Biomass Burning and Gas Flares create the extreme West African Aerosol Plume Which Perturbs the Hadley Circulation and thereby Changes Europe's Winter Climate

Supplementary Information

1 APPENDIX A: THE EIGHT CONTINENTAL SCALE AEROSOL PLUMES

The locations of the eight continental scale aerosol plumes are shown in Figures A1 and A2. The average monthly MERRA-2 AOD level (1980 to 2020) of each plume is shown in Figure A3. Four plumes peak in the boreal summer, one in the boreal winter, two in September and one in August. The major sources of the plumes are shown in Table A1.

All plumes create local climate change when they exist, some cause regional change and at least one causes global change. This paper addresses the changes driven by the West African Plume in Europe.
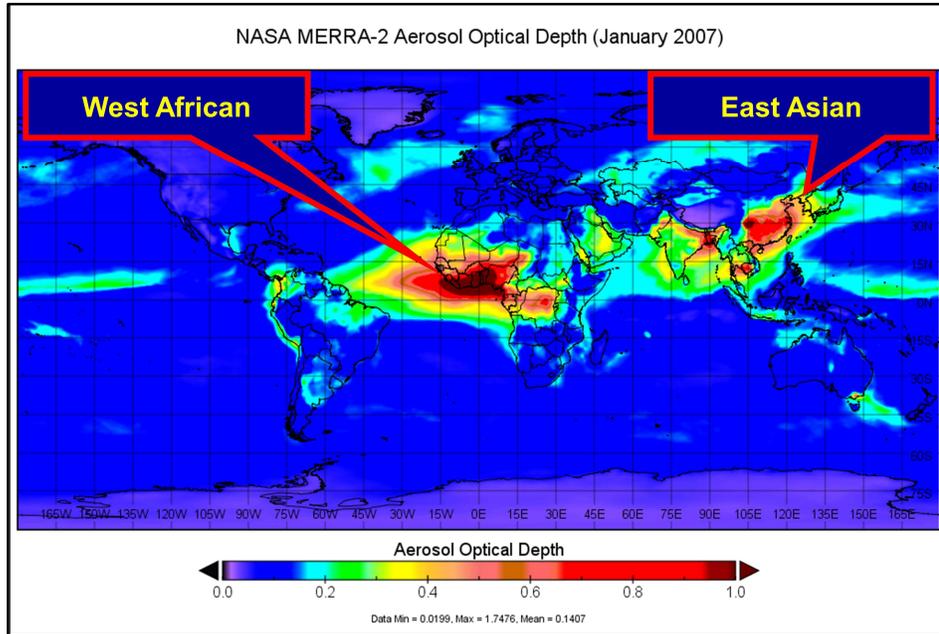

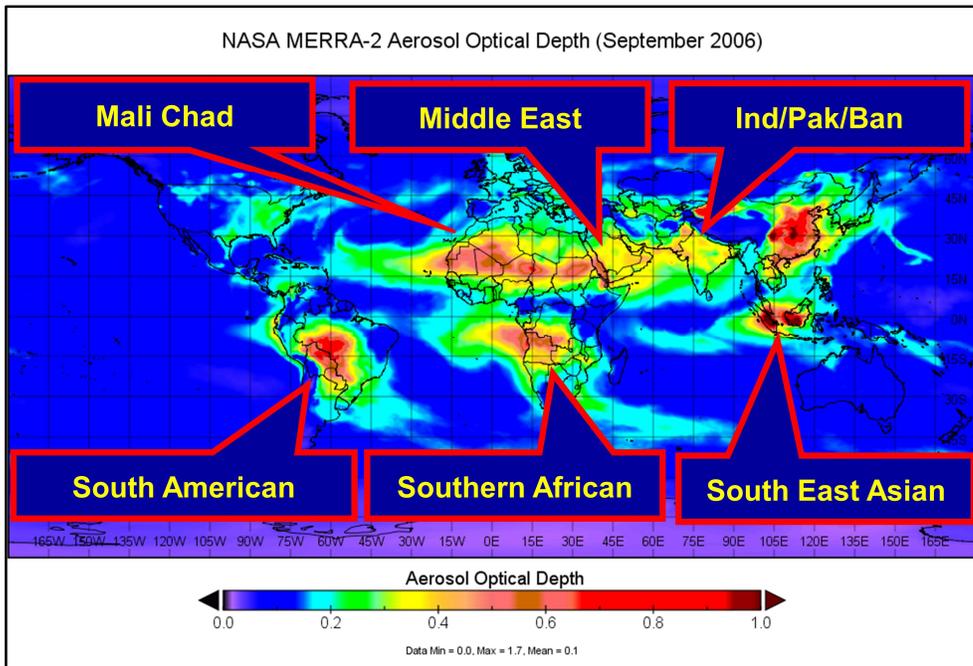**Figure A1**. MERRA-2 AOD Jan 2007 showing two of the eight plumes.

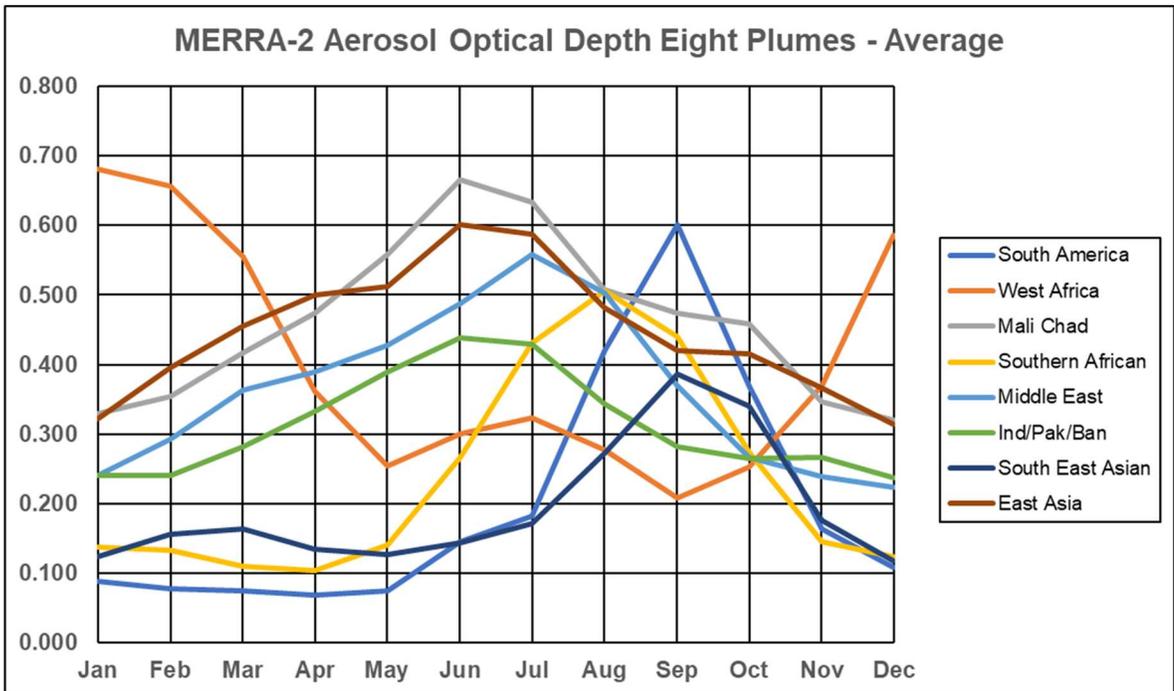**Figure A2**. MERRA-2 AOD September 2006 showing six of the eight plumes.

Figure A3. Average monthly MERRA-2 AOD of the eight plumes 1980 to 2020.

Table AI: The aerosol sources of the eight continental scale aerosol plumes.

Plume	Anthropogenic Source	Natural Source
South American	Biomass	Volcanoes
West African	Biomass, Gas Flares	Dust, Volcanoes
Mali/Chad	Peat fires under dried up lakes?	Dust
Middle East	Gas Flares	Dust, Volcanoes
Southern African	Biomass	Volcanoes, Dust
India/Pakistan/Bangladesh	Biomass, Industry	Dust
South East Asian	Biomass, Gas Flares	Volcanoes
East Asian	Industry, Biomass	Dust

2 APPENDIX B: SOURCES OF THE WEST AFRICAN AEROSOL PLUME

The major sources of aerosols in West Africa are biomass burning and gas flares in the oil production industry. Dust from the Bodélé Depression and wider Sahel may be a minor source from January to March (JFM) and volcanoes are not.

2.1 Biomass Burning

Biomass burning in West Africa is a large direct source of carbonaceous aerosols and is part of the traditional annual agricultural cycle. It occurs during the dry season before the start of the local monsoon in April. The level of biomass burning in the region has increased significantly in recent decades and is expected to continue to increase [1].

In the WAP Area the biomass burning aerosol plume is at its most intense in JFM as Figure 2 shows. The increase in biomass burning in the WAP Area in recent decades has been driven by the increasing population of West Africa which increased from 71 to 307 million between 1950 and 2010 and is expected to increase to 796 million by 2050 (United Nations), an elevenfold increase in 100 years. This increasing population has forced: an increase in food production from tropical agriculture with its attendant smoke/aerosols; and increased rainforest clearing to provide living space and agricultural land.

2.1.1 Forest Clearing

A major source of aerosols in West Africa is forest clearing in Nigeria, the country at the centre of the WAP. Data from The Global Forest Watch in Figure A4 shows the annual forest loss which has trended from under 50,000 Ha in 2001 to 250,000 in 2018, a fivefold increase.
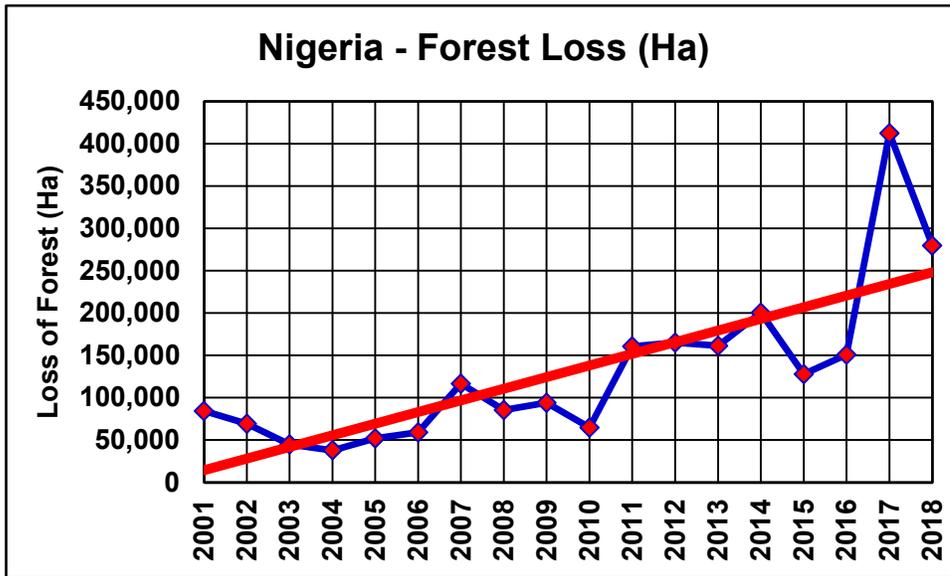
Figure A4. Annual Forest Loss in Nigeria.

2.1.2 *NASA Fire Data*

The archived active fires from Feb 2012 to Feb 2020 from NASA was downloaded for the area 5° to 15°N 0° to 10°E. Over 3.8 million observations for this area are included in the database. The data was summed for each day and the daily total then averaged for each month to avoid double counting fires which are recognized on more than one day. The fire data and MERRA-2 AOD are plotted in Figure A5 to show the close connection between fire and AOD in West Africa which is also shown in the high correlation (0.77 significance <0.01) between the AOD and fire numbers in this period.
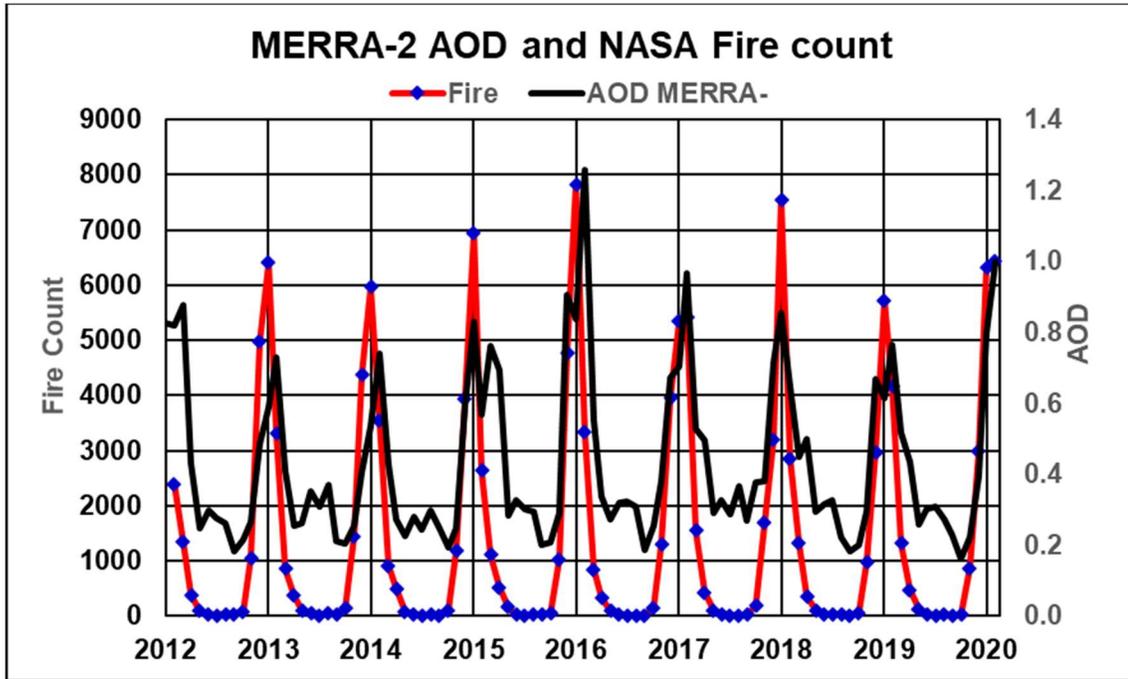
Figure A5. West African Archived Fires (NASA) and NASA MERRA-2 WAP Area AOD.

2.1.3   Literature - African Fires

Biomass burning in West Africa south of 20º N creates significant levels of carbonaceous aerosols in the dry season [2]. The fires which raged in the sub-Saharan belt of Africa on January 30th 2016 are shown in Figure 1 in [3] and the WAP Area incorporates the most concentrated level of detected fires in the region which stretches from Sierra Leone to South Sudan.

Most African fires are anthropogenic [4] and biomass burning and dust are the dominant aerosol sources in the months before the West African monsoon [5].

Wildfires in Africa contribute 57% of the biomass burning emissions of the continent and nearly all are human-ignited [6]. The remainder, 36% for domestic and industrial activities and 3% each for crop residue burning and deforestation, are all anthropogenic sources which obviously implies that nearly all the biomass burning in Africa is anthropogenic.

2.2   Gas Flares

The oil industry flares associated gas (gas dissolved in liquid oil which boils out of the liquid when the oil is produced from deep in the Earth and the pressure reduces to atmospheric levels) when no infrastructure exists to use the gas. The use of gas flares increased over recent decades as oil production in West Africa increased from 274,000 to 2,342,000 barrels of oil per day between 1965 and 2018 (BP Statistical Review of World Energy 2019) with the majority of the increase occurring before 1974. Nigeria is the major producer in the region with 88% of the total oil production in West Africa in 2018.

Over three hundred gas flares exist in Nigeria flaring 15 billion m^3 with 97 of those flares ranking in the top 1,000 globally [5] and the World Bank has established the Global Gas Flaring Reduction Partnership (GGFRP) which estimates Nigeria flares 7.4 billion m^3 of natural gas each year and the gas flare locations are shown in Figure 1. NOAA identified 359 flare locations in West Africa from Congo to Mauretania with Nigeria hosting the majority at 203. Images of such flares producing aerosols are easily found e.g. Figure A6 from NOAA or at the GGFRP web site.

Figure A6. Gas Flare NOAA at https://ngdc.noaa.gov/eog/viirs/download_global_flare.html.

2.3   Dust from the Bodélé Depression

The Bodélé Depression is recognised as one of, if not the, major source of dust in the world. It is located at 18º E and 17º N to the north east of the WAP Area. Figure 4 showing the MERRA-2 AOD for Jan to March 2004 clearly shows that the main centre of the WAP with the highest AOD is over southern Nigeria where Figure 1 shows nearly all the gas flares in the region exist and Figure 1 in [3] shows the greatest concentration of biomass burning fires occur.

Further, whilst the MERRA_2 AOD in Figure 4 clearly shows the Bodélé Depression producing an aerosol plume, the AOD of the plume is about 0.50 close to the Bodélé Depression which, although still a significant level, is less than half the AOD over southern Nigeria at 1.2

2.4   Volcanoes

The Global Volcanism Program (GVP) database of volcanic eruptions [7] shows that the WAP Area hosts several volcanoes with only one, Mount Cameroon, recently active with an estimated 4 months of activity in JFM since 1950 with volcanic explosivity indices of 2. As this is unlikely to have any significant impact on the effects discussed in this paper an analysis of volcanic activity has not been included.

Note: this section on volcanoes is included for completeness as in some regions volcanic activity is a major source of aerosols and a negative finding should be reported.

2.5   Conclusions

1. The measured aerosol data clearly shows the most intense centre of the WAP is coincident with the main centre of biomass burning and gas flares in the region.
2. The literature clearly states that biomass burning fires are anthropogenic
3. The data cited above clearly linked fires in Nigeria to forest loss which is indubitably anthropogenic.
4. Oil industry gas flares are anthropogenic and a significant source of aerosols.
5. Volcanoes are not a significant source of aerosols in the WAP.

It is indisputable that biomass burning in Africa and therefore in West Africa is anthropogenic and is the major source of the WAP aerosols with gas flares being a secondary source in JFM and I conclude that the extreme JFM WAP is anthropogenic.

3   APPENDIX C: AEROSOLS AND CLIMATE

The IPCC Assessment Report 4 (AR4) [8] identifies the two main anthropogenic contributors to climate change as Long-Lived Green House Gases (LLGHG) and aerosols and defines Radiative Forcing (RF) as the global annual average of "the change in the net, downward minus upward, irradiance (expressed in W m–2) at the tropopause". The IPCC AR4 also discusses Surface Forcing (SF), the effects of the forcing agents at the surface of the Earth and Figure A7 from that report shows the evolution of RF and SF from 1850 to the present day. It can be clearly seen that the net anthropogenic RF effect, black line – panel (A), follows the red line of LLGHG reasonably closely. However, the net anthropogenic SF effect, black line – panel (B), clearly follows the evolution of the aerosol direct effect which is much larger than the aerosol direct RF effect. The SF graph also shows that the anthropogenic, globally and annually averaged aerosol direct effect in 2000 at -1.6W/m2 is comparable to the explosive volcanic eruptions of Krakatau (1883) -2.2W/m2 and Pinatubo (1991) -1.8W/m2 which are considered to have affected the mid to high latitude atmospheric circulation patterns [8].
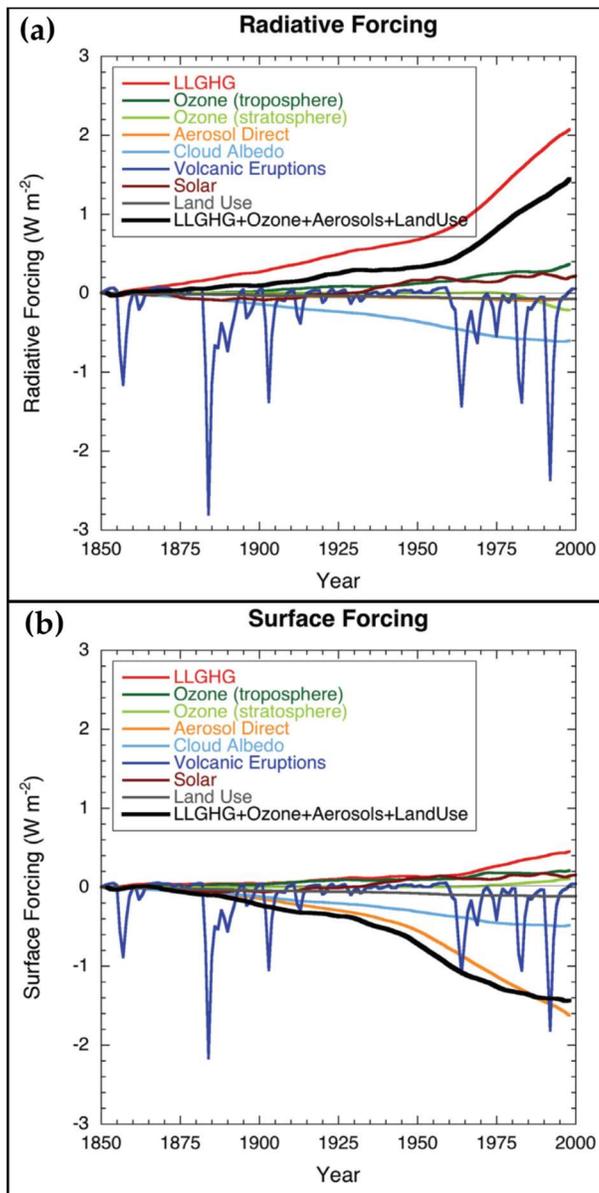
Figure A7. IPCC AR4 Figure 2.23 Chapter 2 page 208 [9]. (a) Globally and annually averaged temporal evolution of the instantaneous all-sky RF; (b) SF due to various agents, as simulated in the MIROC+SPRINTARS model (Nozawa et al., 2005; Takemura et al., 2005). This is an illustrative example of the forcings as implemented and computed in one of the climate models participating in the AR4. Note that there could be differences in the RFs among models. Most models simulate roughly similar evolution of the LLGHGs' RF.

Absorbing aerosols, particularly black carbon, a product of incomplete combustion [10], and organic carbon [11], have been linked to variations in the vertical temperature profile of the atmosphere and the large scale atmospheric circulation [8] [12] [13] [14]. Aerosols may also have a greater influence on the hydrologic cycle than other forcing agents through their SF effects [8].

Discussing the effects of aerosols on the West African monsoon, it was reported that biomass burning in West Africa is a large and direct source of carbonaceous aerosols, is nearly all anthropogenic and occurs mainly during the dry season. It was also noted that experiences from other regions suggest that aerosols can alter regional climate through their influences on clouds and radiation" [1].

Concerns were expressed that the distribution and evolution of aerosol emissions during the 20th century were not well understood [8] and most studies used in the IPCC AR4 omitted carbonaceous aerosols which could have significant effects at regional scales [15] .

The effects of short lived gases and aerosols were found to be substantial compared to LLGHG and to account for as much as 40% of the warming over the summertime United States and the climate response to these forcing agents was not confined to the area of their emission [16].

The global aerosol coverage and forcing is highly variable geographically and temporally and it is "insufficient or even misleading" to emphasise the global average and the aerosol SF is greater than the RF at the top of the atmosphere. Such SF affects the atmospheric circulation and the hydrologic cycle [17].

Investigating the climate of China and India, precipitation and temperature changes were found in the model that were comparable to those observed only if the aerosol ensemble included a large proportion of absorbing black carbon ("soot") which was similar to observed amounts, and noted that absorbing aerosols heat the atmosphere and alter the regional atmospheric stability and vertical motions which, in turn, affects the large-scale circulation and hydrologic cycle with significant regional climate effects [12].

Anthropogenic aerosols have been linked to: the decadal variance in the North Atlantic SST and thus to drought in the Sahel and the Amazon with the dominant mechanism being the reduction in short wave surface radiation [18]; and the expansion of the tropics in the northern hemisphere evidenced by a poleward shift of the Hadley Cells, subtropical dry zones and extra-tropical storm tracks; and West Africa is identified as one of the regions of the globe demonstrating trend increases in black carbon emissions of 1ng/Kg/year from 1970 to 2009 [19]. However [20] investigated the claims in [18] and whilst noting that HadGEM2-ES simulation contains significant discrepancies when compared with observations, accepted that aerosols have probably played a role in forcing the Atlantic multidecadal variability.

The extreme biomass burning episode in south East Asia in 2006 caused increased temperatures over Indonesia during the period of burning. The largest increases were found in October and November between 150 and 400 hPa. In some regions, increases exceeded 0.7º K during SON and it was noted that GCMs should include realistic representations of aerosols which fully represent the interannual variability of biomass burning emissions [21].

The carbonaceous aerosol emission inventories for the Coupled Model Intercomparison Project phase 5 (CMIP5) are based on [22] and are decadal averages designed to investigate long term (decadal to century) climate change, and the paper specifically states the emission inventories for CMIP5 are not designed to investigate "rapid" (ie less than a few years) pollution changes which this paper addresses.

Future emissions of anthropogenic aerosols are "directly addressable by government policy actions". [18]

In summary then the literature states aerosols affect:
1. The hydrologic cycle;
2. The large-scale atmospheric circulation systems; and
3. are not well understood;
and that carbonaceous aerosols:

1. Are an essential parameter in climate models to correctly model observed changes in precipitation;
2. Were omitted from most studies used in the IPCC AR4;
3. Have recently been linked to significant climate events; and
4. Are only included in the CMIP 5 RCP's as decadal averages which cannot model the effects this paper addresses; and
5. Are directly addressable by government policy actions.

The term Aerosol Regional Dimming (ARD) describes the surface radiative forcing effect of continental scale aerosol plumes which immediately alters the large-scale atmospheric circulation systems and regional hydrologic cycle and, crucially, only occurs when the plume exists.

4   APPENDIX D: DATA SOURCES

NASA MERRA-2	https://giovanni.gsfc.nasa.gov/giovanni/
NASA Terra	https://giovanni.gsfc.nasa.gov/giovanni/
NASA Fire Data	https://earthdata.nasa.gov/earth-observation-data/near-real-time/firms/active-fire-data ;
NASA CALIPSO Data	https://eosweb.larc.nasa.gov/project/calipso/calipso_table .
NCEP/NCAR Reanalysis	https://psl.noaa.gov/cgi-bin/data/timeseries/timeseries1.pl
NOAA/ESRL images	http://www.esrl.noaa.gov/psd/ .
LME	https://www.earthsystemgrid.org/
	https://www.earthsystemgrid.org/dataset/ucar.cgd.ccsm4.CESM_CAM5_LME.html
The UK Met Office at	https://www.metoffice.gov.uk/weather/learn-about/past-uk-weather-events
The IPCC Reports	https://www.ipcc.ch/reports/
Google Earth	https://www.google.com/earth/
Forest loss data	https://www.globalforestwatch.org/
BP oil production data	https://www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy.html
The GGFRP	https://www.worldbank.org/en/programs/gasflaringreduction ;
The GVP	http://dx.doi.org/10.5479/si.GVP.VOTW4-2013 ;
UN Population Data	
	https://www.un.org/en/development/desa/population/publications/database/index.asp

4.   APPENDIX E: LME and MERRA-2 MODEL AND TERRA DATA INFORMATION

3.1   *Overview*

The Last Millennium Ensemble (LME) is described in [23] and the LME project website at https://www.cesm.ucar.edu/projects/community-projects/LME/. The LME uses a ~2-degree atmosphere and land, ~1-degree ocean and sea ice version of the Community Earth System Model. CAM-5. The model was used in CMIP 5 (IPCC AR5) and is being used in CMIP 6 (IPCC AR6 due for release in 2022).

NCAR/UCAR provide a wealth of information at https://webext.cgd.ucar.edu/Multi-Case/CVDP_repository/cesm1.lm/ showing the LME output compares well with many other models and real-world data. A vast array of data is provided including inter alia, the NAO, AMOC and ENSO with LME data shown alongside other data from: ERA-20C, CERA-20C, ERAI, HadlSST and HadlSST_1.

The reason for the LME project was the pressing need to evaluate the ability of models such as CESM to capture observed variability on long term time scales and to determine the characteristics of variability associated with the individual natural forcings versus purely internal variability, and to permit a longer-term perspective for detection and attribution studies.[23].

Thus, I have used the LME model for exactly the type of analysis for which it was established.

3.2 *Aerosol Treatment in the LME*

The treatment of aerosols in the LME is shown in Table 1 in [23]. Aerosol emissions are fixed at 1850 values in all simulations except "All" and "Ozone-Aerosol" where the forcing is transient from 1850 to 2005. The reference paper states that the same forcings as the CESM-LE (Large Ensemble) from 1850 to 2005 were included with the addition of orbital changes in insolation not considered in the CESM-LE. The CESM-LME-adopted ozone and aerosol forcings are fixed at the 1850 control values until 1850 and then include the evolving anthropogenic changes to 2005. The CESM-LE forcings are specified in [22] which was also used in the IPCC Assessment Report 5.

3.3 *WAP Aerosols in the LME, MERRA-2 and Terra Data*

The WAP JFM AOD data from the 8 LME runs used in the paper shows:

1. The years when maximum AOD occurred range from 971 (solar 1.23) to 1962 (All 1.27).
2. The years when minimum AOD occurred range from 1033 (land 0.29) to 1918 (volcanic 0.31)
3. The WAP AOD across all the LME data ranges from 0.25 to 1.27
4. In none of the 8 forcing runs does the WAP AOD correlate with the WAP AOD from any other forcing run meaning that the forcing runs are independent time series.

In addition the ranges of WAP AOD are:

1. LME   0.25 to 1.27 average 0.66
2. MERRA-2   0.37 to 0.90 average 0.63 and
3. Terra   0.58 to 1.08 average 0.76

Which shows the LME WAP AOD covers a realistic range with:

1. A lower minimum AOD than MERRA-2 and Terra, as would be expected in a series covering the period before the WAP AOD, existed in its present extreme form as measured by Terra;
2. A slightly higher maximum AOD than Terra however only 33 of 8,248 data points show AOD levels higher than the Terra maximum and 68% of the LME years fall within the Terra limits;
3. The average LME JFM AOD is 0.66 which is slightly lower than the Terra data average at 0.78 which is expected as the Terra data covers the years since 2000 when the WAP was significantly higher as the MERRA-2 data shows.

Finally, the LME WAP AOD simulations show no significant trend as:

1. The average total trend across the 1,156 years of data from the 8 simulations is 0.01 which is insignificant compared with the average; and
2. Post 1950 (55 years) where the average total AOD trend across all eight LME runs is 0.016 compared with an average AOD of 0.67 which is an insignificant 2.4% change.

APPENDIX F: CORRELATION MATRIX FOR LME AND MERRA-2

Table A2. Correlation matrix for LME and MERRA-2 WAP Area AOD/AOD. The average excludes the self-correlations which return 1.00.

	850	All	Aero	GHG	Land	Orbital	Solar	Volc	MERRA-2	Average
850	1.00	0.03	-0.02	0.02	-0.02	-0.01	0.05	-0.01	-0.12	-0.01
All	0.03	1.00	-0.03	0.01	0.00	-0.02	-0.02	-0.02	0.14	0.01
Aero	-0.02	-0.03	1.00	0.01	-0.07	0.06	-0.09	-0.01	-0.08	-0.03
GHG	0.02	0.01	0.01	1.00	0.02	0.01	-0.03	0.03	0.04	0.01
Land	-0.02	0.00	-0.07	0.02	1.00	-0.01	0.01	-0.03	-0.07	-0.02
Orbital	-0.01	-0.02	0.06	0.01	-0.01	1.00	-0.04	0.03	0.23	0.03
Solar	0.05	-0.02	-0.09	-0.03	0.01	-0.04	1.00	-0.06	0.14	0.00
Volc	-0.01	-0.02	-0.01	0.03	-0.03	0.03	-0.06	1.00	-0.26	-0.04
MERRA-2	-0.12	0.14	-0.08	0.04	-0.07	0.23	0.14	-0.26	1.00	0.00
Average	-0.01	0.01	-0.03	0.01	-0.02	0.03	0.00	-0.04	0.00	0.00

Note: There are some small correlations between MERRA-2 AOD and the LME runs, however some are positive and some negative in Table A2, hence the 9 data sets are independent.

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