May-2020 at various global aerosol hotspots. The change is with respect to MODIS satellite derived AOD climatology for the period 2002–2019.

| Month | China | N. Indian Region | SE Asia | Middle East | North Africa | South Africa | Amazon basin | Mexico | Global |
|-------|-------|------------------|---------|-------------|--------------|--------------|--------------|--------|--------|
| Jan   | −9%   | 29%              | 29%     | −6%         | 13%          | −2%          | −13%         | 5%     | 17%    |
| Feb   | −23%  | 23%              | 22%     | −7%         | 6%           | 19%          | 3%           | −5%    | 12%    |
| Mar   | −27%  | 4%               | 25%     | 1%          | −17%         | 2%           | 27%          | −15%   | 1%     |
| Apr   | −22%  | −16%             | 33%     | −12%        | −11%         | −10%         | 32%          | 47%    | −2%    |
| May   | −26%  | −27%             | −3%     | −16%        | −4%          | −4%          | 25%          | 1%     | −5%    |
Myanmar, Thailand, Cambodia and Vietnam amidst of the controlled human activities due to COVID-19 imposed lockdown. Also, fire counts and forest fire peaked in the month of April and May in SE Asian countries like Colombia, Venezuela, Mexico region and Yucatan peninsula originated either naturally or by human activity. Number of fire hotspots detected over south central African region is also very high during the same period. As discussed, the occurrence of dust storms is dominant during April–June over northern hemispheric deserts and mainly controlled by the atmospheric circulation anomalies. However, the wildfires can be triggered by natural or anthropogenic activities and it is highly difficult to identify its origin (natural or anthropogenic). Unlike dust outbreaks, wildfires can be controlled by appropriate mitigation measures.

3.4. Aerosol radiative forcing

The perturbations in the climatic system for a given region by considering only direct effects of the aerosols is referred as the aerosol direct radiative forcing (ARF). Radiative variables of the MERRA-2 reanalysis is used for the aerosol radiative forcing (ARF) calculations (Penna et al., 2018). Monthly average surface net shortwave flux assuming clear sky (SWGNTCLR), surface net shortwave flux assuming clear-sky and no aerosol (SWGNTCLRCLN), surface net longwave flux assuming clear sky (LWGNTCLR) and surface net longwave flux assuming clear-sky and no aerosol (LWGNTCLRCLN) are utilised for surface ARF estimates. The surface ARF is estimated using following equation:

$$\text{ARF}_{\text{SUR}} = (\text{SWGNTCLR}) - (\text{SWGNTCLRCLN}) + (\text{LWGNTCLR}) - (\text{LWGNTCLRCLN}).$$

Fig. 9. Dust aerosol optical depth (AOD) anomalies for the month of (a) April and (b) May 2020. The dust AOD data at 0.5x0.625 resolution is obtained from MERRA-2 reanalysis.
As discussed in earlier section, maximum reduction in aerosol loading is observed in the month of May (please see Figs. 4–8 and Table 1). Therefore, here we calculated the surface ARF for the month of May (please see Fig. 12a–b). Climatology of the ARF for the month of May and anomalies of ARF for May 2020 is depicted in Fig. 12. Climatology of the surface ARF clearly indicates the large cooling due to ARF over aerosol hotspot regions, implies the huge aerosol burden (please see Fig. 12a). Southern hemisphere oceanic regions indicate the positive forcing. It is mainly due to the fact that insignificant anthropogenic emissions over the region. Surface ARF anomalies for May-2020 indicate the positive surface aerosol radiative forcing over major hot spot regions such as India, China, Europe, Middle East, North East Africa and USA (Fig. 12b). However, negative aerosol radiative forcing is seen for Mexico and adjoining areas, parts of Indo-Pakistan region, Amazon basin region in S. America, SE Asian region, North West, Central and South Africa respectively. Surface ARF analysis corroborates with AOD anomaly distribution for the month of May-2020 as discussed earlier. This clearly implies enhancement in the incoming shortwave radiations at the surface in absence of the aerosols over majority of the global aerosol hotspot region in May-2020.

4. Summary and conclusion

Variation in aerosol loading over global aerosol hotspots is studied using MODIS satellite observed data and MERRA reanalysis dataset. Global aerosol hotspots are revisited and its variability is studied using EOF analysis. Analysis suggests an upward trend in the global as well as regional aerosol burden, mainly due to the increased anthropogenic activities in recent past. Due to emergence of the COVID-19 in the beginning of the year 2020, world governments have imposed the lockdown. Initiation of reduction in AOD is seen over China from the month of January itself in backdrop of high aerosol loading over other global aerosol hotspots. After announcement of the global pandemic by WHO in the month of March, regional aerosol hotspots also indicated the
reduction in aerosol loading. Reduction in aerosol loading over majority of the aerosol hotspots with varying concentration is observed from the mid-march 2020. It is interesting to notice that the considerable above normal aerosol loading is identified over the Amazon river basin, parts of South America, Mexico and adjoining region, southern part of the West central Africa and SE Asian region during peak months of the global lockdown. It is also observed that the consistent above normal aerosol loading over SE Asian region up to April-2020 and gradual decline in loading thereafter. Anomalously high dust loading over the north African region mainly due to the seasonal (sub-seasonal) changes in the meteorological conditions in occurrence of the dust episodes over the region (Fig. 9a–b). Time variation and monthly percentage contribution to reduction in aerosol is also corroborated. The surface ARF anomalies for the month of May-2020 is computed. Analysis indicates that positive surface aerosol radiative forcing over major hotspot regions. The surface ARF computation corroborates well with aerosol loading anomalies for the month of May-2020. It is intriguing to note from the analysis that even though anthropogenic emission was controlled by COVID-19 imposed lockdown, high aerosol loading over the regions of Amazon basin, Mexico and parts South central Africa witnessed the occurrence of the wildfire events, which contributed significantly to the global aerosol burden during lockdown. Wildfires are mainly originated by natural or anthropogenic activities and it is highly uncertain to identify its source. However, unlike dust outbreaks, wildfires can be controlled/reduced by appropriate mitigation measures.

**CRediT authorship contribution statement**

S.D. Sanap: conceived the idea, performed the computations.

**Declaration of competing interest**

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence...
SDS is thankful to Dr. M. Mohapatra, Director General of Meteorology, India Meteorological Department, Ministry of Earth Sciences for providing the infra-structure facility, guidance, encouragement and support. The data obtained from MODIS, MERRA-2, FIRM and GFED4 reanalysis is also duly acknowledged. Author thank the two anonymous reviewers for careful reading and their insightful comments and suggestions.

**Acknowledgements**

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.atmosenv.2020.118132.

**References**

Berman, J.D., Ebisu, K., 2020. Changes in US air pollution during the COVID-19 pandemic. Sci. Total Environ. 739, 139864.

Bjornsson, H., Venegas, S.A., 1997. A manual for EOF and SVD analysis of climate data. McGill University. In: CCGCR Report No. 97-1. Montréal, Quebec, p. 52.

Buchard, V., Randel, C.A., Da Silva, A.M., Darmenov, A., Colarco, P.R., Govindaraju, R., Ferrare, R., Hair, J., Beyersdorf, A.J., Ziemba, L.D., Yu, H., 2017. The MERRA-2
aerosol reanalysis, 1980 onward. Part II: evaluation and case studies. J. Clim. 30
(17), 6851–6872.
Chung, C.E., Ramanathan, V., 2006. Weakening of North Indian SST gradients and
the monsoon rainfall in India and the Sahel. J. Clim. 19 (10), 2036–2045.
Ganguly, D., Rusch, P.J., Wang, H., Yoon, J.H., 2012. Fast and slow responses of
the South Asian monsoon system to anthropogenic aerosols. Geophys. Res. Lett.
39 (18), 2012.
Gautam, S., 2020. The influence of COVID-19 on air quality in India: a boon or inutile.
Environ. Contam. Toxicol. 1.
Gelaro, R., McCarty, W., Suárez, M.J., Todling, R., Molod, A., Takacs, L., Randles, C.A.,
Draper, C., Akella, S., Verkaart, R., Cniolkoski, P., Gu, W., Kim, G.K., Koster,
Lucchesi, R., Mullen, D., Nault, E., Parchy, G., Pawson, S., Putman, W., Rinecker,
Schubert, S.D., Sienkiewicz, M., Zhao, B., 2017. The modern-era retrospective analysis
for research and applications, version 2 (MERRA-2). J. Clim. 30, 5419–5454.
https://doi.org/10.1175/JCLI-D-16-0758.1.
Giglio, L., Schroeder, W., Hall, J.V., Justice, C.O., 2015. MODIS Collection 6 Active Fire
Product User’s Guide Revision A. Department of Geographical Sciences.
University of Maryland.
Jain, S., Sharma, T., 2020. Social and travel lockdown impact considering coronavirus
disease (COVID-19) on air quality in megacities of India: present benefits, future
challenges and way forward. Aerosol and Air Quality Research 20, 1222–1236.
Lal, P., Kumar, A., Kumar, S., Kumari, S., Saikia, P., Dayanand, A., Adhikari, D.,
Khan, M.I., 2020. The dark cloud with a silver lining: assessing the impact of the
SARS-COVID-19 pandemic on the global environment. Sci. Total Environ.,
139297.
Lamancusa, C., Wagstrom, K., 2019. Global transport of dust emitted from different
regions of the Sahara. Atmos. Environ. 214, 1–12.
Le Quéré, C., Jackson, R.B., Jones, M.W., Smith, A.J., Abernethy, S., Andrew, R.M.,
De-Gol, A.J., Willis, D.R., Shan, Y., Canadell, J.G., Friedlingstein, P., 2020. Temporary
reduction in daily global CO 2 emissions during the COVID-19 forced confinement.
Nat. Clim. Change 1–7.
Li, J., Carlton, B.E., Licas, A.A., 2013. Application of spectral analysis techniques in the
inter-comparison of aerosol data: 1. An EOF approach to analyse the spatial-
temporal variability of aerosol optical depth using multiple remote sensing data sets.
J. Geophys. Res.: Atmosphere 118 (15), 8640–8648.
Lorenz, E.N., 1956. Empirical Orthogonal Functions and Statistical Weather Prediction.
Cambridge, MA, p. 49.
Mahato, S., Pal, S., Ghosh, R.G., 2020. Effect of lockdown amid COVID-19 pandemic on
air quality of the megacity Delhi, India. Sci. Total Environ., 139086.
Manoj, M.G., Devara, P.C.S., Saiha, P.D., Goswami, B.N., 2011. Absorbing aerosols
facilitate transition of Indian monsoon breaks to active spells. Clim. Dynam. 37
(11–12), 2181–2198.
Menon, S., Hansen, J., Nazarenko, L., Luo, Y., 2002. Climate effects of black carbon
aerosols in China and India. Science 297 (5590), 2250–2253.
Muhammad, S., Long, X., Salaman, M., 2020. COVID-19 pandemic and environmental
pollution: a blessing in disguise? Sci. Total Environ., 138269.
Nicolae, V., Talian, C., Andrei, S., Antonescu, B., Ene, D., Nicolae, D., Dandoczi, A.,
Toader, V.-E., tefan, S., Savu, T., et al., 2019. Multityear typology of long-range
transported aerosols over Europe. Atmosphere 10, 462.