How extreme apparitions of the volcanic and anthropogenic south east Asian aerosol plume trigger and sustain: El Niño and Indian Ocean Dipole events; and drought in south eastern Australia. First attribution and mechanism using Global Volcanism Program, Last Millennium Ensemble, MERRA-2 reanalysis and NASA satellite data.

SUPPLEMENTARY INFORMATION

S1 APPENDIX A: THE VOLCANIC SOUTH EAST ASIAN AEROSOL PLUME

This paper analyses the volcanic South East Asian aerosol Plume (SEAP) which is created by volcanoes within the region 90º to 160º E 10º S to 10º N (SEAP Area). Figure 1 in the paper shows this region which includes nearly all Indonesia, Malaysia, Brunei, Papua New Guinea and parts of the Philippines and Thailand and the Global Volcanism Program (GVP) overlay of volcano locations, each red triangle is either one or, at this scale, a cluster of volcanoes.

The GVP database of volcanic eruptions (Venzke, 2013) shows that the SEAP Area hosted over 26% of all the global volcanic eruptions from 1800 to 2020 whilst covering only 3% of the Earth's surface. Simkin and Siebert (2000) reported that 16 volcanoes have been erupting nearly continuously for 30 years and that 5 of these volcanoes are in the SEAP Area. Hence the SEAP Area hosts an unusually high percentage of the global volcanic activity and within it Indonesia is "the most volcanically active nation on Earth" (USGS) https://www.usgs.gov/center-news/revolutionizing-volcano-monitoring-indonesia .

It is also worth noting that the median duration of a volcanic eruption is 7 weeks (Simkin and Siebert, 2000). The Intergovernmental Panel on Climate Change (IPCC) Assessment Report 5 (AR5) in Fig. 1 of section FAQ 11.2 notes that the effect of volcanic eruptions on the lower atmosphere (and therefore the surface) is "cooling because the reduction of sunlight overwhelms any increased downward energy emitted by the volcanic cloud" and also states the residence time for volcanic ash in the troposphere is 1 to 3 weeks. Hence a volcanic ash plume will have a median residence time of 8 to 10 weeks in the atmosphere – 7 weeks of eruption followed by 1 to 3 weeks of residence and crucially, during this time, because the source is at a fixed location, the plume is effectively stationary on the Earth's surface.

The volume of tephra ejected by volcanoes in the SEAP Area was calculated as shown in Appendix C.

The VEIT data was summed for each decade from 1870 to the present and when restricted to the April to October (the wet season in South Eastern Australia (SEAus)) Fig. S1 shows the 2000 to 2009 VEIT level was 2.89 times the 20th century average. This is a period which closely matches the SEAus Millennium Drought, 1998 to 2008, the cause of which has not yet been determined.

Spread of tropospheric volcanic tephra: Figure S2 shows an image of the eruption of the Sangeang Volcano in Indonesia which continued for 1.5 years from May 2014 to November 2015 (GVP database) at an estimated VEI of 3 (GVP) suggesting the majority of the tephra remained in the troposphere. This image demonstrates how quickly the aerosol plume spreads from a point source to about 250 km width in the lower right of the image after travelling about 400 Km. Noting that Indonesia, which covers a significant part of the SEAP Area, is "the most volcanically active nation on Earth" (USGS) it is easy to see how volcanic tephra from multiple simultaneous eruptions can significantly affect the AOD and the surface solar radiation in the SEAP Area.

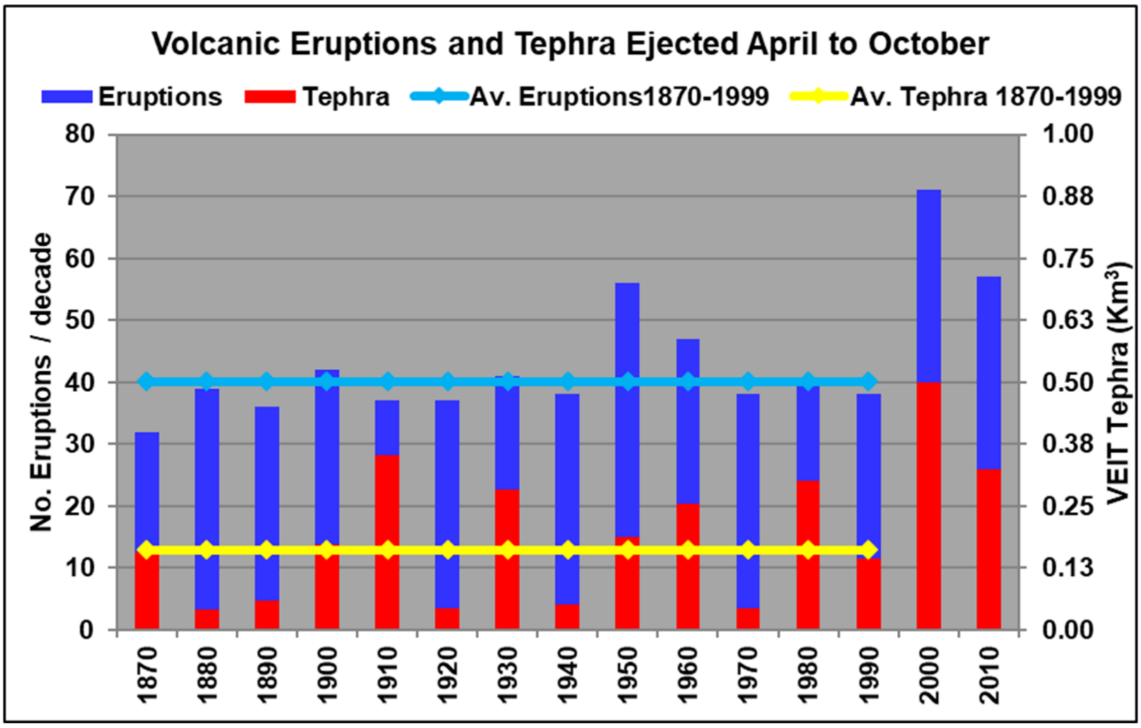

Figure S1: Decadal total and average volcanic eruptions and tephra volume in the SEAP Area from April to October. Averages from 1870 to 1999. Source GVP database.

Figure S2: Aerosol plume emanating from Sangeang Volcano May 2014. Source NASA.

S1.1 Tectonic activity SEAP Area

The increased level of volcanic/tectonic activity in the SEAP Area in recent decades is confirmed by the increase in the number of earthquakes. Earthquake activity increased from the early 1980's to 2005, declined to 2009 and has since increased again. The USGS provides earthquake data from 1973 at: https://www.usgs.gov/natural-hazards/earthquake-hazards/science/20-largest-earthquakes-world?qt-science_center_objects=0#qt-science_center_objects and Fig. S3 shows that the average number of earthquakes per month in the SEAP Area was 71 between 1973 and 1982. The red line marks this average plus 3 standard deviations calculated from the same period and shows that from 1995 to 2009 and 2013 to 2020 there was a significant (> 3 std deviations) increase in the number of earthquakes which peaked at 1,303 in January 2005 after the Boxing Day earthquake and tsunami. In May 2009 the number of earthquakes fell below the red line for the first time since January 1995 for a short time but in 2013 increased again and continued at this level until 2020.

The spate of major earthquakes, magnitude greater than 8.0, from 1985 to 2015 seen in Fig. S3 also confirms the exceptional increase in tectonic activity in this period.

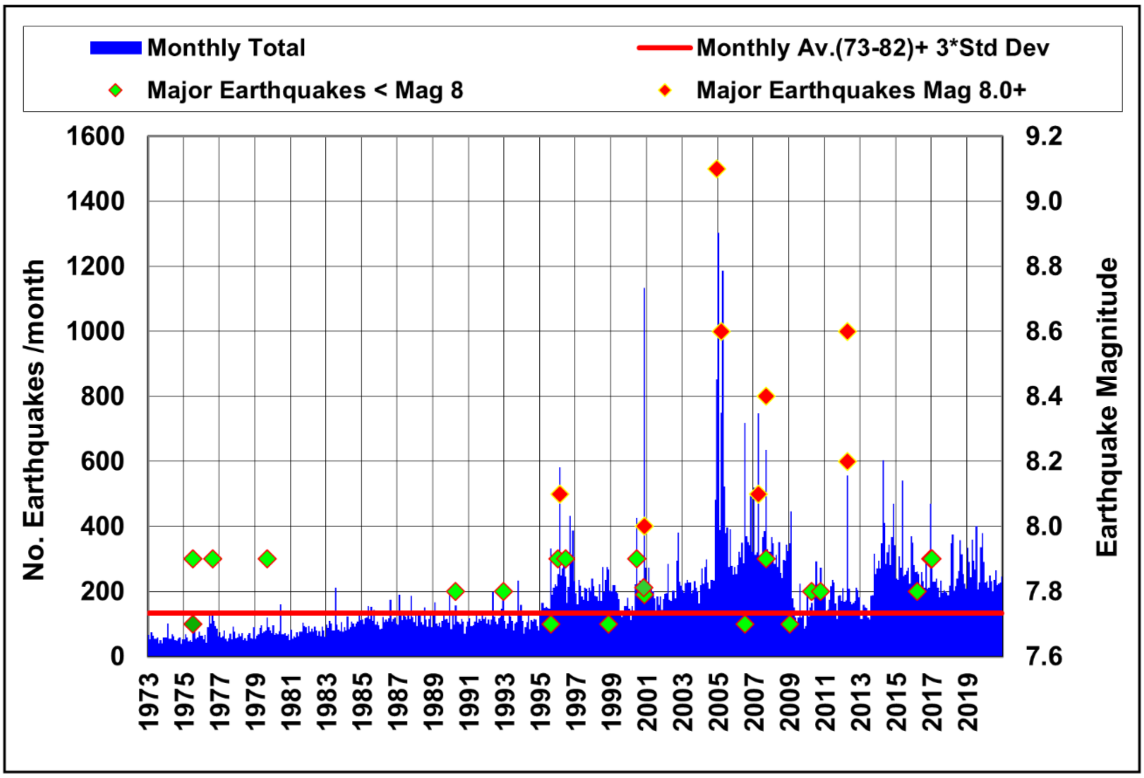

Figure S3: Total monthly earthquakes 1973 – 2020 SEAP Area with major events magnitude 7.7+ shown. Source: USGS earthquake database.

S2 APPENDIX B: THE ANTHROPOGENIC SOUTH EAST ASIAN PLUME

The anthropogenic SEAP is one of eight continental scale plumes, Fig. S4 and S5, and the AOD of the SEAP is shown in Fig. S6 where it is clear that SON is the season when the AOD is at its maximum.

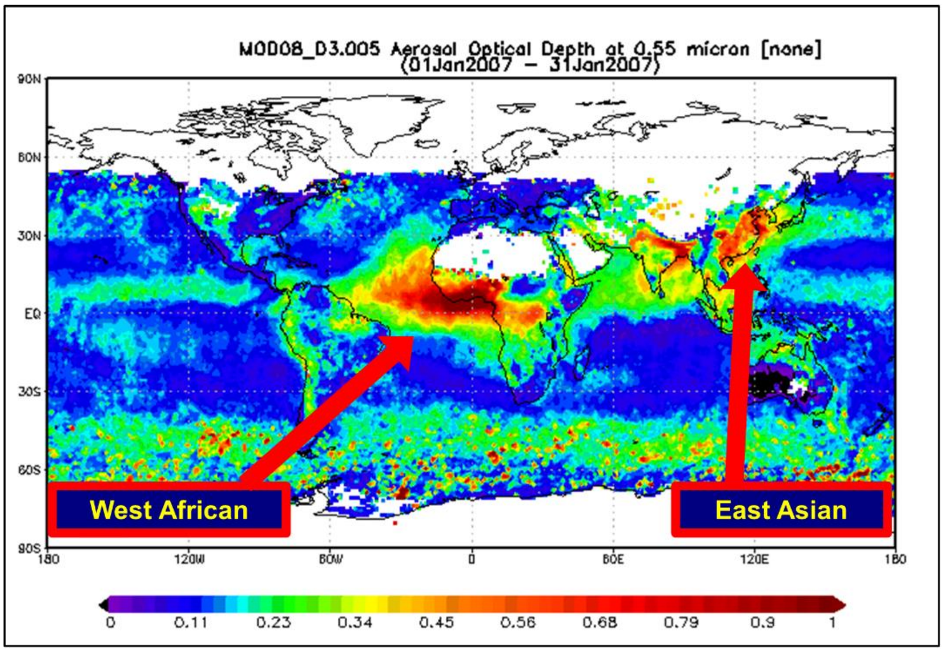

Figure S4: Two of eight continental scale aerosol plumes. Source NASA January 2007

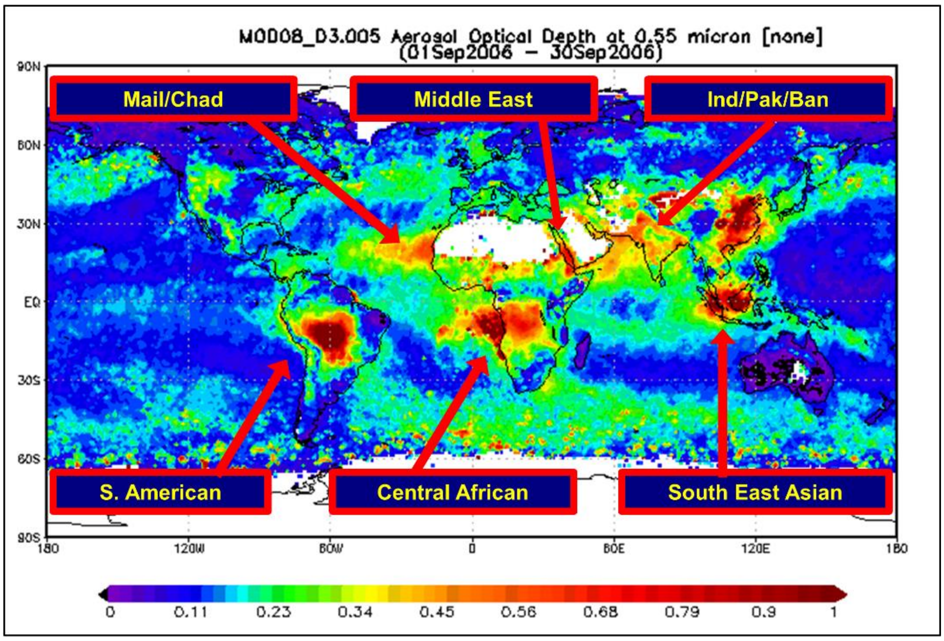

Figure S5: Six of eight continental scale aerosol plumes. Source NASA. September 2006.

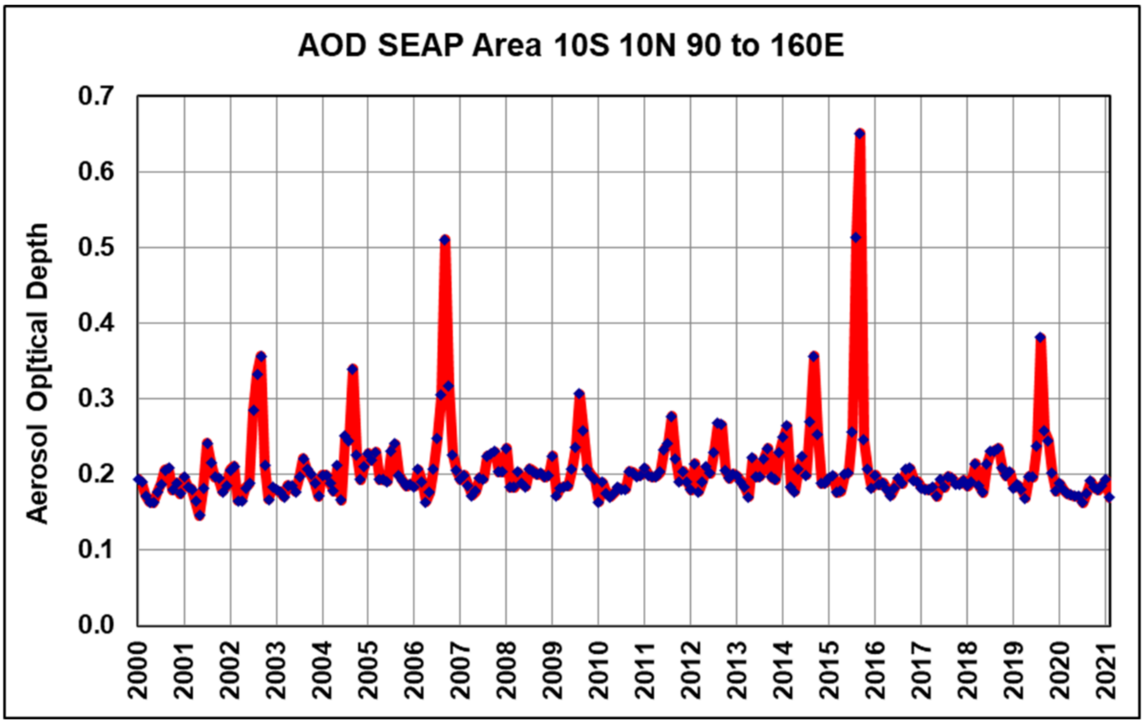

Figure S6: Monthly average MODIS Terra AOD in the CSEAP Area 5º S-5º N and 100º E-120º E.

S2.1 Biomass burning

Biomass burning in the tropics is part of the annual agricultural cycle and usually occurs at the end of the dry season before the start of the local monsoon. In the SEAP Area the monsoon commences in November and the biomass burning aerosol plume is at its most intense in SON. The increase in biomass burning in the SEAP Area in recent decades has been driven by the increasing population of the SEAP Area. The population of Indonesia, Malaysia and Papua New Guinea has increased from 77 to 277 million between 1950 and 2010 (United Nations https://www.un.org/en/development/desa/population/publications/database/index.asp). 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. There has also been increasing levels of commercial activity including rainforest logging. In SON in 1982, 1991, 1997, 2002, 2004, 2006, 2009, 2014 and 2015 the AOD or AI increased significantly compared to the intervening years (Fig. S6) due to the clearing of the rainforest for palm oil plantations.

Applegate et al. (2001) found that there was a number of direct causes of fire in the 1997-98 fires in Indonesia:

- Fire being used to assist with land clearing;
- Fire used as a weapon in land tenure or land use disputes;
- Accidental or escaped fires;
- Fire connected with resource extraction.

Neither climate change nor ENSO events are identified as a primary cause of fire in 1997-98 and the other major fire events in 1982/1983, 1987, 1991 and 1994 although this is commonly stated to be the case in the literature relating to ENSO events. ENSO is only noted as a reason for the spread of fire started by the causes noted above in certain years.

The 6th International Wildland Fire Conference held by the United Nations International Strategy for Disaster Reduction and their Food and Agriculture Organization in Korea, in 2015 released the Pyeongchang Declaration "Fire Management and Sustainable Development" (https://gfmc.online/allgemein/korea-2015.html) which stated in the Regional Statement for southeast Asia that "Most vegetation fires occurring in the member countries of the Association of Southeast Asian Nations are due to human interventions, notably by local communities and industrial corporations."

Reports in the popular press as well as governments in the region attribute the cause of such fires to land clearing in Indonesia and on Nov 9 2006 Reuters reported "Environment ministers from five Southeast Asian countries endorsed a plan of action on Thursday to fight forest fires in Indonesia that have spread choking smoke across the region." and "Indonesia's neighbours have grown increasingly frustrated by the fires, most of which are deliberately lit by farmers or by timber and palm oil plantation companies to clear land for cultivation." In September 2015 the Times in London reported that "Singapore has taken legal measures against Indonesian businesses for the vast forest fires that are choking millions of people across southeast Asia." See CIFOR at https://forestsnews.cifor.org/37016/clearing-the-smoke-the-causes-and-consequences-of-indonesias-fires?fnl=en which states that 115,000 fires were burning in Indonesia in October 2015.

The connection between AOD in the CSEAP Area and fire is demonstrated in three ways:

One: The burned areas in Indonesia from NASA at https://search.earthdata.nasa.gov/projects?p=C1457414586-SEDAC!C1457414586-SEDAC&pg[1][v]=t&pg[1][m]=download&q=burned%20area%20indonesia&tl=1563231391!4!! (Center for International Earth Science Information Network - CIESIN - Columbia University, 2018) from 1997 to 2015 was extracted. Correlating the MERRA-2 AOD in SON, the burning season, with the areas burned in Indonesia gives 0.96 significance <0.01. The data is shown in Fig. S7

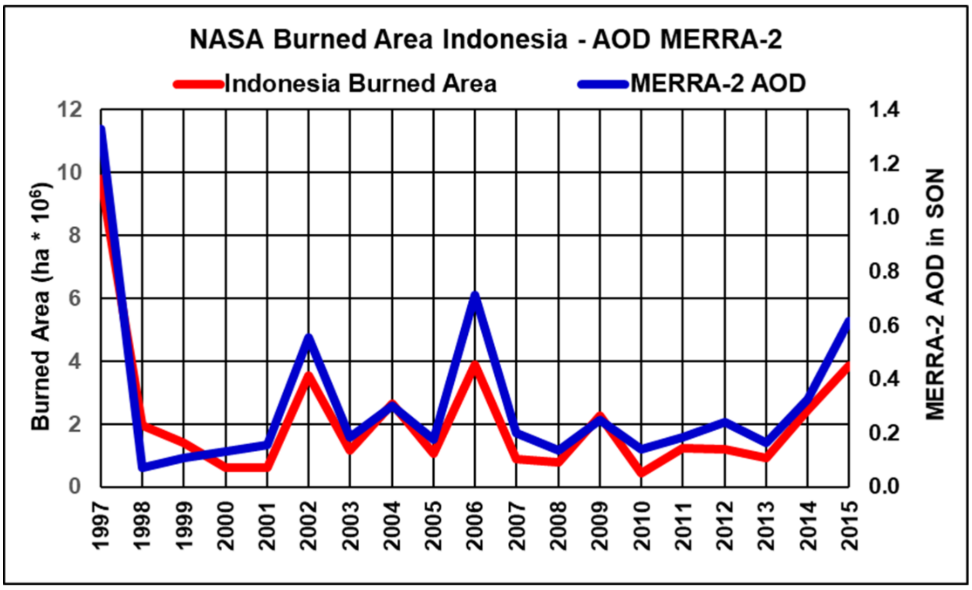

Figure S7: NASA MERRA-2 AOD in SON and area burned.

Two: The NASA MODIS FIRMS (Fire Information for Resource Management Systems) at https://firms.modaps.eosdis.nasa.gov/ from November 2000 to 2020 for Indonesia was downloaded. The daily total number of fire locations was calculated and then the average number per month was then calculated to avoid double counting fires identified on more than one day. The resulting fire count data for all months and the SON average is shown in Fig. S8 with trend lines, R^2 and trend line equation. The "all months" and SON datasets show correlations between the CSEAP AOD and fire count of 0.82 and 0.96 respectively significance < 0.01 for both. Figure S8 clearly shows significant increases in AOD as the fire count increases - +0.5 and +0.7 per 1,000 fire count increase respectively. The CSEAP AOD is used in this analysis as the fire count is for Indonesia and the CSEAP Area covers most of Sumatra and Borneo the location of the majority of the fires.

Note: The three highest monthly AOD levels in Fig. S8 are all in SON (Oct 2006 and Sept and Oct 2015)

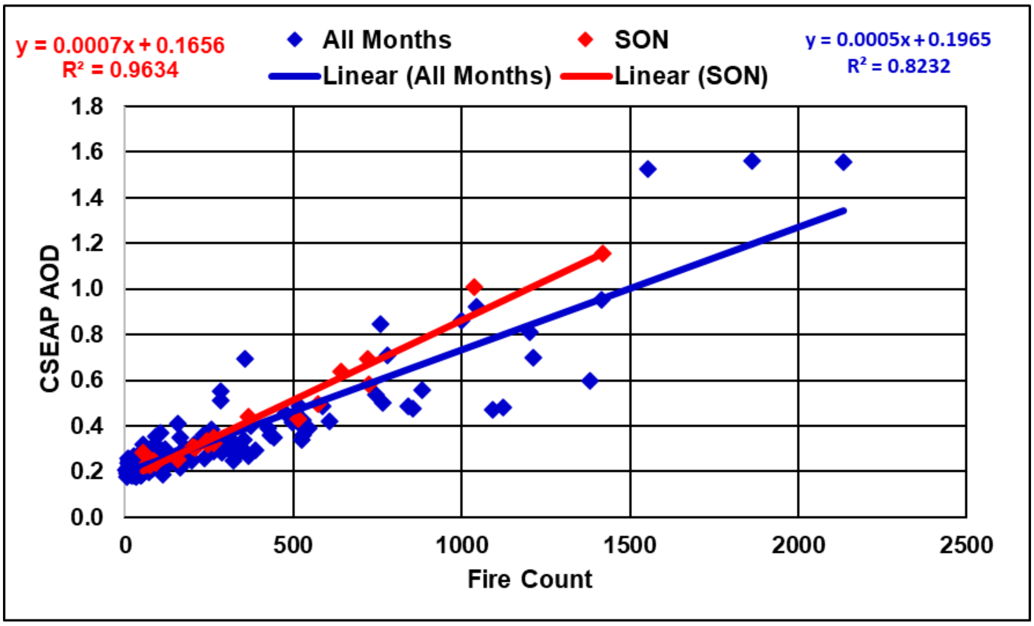

Figure S8: NASA fire information for resource management (Indonesia) and CSEAP AOD

Three: Correlating the Black Carbon (BC) Emissions from the Global Fire Emissions Database (GFED4.1) (Randerson et al., 2017) for the Equatorial Asian (EQAS) Region and of similar extent to the SEAP Area) from fires at https://daac.ornl.gov/cgi-bin/dsviewer.pl?ds_id=1293 for the period 1997 to 2020 with the SON AOD of the CSEAP Area gives 0.96. The data is shown in Fig. S9.

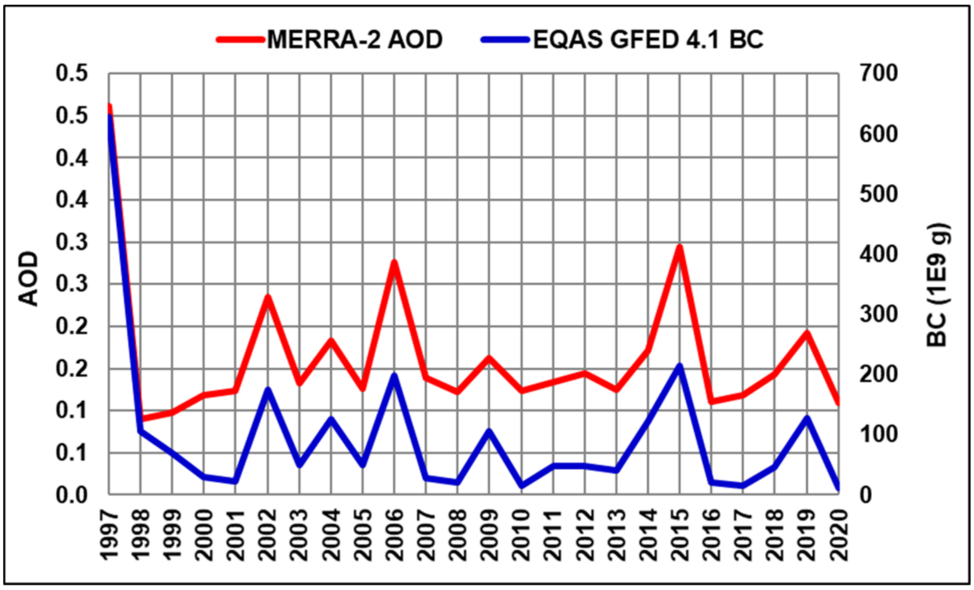

Figure S9: Equatorial Asian region black carbon emissions from the GFED database 4.1 and the CSEAP Area SON MERRA-2 AOD.

S2.1.1 Conclusion

165 Together the burned area, fire and BC data show that the extreme AOD in SON in some years is created by fires in south east Asia, mainly Indonesia.

S2.2 Gas flares

Gas Flares in the oil production industry increased in number over recent decades as oil production in south east Asia (Indonesia, Malaysia, Thailand and Brunei) increased from 567,000 to 1,856,000 barrels of oil per day between 1965 and 2020 (BP Statistical Review of World Energy 2021). Reid et al. (2013) discuss the composition of the SEAP.

The World Bank has established the GGFRP which estimates SE Asia flares 4.03 billion m^3 of natural gas each year and the gas flare locations are shown in Fig. 1 of the paper. NOAA identifies about 387 flare locations in the SEAP Area. Images of such flares producing aerosols are easily found in Google Earth (Fig. S10) or at the GGFRP web site.

Figure S10: LNG Badak. Credits: Left Ridho Akbari, Right Fauzi (from ©Google Earth)

S3 APPENDIX C: VOLCANO DATA PROCESSING

The volcanic eruption data was downloaded from the Global Volcanism Program database at https://volcano.si.edu/list_volcano_holocene.cfm (Venzke, 2013). Then:

- Eruptions from 1870 were extracted;
- The Volcanic Explosivity Index (VEI) was extracted. Any eruptions without a listed VEI were allocated a VEI of 0;
- VEI was converted to Tephra (VEIT) in Km^3 using the table in Newhall and Self (1982) which is a pseudo logarithmic scale – level 2 is 100 times greater than level 1 whilst all other levels increase by a factor of 10;
- The eruption start year was extracted;
- The eruption start month was extracted. Eruptions with no start month were allocated sequentially to January then February and so on;
- The end year and month was extracted. For eruptions with no end date the end date was calculated using the start date and the median eruption length in (Simkin and Siebert, 2000) of 7 weeks (2 months);
- The length of each eruption in months was calculated;
- The average monthly VEIT for each eruption was calculated and allocated equally to each month of the eruption starting with the start month and ending with the end month.
- The VEIT for each month from 1870 to 2020 was summed;
- The monthly VEIT was summed to give annual VEIT data;
- In all the analyses except for the SEAus pressure and rainfall the annual VEIT data was allocated to segments and averaged and the corresponding monthly Nino or associated parameter was allocated to the same segment and averaged;
- For the SEAus pressure and rainfall only, the analysis covered the months from April to October as this is the wet season in SEAus. The monthly values were summed to give a value for each year;
- The VEIT, on a logarithmic scale, and the Nino and associated parameters were then displayed on scatter plots with the trend line, trend line equation and R^2 value.

S4 APPENDIX D: – CORRELATION MATRIX FOR LME AND MERRA-2

	850	All	GHG	Land Use R3	Orbital R3	Ozone Aerosol R2	Solar	Volcanic R5	MERRA 2
850	1.00	0.02	0.03	-0.04	0.08	-0.08	0.07	-0.02	-0.37
All	0.02	1.00	0.02	0.00	-0.02	0.54	-0.04	-0.02	0.12
GHG	0.03	0.02	1.00	0.00	0.09	-0.06	0.04	0.01	-0.05
Land Use R3	-0.04	0.00	0.00	1.00	0.00	0.02	0.00	0.02	-0.03
Orbital R3	0.08	-0.02	0.09	0.00	1.00	0.12	-0.01	0.03	-0.09
Ozone Aerosol R2	-0.08	0.54	-0.06	0.02	0.12	1.00	-0.15	0.12	-0.09
Solar	0.07	-0.04	0.04	0.00	-0.01	-0.15	1.00	-0.07	0.25
Volcanic R5	-0.02	-0.02	0.01	0.02	0.03	0.12	-0.07	1.00	-0.39
MERRA 2	-0.37	0.12	-0.05	-0.03	-0.09	-0.09	0.25	-0.39	1.00
Average	-0.04	0.08	0.01	0.00	0.03	0.05	0.01	-0.04	-0.08

Table S1: Correlation matrix for LME and MERRA-2 CSEAP AODVIS/AOD. The average excludes the self-correlations which return 1.00.

There is only one significant positive correlation between the All and Ozone Aerosol data in Table S1 hence 8 of the 9 data sets are independent.

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