Beyond the lockdowns: satellite observations of aerosol optical depth through 2020, the first year of the COVID-19 pandemic

Sarah Elise Smith, Mingfang Ting, Yutian Wu and Cheng Zheng

Lamont-Doherty Earth Observatory, Columbia University, New York, NY, United States of America

* Author to whom any correspondence should be addressed.
E-mail: sarahs@ldeo.columbia.edu

Keywords: COVID-19, satellite observations, AOD, emissions

Supplementary material for this article is available online

Abstract

Anticipated future reductions in aerosol emissions are expected to accelerate warming and substantially change precipitation characteristics. Therefore, it is vital to identify the existing patterns and possible future pathways of anthropogenic aerosol reductions. The COVID-19 pandemic prompted abrupt, global declines in transportation and industrial activities, providing opportunities to study the aerosol effects of pandemic-driven emissions changes. Here, measurements of aerosol optical depth (AOD) from two satellite instruments were used to characterize aerosol burdens throughout 2020 in four Northern Hemisphere source regions (Eastern & Central China, the United States, India, and Europe). In most regions, record-low measures of AOD persisted beyond the earliest ‘lockdown’ periods of the pandemic. Record-low values were most concentrated during the boreal spring and summer months, when 56% to 72% of sampled months showed record-low AOD values for their respective regions. However, in India and Eastern & Central China, the COVID-19 AOD signature was eclipsed by sources of natural variability (dust) and a multi-year trend, respectively. In the United States and Europe, a likely COVID-19 signal peaks in the summer of 2020, contributing as much as −.01 to −.03 AOD units to observed anomalies.

1. Introduction

Current estimates suggest that atmospheric aerosols contributed a global net radiative surface forcing of −.71 to −.14 W m⁻² in 2005–2015 (Bellouin et al 2020). Efforts to reduce greenhouse gases (GHGs) are expected to result in fewer co-emitted aerosols, improving air quality but depleting the aerosol-offset to GHG-driven warming (Philipona et al 2009, Szopa et al 2021). As short-lived species, atmospheric aerosols are expected to decline more rapidly than long-lived GHGs, unmasking additional near-term warming even as emissions of long-lived forcers decline (Szopa et al 2021). Aerosol radiative effects depend on spatially varying characteristics such as deposition rates, surface albedo, and aerosol composition. The precise impact of anticipated aerosol reductions therefore depends on complex and regionally inhomogeneous interactions between aerosols and hydrological cycles, atmospheric circulation, and geochemical cycles—interactions that can directly impact human livelihoods in addition to their effects on the radiative balance. While laboratory and modeling studies continue to constrain some of the uncertainties related to aerosol reductions, real-world observations provide crucial validation of model results, yet are rarely possible when considering anticipated future scenarios.

The COVID-19 pandemic prompted global reductions in transportation and industrial activities, providing an unprecedented opportunity to study the effects of aerosol reductions in multiple source regions. Thus far, studies of COVID-19-related aerosol reductions have largely focused on the highly-restrictive ‘lockdown’ periods that characterized the early months of the pandemic (e.g. Chen et al 2020, Forster et al 2020, Sharma et al 2020). To our knowledge, all observations of the COVID-19 effect on aerosol burdens consider only the first half of 2020, despite economic disruptions persisting through at least the remainder of that year (e.g. Chowdhury et al 2021, Onyeaka et al 2021). In many Northern Hemisphere
(NH) source regions, climatological values of aerosol optical depth (AOD), a column-integrated measure of aerosol burdens, characteristically peak in mid- to late-summer, making observations during these months essential for quantifying the aerosol-mediated effect of the pandemic on the global climate (e.g. Huang et al 2013, Mehta et al 2016).

Studies of lockdown-related changes in aerosol burdens have included bottom-up estimates of emissions reductions, in situ observations of PM$_{2.5}$, and satellite measures of AOD (e.g. Koo et al 2020, Le Quéré et al 2020, Sharma et al 2020, Venter et al 2020). Emissions estimates from Forster et al (2020) found $\sim20\%$ global reductions in sulfur dioxide ($\text{SO}_2$), a precursor to the highly reflective aerosol sulfate, during the early months of the pandemic. These estimates were used to develop scenarios for a model intercomparison project (Covid-MIP) designed to assess the climate impacts of the COVID-19 lockdowns (Lamboll et al 2021; see also D’Souza et al 2021, Fiedler et al 2021). In situ records during the pandemic are largely restricted to surface-level observations in relatively populated localities. Such studies are of particular interest to public health, yet validating the modeled climate impacts of the pandemic requires consideration of aerosol burdens throughout the total depth of the troposphere, and at regional to global scales (Chen et al 2020, Sharma et al 2020).

Satellite observations of AOD can be used to characterize aerosol burdens throughout the vertical column on a global scale with near-continuous coverage. By definition, AOD measures aerosol burdens according to optical properties, which is particularly appropriate for climate applications as radiative forcing arises from the aerosol’s reflection or absorption of shortwave radiation. The passive sensor Moderate Resolution Imaging Spectroradiometer (MODIS) is commonly used for AOD retrievals, while the cloud-aerosol lidar with orthogonal polarization (CALIOP) instrument has the additional advantage of calculating extinction coefficients along a vertical profile (Barnes et al 2003, Winker et al 2009). Processing the CALIOP retrievals also requires discrimination between seven different aerosol classifications: dust, polluted dust, elevated smoke, polluted continental, clean continental, clean marine, and dusty marine, which can provide insight into the relative contributions of natural and anthropogenic drivers of AOD variability (Tackett et al 2018). While other AOD products are available (e.g. advanced very-high-resolution radiometer, visible infrared imaging radiometer suite), the ubiquity of MODIS and the unique capabilities of CALIOP make the use of these two products ideal (Choi et al 2019).

Studies using MODIS retrievals during the lockdowns have found anomalously low AOD in India, Bangladesh, China, Europe, and the United States during the early months of 2020 (Lal et al 2020, Ranjan et al 2020, Acharya et al 2021, Bilal et al 2021). Data from CALIOP have provided additional context to such lockdown observations; in sub-Saharan Africa, analysis of CALIOP retrievals showed an increase in smoke, possibly due to diminished enforcement of land management policies (Kganyago and Shikwambana 2021, Qiu et al 2021). In India and Bangladesh, anomalously low dust contributed substantially to the low AOD signals at least as late as April and May, respectively, suggesting that non-anthropogenic sources of variability should be considered in any extended studies (Prijith and Srinivasulu 2021, Qiu et al 2021).

In many NH source regions, efforts to curtail air pollution have resulted in multi-year declines in AOD, yet few lockdown studies contextualize pandemic AOD anomalies against the backdrop of these longer-term trends (e.g. Kuklinska et al 2015, Zheng et al 2020, Ming et al 2021). This background is important not only for appropriately quantifying the COVID-19 effect on AOD, but also for comparing the ancillary impacts of pandemic-related lifestyle changes to those of targeted public efforts to decrease air pollution. More than half of the estimated reductions in black carbon and $\text{SO}_2$ in April of 2020 came from India, China, Europe, and the United States (Forster et al 2020). As a result, in this study we considered the 2020 AOD signal in four NH source regions: Eastern & Central China, the United States, India, and Europe. We consider not only observed anomalies relative to multi-year trends, but also the vertical profile of extinction coefficient anomalies as well as contributions from various aerosol subtypes.

2. Satellite data and methods

We obtained monthly mean AOD datasets generated from two satellite instruments, the NASA MODIS (Aqua) and NASA Cloud-Aerosol LiDAR with Orthogonal Polarization CALIOP (Calipso). For both instruments we used level-3 gridded datasets: the global joint product (MYD08_M3, $1^\circ \times 1^\circ$, AOD$_{550}$ Dark_Target_Dark_Blue) from MODIS Collection 6.1 and the tropospheric aerosol ‘all sky’ profile (CAL_LID_2.3_Tropospheric_APro-Standard-V4-20/21, $2^\circ \times 5^\circ \times 60 \text{ m}$) from CALIOP, which includes both AOD and extinction coefficient vertical profiles.

Validation of data products from both instruments against ground-based Aerosol Robotic Network (AERONET) AOD resulted in low errors globally, though the MODIS values tended show high biases while CALIOP datasets underestimated AERONET AOD, with mean absolute errors (MAEs) of .08 and -.051, respectively (Kim et al 2018, Wei et al 2019). MODIS data also showed biases slightly higher than the global average in two of the land regions examined here, with India and East Asia showing MAEs of .12 and .11, respectively (Wei et al 2019).
The CALIOP data product includes both day and night retrievals, which we treated as separate datasets. AOD and extinction coefficient contributions from three aerosol subtypes (dust, polluted dust, elevated smoke) are also available in the CALIOP datasets; we subtract these three subtypes from the all-aerosol data to create a composite subtype, 'continental,' which includes contributions from the two remaining aerosol subtypes available over land (clean continental, polluted continental), encompassing both carbonaceous aerosol from industrial sources as well as background/rural aerosol. Kim et al. (2017) note that solar reflectance during the daytime results in a lower signal-to-noise ratio for CALIOP (day) retrievals. For this reason, we use the CALIOP (night) data products when examining different aerosol subtypes along vertical profiles.

Although MODIS and CALIOP products consider AOD at slightly different wavelengths (550 nm and 532 nm, respectively), our analysis does not directly compare the datasets and wavelength disparity is expected to contribute relatively little to the significance of the 2020 AOD anomalies. A considerable difference in the viewing swath widths means that the sampling frequency of MODIS is substantially higher than CALIOP (1–2 days versus ~16 days), which may lead to discrepancies between the instruments when examining short-lived, transient signals.

Where AOD data was missing, we applied a 2D bilinear interpolation to fill the missing data, and excluded from the analysis any locations where more than two contiguous pixels of data were missing at any point in the timeseries (figure S1). The results remain very similar with the interpolation (not shown). In recent years the CALIOP LiDAR has produced low-energy laser shots over South America, leading to poor data quality in the region. Retrievals over this region have therefore been excluded from the CALIOP datasets used in this analysis.

3. Results and discussion

3.1. Global reductions in 2020 AOD

Figure 1 shows the 2020 annual mean AOD percent anomalies with respect to a 2007–2019 climatology (a)–(c) and 2019 AOD values (d)–(f) for MODIS, CALIOP (night) and CALIOP (day). The comparison allows us to investigate the short-term effects of COVID-19 on AOD, and other potential influences on 2020 AOD values, such as long term trends and natural variability. With respect to the 2007–2019 climatology, all three datasets showed anomalously low AOD in 2020 throughout much of the global land regions. While there are general reductions in AOD over much of the Eurasian landmass, negative anomalies are attenuated when calculated against 2019 values.

In India, both CALIOP datasets show 10%–20% reductions throughout much of the subcontinent, with the anomalies calculated against 2019 values showing slightly clearer signals. However, the sign of MODIS AOD anomalies (a) is inconsistent with the other datasets. In Central China, reductions in AOD are apparent at annual resolution in all datasets, even when compared only to 2019 values. However, the strong (~20% to ~50%) and spatially uniform signal apparent in panels (a)–(c) is less clear when compared to 2019 values (d)–(f). In all panels, the maritime continent shows AOD reductions as substantial as 40%. The Middle East and Iranian Plateau also show 20%–45% reductions in AOD in panels (a)–(c), although the CALIOP data indicate that these anomalies are due to reductions in dust (figure S2).

In eastern North America and western Europe, we observe 10%–40% reductions in AOD, which appear slightly weaker when calculated against 2019 values than the 2007–2019 climatology. In the western United States AOD increases exceeding 40% are evident in all datasets, consistent with record-breaking wildfires in this area during August and September (Abatzoglou et al. 2021). Spatial discrepancies in these positive anomalies between MODIS and CALIOP likely relate to the different sampling frequencies of the two instruments; transient and quick-moving, high-elevation smoke plumes are more likely to be observed in source regions by the more frequent sampling of MODIS.

Similarly, in Southern Africa the CALIOP data show 30%–50% reductions in AOD while the MODIS dataset saw differences in sign throughout the region. Research supporting a COVID-19-related increase in biomass burning throughout sub-Saharan Africa could explain the differences between instruments (Kganyago and Shikwambana 2021). While CALIOP data over South America are excluded from the analysis, MODIS data show increases in AOD exceeding 40% in the southern Amazon and Pampas. Other studies have found a lockdown-related increase in biomass burning in the Northern Amazon during the earliest months of the pandemic; our findings suggest that the possible contribution of biomass burning to Southern Amazonian AOD anomalies throughout 2020 is worthy of further investigation (Mendez-Espinosa et al. 2020, Sanap 2021).

3.2. Changes in AOD across four source regions

To further determine how 2020 AOD changed across different source regions throughout the year, we selected four main source regions for further analysis. These regions cover the land areas of Eastern & Continental China (ECC, 24°–42° N 100°–125° E), the contiguous United States (US, 25°–50° N, 130°–70° W), India (IND, 8°–32° N, 70°–90° E), and Europe (EUR, 38°–54° N, 10° W–30° E), as indicated by the yellow boxes in figure 1. For each month of the sampling period (2007–2020), we calculated the area-weighted monthly AOD for the three datasets. Figure 2 shows that across all datasets and regions, 81% of months in
2020 showed below-average AOD, and 40% showed record-low AOD. For ECC, the US, and EUR, record-low values were mostly concentrated in the boreal spring and summer, when 72%, 67%, and 56% of the sampled months showed record- lows, respectively.

In both ECC and EUR, AOD values below the first quartile persisted for a majority of datasets from September to December, demonstrating that in these regions, reductions endured well past the lockdown periods examined in previous studies (see also figure S3). In contrast, the IND signal proved less persistent; 67% of months sampled in MAM showed record- lows, yet only three record-lows appear in the rest of the year. Still, the CALIOP datasets showed AOD below the first quartile through the remainder of the monsoon season (JJAS), indicating that an enduring, if less extreme, signal continued through the late summer. In the US, extreme wildfire events beginning in August overwhelmed the autumn AOD signal, producing record-high values in September and October, which are linked to wildfires. Although December saw a return to anomalously low AOD in the US, it is yet unclear whether this indicates the persistence of emissions-related reductions late into 2020.

For the US and EUR, there is a clear seasonality of AOD that peaks in the summer months (May–August) but that is not reflected in the CALIOP (day) data for EUR, and is substantially dampened in the CALIOP (day) data for the US. Further analysis shows that the CALIOP (day) dataset poorly captures elevated smoke, which contributes ∼20% and 35% to the mean AOD signature in the summer EUR and US CALIOP (night) datasets, respectively (figure S4). Similarly, in ECC discrepancies between the seasonality of CALIOP (day) and the other two datasets may be explained by an underestimate of elevated smoke and, to a lesser extent, polluted dust (figure S4). In IND, mean CALIOP AOD values peak at the end of the pre-monsoon season (May), while MODIS shows a maximum in July, reflecting a substantial change in instrument bias during the monsoon season (JJAS). Different handling of clouds by passive versus LiDAR instruments during the monsoon is a likely contributor to the differences between instruments in IND (Kim et al 2017). Despite the anomalies in figure 1, none of the regions show substantial changes in AOD seasonality in 2020; AOD minima and maxima for each region and dataset remain generally consistent with previous years, with the clear exception of the extreme September and October AOD values in the US, which are linked to wildfires.

### 3.3. Causes of low 2020 AOD

While figure 2 shows that AOD in all four source regions is at record-low values at some point in 2020, it is not clear whether these low values are driven by COVID-19-related anthropogenic aerosol reductions. Specifically, enhanced air quality regulations and thus a decreasing trend in AOD over this period could contribute to the low values, as could natural variability unrelated to the COVID shutdowns. To quantify monthly trends from a 13 year climatology, we calculated 3 month running means of observed regional AOD anomalies for each dataset, then determined the linear trend of these values for each month for the 2007–2019 period. Extrapolating from this linear trend, we then predicted three month
Figure 2. Distribution of 2007–2020 monthly mean AOD by dataset in Eastern & Central China (ECC), the contiguous United States (US), India (IND) and Europe (EUR). Colored circles indicate 2020 values. Whiskers span up to 1.5 times the interquartile range; outliers beyond this range are shown with diamond markers (2007–2019) or colored circles (2020).

Figure 3. Predicted (blue) and observed (red) three month running mean AOD anomalies in 2020, and their differences (i.e. detrended anomalies) for ECC, US, IND, and EUR.

running mean AOD anomalies for 2020. Figure 3 shows the observed (red) and predicted (blue) anomalies, as well as their differences, which correspond to the detrended AOD values.

Negative trends in AOD, indicated by the predicted AOD anomalies, characterize almost all months in ECC, US, and EUR (MODIS shows a negligibly positive trend in August and September in the US), whereas the IND trend is consistently positive. The positive IND trend is mostly steady throughout the year, contributing ~0.05 AOD units to the detrended negative anomalies in much of 2020.

In ECC, the contribution of the trend to 2020 anomalies is up to an order of magnitude greater than in EUR and the US, ranging from ~0.07 to ~0.15 AOD units. Despite slight differences between datasets, in ECC multi-year trends consistently eclipse the detrended anomalies. These trends reflect concerted efforts within China, beginning in 2013, to aggressively curtail air pollution, primarily by filtering pollutants prior to emission (Zhang et al 2019, Itahashi et al 2021). Plans announced in 2018 promised additional measures, including a shift to low carbon energy sources, which were expected to continue through 2020 (Ministry of Ecology and Environment, People’s Republic of China 2018).

As other studies have noted, this multi-phase approach has made quantifying the AOD trend in
ECC challenging; a linear trend from 2007 to 2019 might not provide the most appropriate fit, yet with a relatively short time series the validity of higher-order regressions is difficult to establish (e.g. van der A 2017, Tao et al 2020). Regardless, investigation of the entire time series shows that monthly AOD anomalies in 2018 and 2019 were consistently and substantially negative, ranging from −.05 to −.14 AOD units, similar to those observed in 2020 (figure S5).

Notably, emissions inventories and satellite measures of NOx during the lockdowns have found more significant 2020 anomalies than are apparent in AOD observations; increased atmospheric stability over East Asia during the lockdowns may have bolstered aerosol accumulation, masking the effect of COVID-19-emissions reductions on AOD (Fan et al 2020, Zheng et al 2021). Still, multi-year emissions reductions likely account for nearly all of the observed ECC anomalies in 2020, as the effects of any pandemic-related emissions reductions were small relative to these trends and other sources of variability.

In the US and EUR, negative trends are more modest, contributing −.01 to −.02 AOD units in the US and up to −.03 in EUR to 2020 AOD anomalies. The detrended anomalies appear most substantial in late spring to summer, despite the most restrictive lockdowns occurring largely in March and April (Taylor 2021). This observation contradicts earlier studies’ assumptions that COVID-19-related AOD reductions would be most significant in the early spring, and may reflect seasonal differences in the trend as well as greater climatological values of anthropogenic AOD in the summer (figure S4) (e.g. Huang et al 2013, Mehta et al 2016). Even when detrended anomalies were apparent, in many months the effect of the trends in the US and EUR was greater than the detrended anomalies, suggesting that for much of the year, longer-term efforts to reduce emissions in these regions had a more substantial effect on 2020 AOD than COVID-related lifestyle changes.

To further determine the contributions of anthropogenic and non-anthropogenic aerosol subtypes to the total 2020 AOD reductions, and to understand how the COVID-19 pandemic may have affected the vertical profile of aerosols, we compared the climatological mean annual vertical profiles (2007–2019) in each region to those of 2020, and decomposed the vertical profile anomalies to contributions from each aerosol subtype. Here, we used the CALIOP (night) data to examine the contribution of each aerosol subtype to changes along the vertical profile (figure 4, column labeled ‘annual mean vertical profile’). Annual mean vertical profiles in ECC, the US, and EUR all show reductions in the lowest 2 km below the 95% confidence interval for the climatological mean, resulting in a flattening of the profiles. In the US and EUR, these negative anomalies are almost exclusively driven by reductions in continental aerosol. In ECC, reductions are attributable to polluted dust and continental subtypes, indicating that in these regions, 2020 reductions were primarily driven by anthropogenic sources. In contrast to the other three regions, changes in the IND annual mean vertical profile show a bimodal pattern, with slight reductions at the lowest levels (<.5 km) and another observable reduction from ~2 to 5 km. While all other regions show substantial negative anomalies in continental aerosol, IND actually saw an increase consistent with the positive trend in continental aerosol noted in figure S6.

To determine when contributions from the different subtypes to 2020 extinction coefficient anomalies occurred, we calculated monthly extinction coefficient anomalies for each subtype and for the sum of all aerosol subtypes (‘all-aerosol’). In figure 4 we show monthly vertical profile anomalies for each subtype (columns labeled ‘dust’-’continental’) and the all-aerosol, which we normalized by the monthly mean climatological all-aerosol extinction coefficients. During the months of August through October (ASO), the effects from wildfires in the US are clearly evident in the elevated smoke and polluted dust subtypes. In EUR, a similar signature in September and October appears above ~4 km, indicating transport of pyrogenic aerosols across the Atlantic. While in the US ASO all-aerosol is dominated by the effects of wildfire, reductions in continental aerosol in the lowest 2 km of the column persisted through these months, suggesting that reductions in anthropogenic aerosol continued throughout the remainder of 2020 but were masked by natural sources. In EUR, continental aerosol is consistently and substantially negative throughout 2020, showing that the persistence of AOD reductions in EUR is driven by enduring reductions in anthropogenic aerosol in the lowest levels of the troposphere.

In ECC, changes in the annual mean vertical profile were driven by low anomalies in polluted dust and continental subtypes, with polluted dust dominating from January to March and continental dominating from June to September. Because polluted dust is a mixture of dust and carbonaceous aerosol, continental aerosol subtype burdens can be modulated by dust availability. Anomalously low dust in the early months of 2020 appears to have resulted in less mixing, which likely increased the proportion of anthropogenic aerosols characterized as continental, independent of any other changes in emissions. However, the combined negative contribution from continental and polluted dust suggests that 2020 anomalies were primarily anthropogenic. However, as indicated earlier, a multi-year trend is likely the predominant cause of the anthropogenic signal in ECC.

Figure 4 also shows that negative anomalies in IND were largely due to reductions in dust and polluted dust, with mid-year reductions in dust appearing most anomalous between 2 and 5 km. These were
Figure 4. Annual mean vertical profiles and normalized monthly extinction coefficient $\alpha$ anomalies from CALIOP (night) for ECC, US, IND and EUR. Column titled ‘Annual mean vertical profile’ shows all-aerosol annual mean 2020 (black, dashed) and climatological (black, solid with shaded 95% confidence interval) vertical profiles, and the 2020 annual mean vertical profile anomalies of the four subtypes (colored, dashed). The colorbar for extinction coefficient anomalies for each subtype (‘dust’–‘continental’) and ‘all-aerosol’ corresponds to the fraction of 2020 extinction coefficient anomalies relative to the all-aerosol climatological mean.

4. Conclusion

In EUR and the US, genuine COVID-19 signatures can be identified, even after natural aerosol sources and the effects of multi-year trends are considered. In these two regions, anomalously low AOD persisted later into the year than early studies expected, and indeed, absolute COVID-19 signals appear strongest in the post-lockdown periods. While AOD trends are difficult to quantify, they nevertheless suggest that the COVID-19 signature may be smaller than otherwise expected. In ECC, no clear COVID-19 AOD signature at a regional scale is apparent, as detrended anomalies are small relative to the trend. In IND, variability in natural aerosol sources (dust) dominated the observations. This may suggest a connection to the anomalously low dust over the Middle East, as prevailing winds would typically transport dust from the Arabian Peninsula and East Africa (Banerjee and Kumar 2016, Ramaswamy et al 2017).

Our analysis suggests that satellite observations of AOD reductions during the 2020 COVID-19 pandemic may be more complex than initially thought. Even in regions with a notable COVID-19 signature, the effects of multi-year emissions trends often match or exceed those of COVID-19, suggesting that even extreme and universally adopted lifestyle changes may be no more effective in reducing emissions than policy-driven approaches. Whether economic differences, such as differing sectoral (e.g. transportation) contributions to a region’s overall emissions, or the prevalence of livelihoods conducive to extended work-from-home arrangements, affected regional differences in 2020 AOD observations should be considered. It is clear from our analysis that anthropogenic aerosol emissions are...
decreasing in major source regions, particularly in China, even in the absence of a COVID-19 signature. Thus, their impact on precipitation in these regions, as well as on accelerated greenhouse warming through reduced aerosol cooling, are urgent issues that need to be addressed.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: 10.5067/CALIOP/CALIPSO/CAL_LID_L3_Tropospheric_APro_AllSky-Standard-V4-20.

Acknowledgments

This work was supported by the National Science Foundation’s Office of Polar Research (Grant No. OPP-1825858) and the National Science Foundations Division of Atmospheric and Geospace Sciences (Grant No. AGS-1607348).

ORCID iDs

Sarah Elise Smith https://orcid.org/0000-0002-5195-7334
Mingfang Ting https://orcid.org/0000-0002-4302-4614
Yutian Wu https://orcid.org/0000-0002-4428-6624
Cheng Zheng https://orcid.org/0000-0002-8039-346X

References

Abatzoglou J T, Rupp D E, O’Neill L W and Sadegh M 2021 Compound extremes drive the Western Oregon wildfires of 2020 Geophys. Res. Lett. 48
Acharya P, Barik G, GAYEN B K, Bar S, Mati A, Sarkar A, Ghosh S, De S K and Sreekesh S 2021 Revisiting the levels of aerosol optical depth in south-southeast Asia, Europe and USA amid the COVID-19 pandemic using satellite observations Environ. Res. 193 110514
Banerjee P and Kumar S P 2016 ENSO modulation of interannual variability of dust aerosols over the Northwestern Indian Ocean J. Clim. 29 1287–303
Barnes W L, Xiong X, Guenther B W and Salomonson V 2003 Development, Characterization, and Performance of the EOS MODIS Sensors (San Diego, CA) ed W L Barnes p 337
Belouin N et al 2020 Bounding global aerosol radiative forcing of climate change Rev. Geophys. 58
Bilal M et al 2021 Uncertainty in aqua-MODIS aerosol retrieval algorithms during COVID-19 lockdown IEEE Geosci. Remote Sens. Lett. 19 1002250
Chen Y, Zhang S, Peng C, Shi G, Tian M, Huang R-J, Guo D, Wang H, Yao X and Yang F 2020 Impact of the COVID-19 pandemic and control measures on air quality and aerosol light absorption in Southwestern China Sci. Total Environ. 749 141419
Choi M, Lim H, Kim J, Lee S, Eck T F, Holben B N, Garay M J, Hyer E J, Saide P E and Liu H 2019 Validation, comparison, and integration of GOCI, AHI, MODIS, MISR, and VIIRS aerosol optical depth over East Asia during the 2016 KORUS-AQ campaign Atmos. Meas. Tech. 12 4619–41
Chowdhury P, Paul S K, Kaisar S and Moktadir M A 2021 COVID-19 pandemic related supply chain studies: a systematic review Transp. Res. E 148 102271
D’Souza J, Prasanna F, Valayannopoulos-Akrivou L-N, Sherman P, Penn E, Song S, Archibald A T and McElroy M B 2021 Projected changes in seasonal and extreme summertime temperature and precipitation in India in response to COVID-19 recovery emissions scenarios Environ. Res. Lett. 16 114025
Fan C, Li Y, Guang J, Li Z, Elnashar A, Allam M and de Leeuw G 2020 The impact of the control measures during the COVID-19 outbreak on air pollution in China Remote Sens. 12 1613
Fiedler S, Wyse K, Rogelj J and van Noije T 2021 Radiative effects of reduced aerosol emissions during the COVID-19 pandemic and the future recovery Atmos. Res. 264 105866
Forster P M et al 2020 Current and future global climate impacts resulting from COVID-19 Nat. Clim. Change 10 913–9
Huang L, Jiang J H, Tackett J L, Su H and Fu R 2013 Seasonal and diurnal variations of aerosol extinction profile and type distribution from CALIPSO 5-year observations J. Geophys. Res. 118 4572–96
Itahashi S, Sakurai T, Shimadera H, Araki S and Hayami H 2021 Long-term trends of satellite-based fine-mode optical aerosol depth over the Seto Inland Sea, Japan, over two decades (2001–2020) Environ. Res. Lett. 16 054062
Kganyago M and Shikwambana L 2021 Did COVID-19 lockdown restrictions have an impact on biomass burning emissions in sub-Saharan Africa? Aerosol Air Qual. Res. 21 200470
Kim M-H et al 2018 The CALIPSO version 4 automated aerosol classification and lidar ratio selection algorithm Atmos. Meas. Tech. 11 6107–35
Kim M-H, Omar A H, Vaughan M A, Winker D M, Trepte C R, Hu Y, Liu Z and Kim S-W 2017 Quantifying the low bias of CALIPSO’s column aerosol optical depth due to undetected aerosol layers: undetected aerosols in CALIPSO AOD J. Geophys. Res. 122 1098–113
Koo J-H, Kim J, Lee Y G, Park S S, Lee S, Chong H, Cho Y, Kim J, Choi K and Lee T 2020 The implication of the air quality pattern in South Korea after the COVID-19 outbreak Sci. Rep. 10 22462
Kukinska K, Wolska I, and Namiesnicki J 2015 Air quality policy in the U.S. and the EU—a review Atmos. Pollut. Res. 6 129–37
Lal P, Kumar A, Kumar S, Kumari S, Saikia P, Dayanandan A, Adhikari D and 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. 732 139297
Lamboll R D, Jones C D, Skeie R B, Fiedler S, Samset B H, Lamborg J R, Jones C D, Skeie R B, Fiedler S, Samset B H, Gallet N P, Rogelj J and Forster P M 2021 Modifying emissions scenario projections to account for the effects of COVID-19: protocol for CovidMIP Geosci. Model Dev. 14 3683–95
Le Quéré C et al 2020 Temporary reduction in daily global CO₂ emissions during the COVID-19 forced confinement Nat. Clim. Change 10 647–53
Mehta M, Singh R, Singh A and Singh N 2016 Recent global aerosol optical depth variations and trends—a comparative study using MODIS and MISR level 3 datasets Remote Sens. Environ. 181 137–50
Mendez-Espinosa J F, Rojas N Y, Vargas J, Pachón J E, Solórzano C, Mendez-Espinosa J F, Rojas N Y, Vargas J, Pachón J E, Solórzano C, Mendez-Espinosa J F, Rojas N Y, Vargas J, Pachón J E, Solórzano C and Mendez-Espinosa J F, Rojas N Y, Vargas J, Pachón J E, Solórzano C 2020 Assessing the Influence of COVID-19 on the shortwave radiative fluxes over the east asian marginal seas Environ. Res. Lett. 15 034018
Mishra A, Chakraborty R, Saha N, Mandal S, Pandit R and Biswas M 2021 Uncertainty in MODIS aerosol optical depth over India Atmos. Res. 260 105115
Forster P M et al 2020 Assessing the Influence of COVID-19 on the shortwave radiative fluxes over the east asian marginal seas Environ. Res. Lett. 15 034018
Fujii T, Shieh T Y, Lin S F, Hsueh P R and Hsu W C 2021 Assessing the Influence of COVID-19 on the shortwave radiative fluxes over the east asian marginal seas Environ. Res. Lett. 15 034018
Fujii T, Shieh T Y, Lin S F, Hsueh P R and Hsu W C 2021 Assessing the Influence of COVID-19 on the shortwave radiative fluxes over the east asian marginal seas Environ. Res. Lett. 15 034018
Fujii T, Shieh T Y, Lin S F, Hsueh P R and Hsu W C 2021 Assessing the Influence of COVID-19 on the shortwave radiative fluxes over the east asian marginal seas Environ. Res. Lett. 15 034018
Fujii T, Shieh T Y, Lin S F, Hsueh P R and Hsu W C 2021 Assessing the Influence of COVID-19 on the shortwave radiative fluxes over the east asian marginal seas Environ. Res. Lett. 15 034018
Fujii T, Shieh T Y, Lin S F, Hsueh P R and Hsu W C 2021 Assessing the Influence of COVID-19 on the shortwave radiative fluxes over the east asian marginal seas Environ. Res. Lett. 15 034018
Onyeaka H, Anumudu C K, Al-Sharify Z T, Egele-Godswill E and Mbaegbu P 2021 COVID-19 pandemic: a review of the global lockdown and its far-reaching effects Sci. Prog. 104 003685042110198

Philipona R, Behrens K and Ruckstuhl C 2009 How declining aerosols and rising greenhouse gases forced rapid warming in Europe since the 1980s Geophys. Res. Lett. 36

Prijith S S and Srinivasulu J 2021 Dominance of natural aerosols over India in pre-monsoon: inferences from the lockdown effects Curr. Sci. 120 8

Qiu Z et al 2021 Spatiotemporal investigations of multi-sensor air pollution data over Bangladesh during COVID-19 Lockdown Remote Sens. 13 877

Ramaswamy V, Muraleedharan P M and Babu C P 2017 Mid-troposphere transport of middle-East dust over the Arabian Sea and its effect on rainwater composition and sensitive ecosystems over India Sci. Rep. 7 13676

Sanap S D 2021 Global and regional variations in aerosol loading during COVID-19 imposed lockdown Atmos. Environ. 246 118132

Sharma S, Zhang M, Gao J, Zhang H and Kota S H 2020 Effect of restricted emissions during COVID-19 on air quality in India Sci. Total Environ. 728 138878

Szopa S et al 2021 Short-lived climate forcers supplementary material Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (Cambridge: Cambridge University Press) ed V Masson-Delmotte et al (available at: www.ipcc.ch/)

Tackett J L, Winker D M, Getzewich B J, Vaughan M A, Young S A and Kar J 2018 CALIPSO lidar level 3 aerosol profile product: version 3 algorithm design Atmos. Meas. Tech. 11 4129–52

Tao M, Wang L, Chen L, Wang Z and Tao J 2020 Reversal of aerosol properties in eastern China with rapid decline of anthropogenic emissions Remote Sens. 12 523

Taylor D B 2021 A timeline of the coronavirus pandemic New York Times (available at: www.nytimes.com/article/coronavirus-timeline.html) (Accessed 17 March)

van der A R J, Mijling B, Ding J, Koukouli M E, Liu F, Li Q, Mao H and Theys N 2017 Cleaning up the air: effectiveness of air quality policy for SO$_2$ and NO$_x$ emissions in China Atmos. Chem. Phys. 17 1775–89

Venter Z S, Aunan K, Chowdhury S and Lelieveld J 2020 COVID-19 lockdowns cause global air pollution declines Proc. Natl Acad. Sci. 117 18984–93

Wei J, Li Z, Peng Y and Sun L 2019 MODIS Collection 6.1 aerosol optical depth products over land and ocean: validation and comparison Atmos. Environ. 201 428–40

Winker D M, Vaughan M A, Omar A, Hu Y, Powell K A, Liu Z, Hunt W H and Young S A 2009 Overview of the CALIPSO mission and CALIOP data processing algorithms J. Atmos. Ocean. Technol. 26 2310–23

Zhang Q et al 2019 Drivers of improved PM$_{2.5}$ air quality in China from 2013 to 2017 Proc. Natl Acad. Sci. 116 24463–9

Zheng B et al 2020 Satellite-based estimates of decline and rebound in China’s CO$_2$ emissions during COVID-19 pandemic Sci. Adv. 6 eabd4998

Zheng B, Zhang Q, Geng G, Chen C, Shi Q, Cui M, Lei Y and He K 2021 Changes in China’s anthropogenic emissions and air quality during the COVID-19 pandemic in 2020 Earth Syst. Sci. Data 13 2895–907