The South East Asian Aerosol Plume: The Cause of All El Niño Events

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Abstract

ENSO events are the most significant interannual perturbation of the climate system. Previous attempts to link ENSO with volcanic eruptions failed because only large eruptions across the globe, which typically eject tephra into the stratosphere, were considered. I have analysed all volcanic eruptions in South Eastern (SE) Asia, about 10ºS to 10ºN and 90ºE to 160ºE (4d), the most volcanically active area in the world with over 23% of all eruptions in the Global Volcanism Program database since 1500 occurring here and with 5 volcanoes stated in the literature to have erupted nearly continuously for 30 years. SE Asia is also the region where the convective arm of the thermally direct Walker Circulation occurs driven by the intense equatorial solar radiation which creates the high surface temperature. The volcanic tephra plume intercepts some of the solar radiation by absorption/reflection which cools the surface and heats the atmosphere creating a temperature inversion compared to periods without the plume. This reduces convection and causes the Walker Circulation and Trade Winds to weaken. This reduced wind speed causes the central Pacific Ocean to warm creating convection there and further weakening the Walker Circulation. With the reduced wind stress the western Pacific warm pool migrates east. This creates an ENSO event which continues until the tephra plume reduces, typically when the SE Asian monsoon commences, and convection is re-established over SE Asia and the Pacific warm pool migrates back to the west. Correlations of SE Asian tephra and the ENSO indices are typically over 0.80 at $\rho < 0.02$ at 5c below. In recent decades the anthropogenic SE Asian aerosol Plume (SEAP) has intensified the volcanic plume in some years from September to November (SON). Using NASA satellite data and the NASA MERRA-2 reanalysis dataset I show correlation coefficients typically over 0.70 and up to 0.99 at $\rho < 0.01$ between the aerosol optical depth (AOD) or aerosol index (AI) and the ENSO indices on a detrended basis in SON at 5a. If two events A and B correlate 5 options are possible: (1) A causes B; (2) B causes A; (3) C, another event, causes A & B simultaneously; (4) It's a coincidence; and (5) The relationship is complex with feedback. The volcanic results: only allow options 1 or 4 as ENSO cannot cause volcanic eruptions; and are backed up by 4 independent satellite datasets and NASA's MERRA-2 reanalysis which assimilates aerosol observations. I conclude volcanic and anthropogenic aerosols over SE Asia are the sole cause of all ENSO events.

The South East Asian Aerosol Plume: The Cause of All El Niño Events

Volcanic Tephra ejected in south eastern Asia is the sole cause of all historic ENSO events.
This natural aerosol plume has been intensified by an anthropogenic plume in the same region in recent decades, which has intensified some ENSO events and altered the Southern Oscillation Index and Niño 3.4 SST characteristics.

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1. Abstract

ENSO events are the most significant interannual perturbation of the climate system. Previous attempts to link ENSO with volcanic eruptions failed because only large eruptions across the globe, which typically eject tephra into the stratosphere, were considered. I have analysed all volcanic eruptions in South Eastern (SE) Asia, about 10ºS to 10ºN and 90ºE to 160ºE (4d), the most volcanically active area in the world with over 23% of all eruptions in the Global Volcanism Program database since 1500 occurring here and with 5 volcanoes stated in the literature to have erupted nearly continuously for 30 years.

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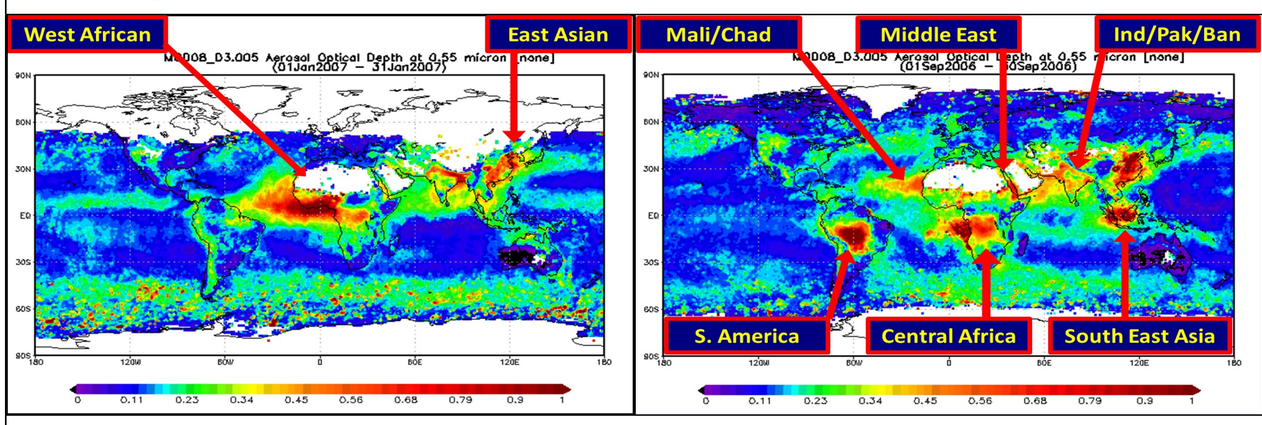
With the reduced wind stress the western Pacific warm pool migrates east. This creates an ENSO event which continues until the tephra plume reduces, typically when the SE Asian monsoon commences, and convection is re-established over SE Asia and the Pacific warm pool migrates back to the west. Correlations of SE Asian tephra and the ENSO indices are typically over 0.80 at ρ< 0.02 at 5c below.

In recent decades the anthropogenic SE Asian aerosol Plume (SEAP) has intensified the volcanic plume in some years from September to November (SON). Using NASA satellite data and the NASA MERRA-2 reanalysis dataset I show correlation coefficients typically over 0.70 and up to 0.99 at ρ < 0.01 between the aerosol optical depth (AOD) or aerosol index (AI) and the ENSO indices on a detrended basis in SON at 5a.

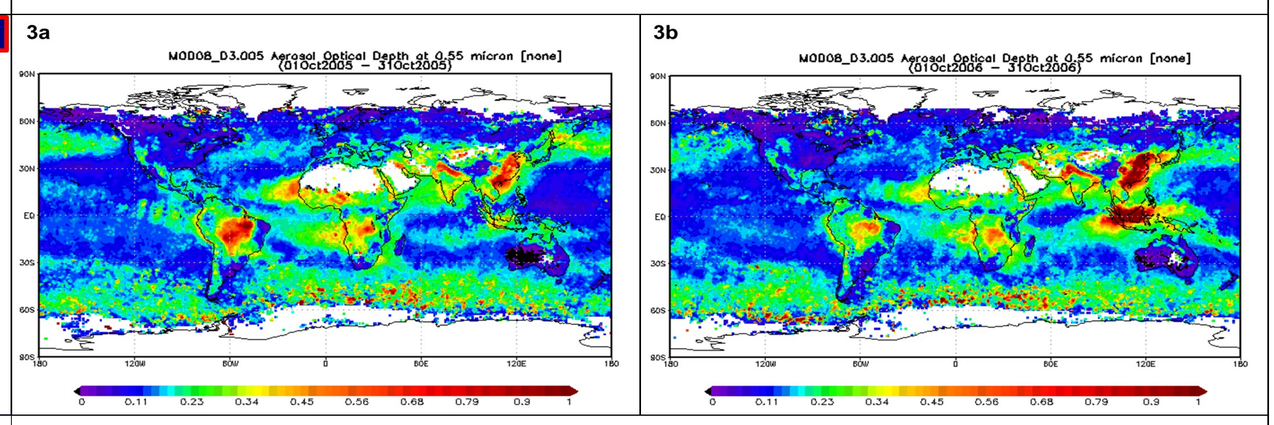
If two events A and B correlate 5 options are possible: (1) A causes B; (2) B causes A; (3) C, another event, causes A & B simultaneously; (4) It's a coincidence; and (5) The relationship is complex with feedback. The volcanic results: only allow options 1 or 4 as ENSO cannot cause volcanic eruptions; and are backed up by 4 independent satellite datasets and NASA's MERRA-2 reanalysis which assimilates aerosol observations.

I conclude volcanic and anthropogenic aerosols over SE Asia are the sole cause of all ENSO events.

2. The Eight Great Aerosol Plumes - Jan and Sep (NASA Giovanni - Terra AOD)



3. Interannual Variation - SEAP Oct 2005 and 2006 (NASA Giovanni - Terra AOD)



4. The South East Asian aerosol Plume (SEAP)

The natural and historic SEAP: ***The SEAP Area (4d) is the most tectonically active area in the tropics*** with the USGS earthquake database showing 25% (5 of 20) of the major earthquakes (magnitude >= 8.4) in the world since 1900 occurred in the SEAP Area and the Global Volcanism Program's database showing that from 1500 to 2016 over 23% of the global volcanic eruptions occurred in the SEAP Area. The figures below show the number of earthquakes (4a), volcanic eruptions and the volume of tephra ejected in the SEAP Area through the last century (4b) and it is clear that the level of activity varies hugely. Tephra from volcanic eruptions such as Pinatubo (4c) and Sangeang (page 2 9.1) are the natural and historic source of aerosols in the SEAP Area.

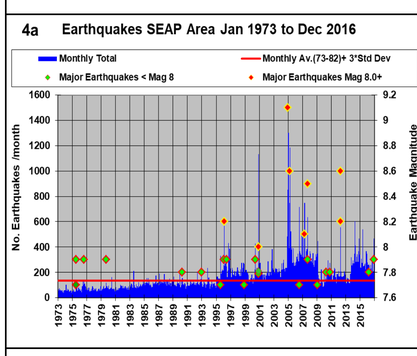
The anthropogenic and recent SEAP: Is one of eight, continental scale, aerosol, plumes (2.) which now occur annually. It can be seen on the monthly mean AOD data from the NASA Giovanni System. Two areas are used to describe the SEAP: the SEAP Area, its location; and the Central SEAP (CSEAP) Area where it is most intense (4d).

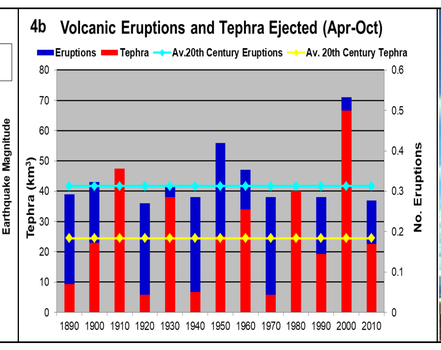
The increase in the monthly AI/AOD of the CSEAP Area since 1979 (4e) demonstrates the peak anthropogenic aerosol emission season is SON, the end of the dry season in SE Asia, and was very high in 1997, 2002, 04, 06, 09, 14 & 15 compared with the intervening years. 3b shows the extent of the Oct. 2006 extreme apparition of the SEAP.

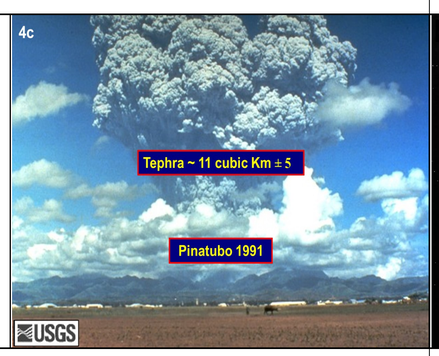
This paper focuses on Sep, Oct and Nov (4f) because the anthropogenic SEAP is at its most intense and will therefore have its greatest effect in this season. The maximum AOD and AI for the CSEAP Area was 1.282 (Oct 2006) and 1.811 (Sept 1997). The AI of the CSEAP Area grew from 0.050 in Sep 1979 to 0.297 in 1992 and to 0.396 in 2000 a 491% and 687% increase respectively in years without extensive biomass burning.

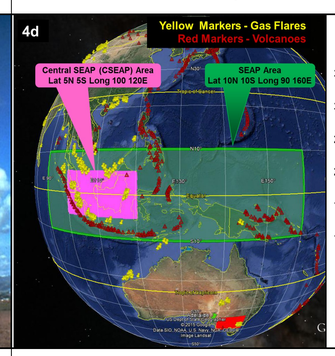
From 1979 to 1997 (a major biomass burning event year) the increase in AI in September was 3.499%. Page 2 at section 10 shows the theoretical reduction in surface radiation caused by the SEAP.

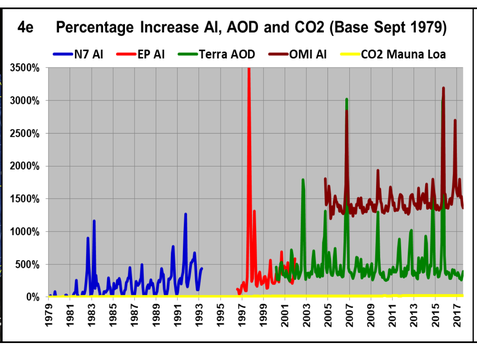
The major anthropogenic sources of aerosols are biomass burning driven by an increasing population needing agricultural land and living space as well as commercial activity and gas flares in the oil industry. NOAA (National Oceanic and Atmospheric Administration, USA) estimates SE Asia flares 4.03 billion cubic metres of gas per year.

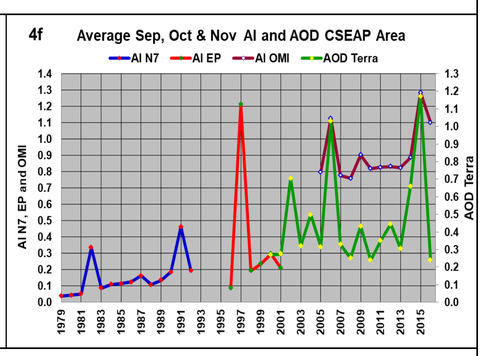












5. El Niño / ENSO Events, Tephra and Aerosols

El Niño events are closely linked with changes in the Walker Circulation (9a) - especially the Trade Winds. The literature, NASA, NOAA, IPCC and UK Met Office state in reports or on their websites that El Niño events start when the Trade Winds in the central and western Pacific Ocean relax or reverse. The Trade Winds form the lower limb of the Walker Circulation a "Direct thermally driven zonal overturning circulation in the ***atmosphere*** over the tropical Pacific Ocean, with rising air in the western and sinking air in the eastern Pacific" (IPCC). As the Walker Circulation is directly thermally driven the heat must be applied ***at the Earth's surface in SE Asia - the SEAP Area*** - to drive the circulation. Since the variation in solar radiation at the top of the atmosphere cannot explain the reduction in surface heating and the Trade Wind relaxation, the reduction in heat must be caused in the atmosphere by aerosols.

First: I show the SON and annual correlations of the AI/AOD of the CSEAP Area and the various indices used to monitor ENSO events identified in the IPCC Assessment Report 5 (AR5), shown in red, as well as other parameters in 5a & 5b. They demonstrate that when an aerosol plume exists in the SEAP Area from 1979 to 2016:

- The level of OLR increases - implying a decrease in the radiation reaching the surface;
- Convection in the CSEAP Area reduces and the Sea Surface Temperature (SST) of the SEAP Area reduces;
- The Trade Winds relax;
- The SST in the Niño Areas 1+2 and 3.4 increases as does the Oceanic Niño Index; and
- The Southern Oscillation Index (SOI) decreases.

Second: Table 5c shows the relationship between: volcanic tephra in the SEAP Area; Niño 3.4 SST; the SOI and CSEAP Area omega. Tephra (4c) data was calculated from the Volcanic Explosivity Index (VEI) data, VEI Tephra (VEIT), deskewed, segmented, averaged/segment and then correlated with the segmented averages of the other parameters from 1870, 1876 and 1948 respectively to 2016. Graphs of VEIT, SST and SOI are at 5j and 5l.

Third: Table 5c and the graph at 5k show that the HadCRUT4 global temperature rises with increasing tephra.

Fourth: The maps 5e - 5i (NCEP reanalysis) show the anomalies caused by the SEAP by deducting years of low SEAP AOD (2000, 01 and 05) from years of high AOD (2002, 04 and 06) in SST, SLP, omega, wind speed & OLR.

Fifth: The graphs 5j to 5l show that higher levels of VEIT result in:

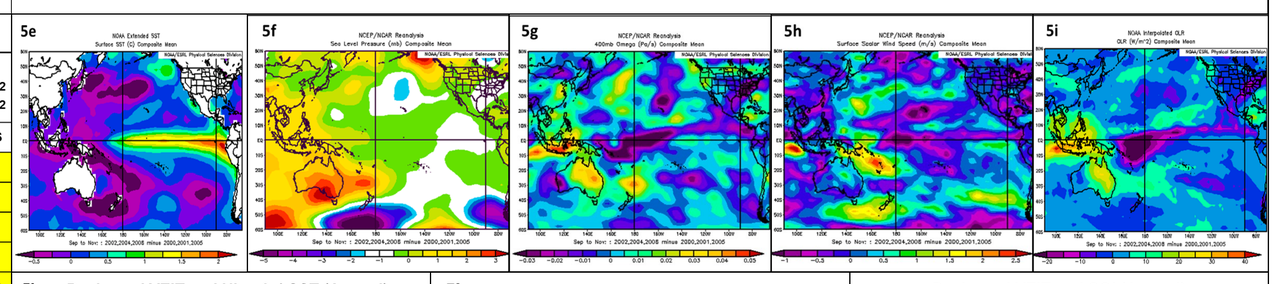
- Increased Niño 3.4 SST levels;
- Lower SOI levels; and
- ***Increased HadCRUT4 global temperatures.***

5a Sept Oct Nov - Detrended Series – Correlations

		AOD Terra	AI Nimbus 7	AI E Probe	AI OMI	AI N7 + EP	AI N7+EP +OMI	AOD MERRA-2 MERRA-2
		2000-16	1979-92	1996-01	2004 - 16	1979-01	1979-16	1980-16
1	CSEAP Area Omega	0.93	0.75	0.97	0.83	0.75	0.73	0.84
2	NOAA T. Wind Index	-0.84	-0.72	-0.99	-0.83	-0.81	-0.82	0.93*
3	SST Niño 3.4	0.85	0.71	0.96	0.76	0.78	0.75	0.81
4	SST Niño 1 and 2	0.86	0.64	0.97	0.81	0.87	0.84	0.80
5	SOI	-0.74	-0.74	-0.88	-0.66	-0.69	-0.66	-0.89**
6	Oceanic Niño Index	0.85	0.70	0.97	0.77	0.78	0.76	0.79
7	SST SEAP Area	-0.86	-0.89	-0.88	-0.71	-0.87	-0.81	-0.74
8	Rainfall CSEAP Area	-0.82	-0.78	-0.89	-0.75	-0.60	-0.60	-0.85
9	NOAA Interpl'd OLR	0.94	0.80	0.99	0.81	0.76	0.75	0.83

5b Annual – Detrended Series – Correlations

		AOD Terra	AI Nimbus 7	AI E Probe	AI OMI	AI N7 + EP	AI N7+EP +OMI	AOD MERRA-2 MERRA-2
		2000-16	1979-92	1996-01	2004 - 16	1979.01	1979-16	1980-16
1	CSEAP Area Omega	0.88	0.84	0.97	0.70	0.76	0.72	0.78
2	NOAA T. Wind Index	-0.75	-0.76	-0.81	-0.73	-0.70	-0.75	0.71 *
3	SST Niño 3.4	0.71	0.68	0.81	0.65	0.67	0.66	0.77
4	SST Niño 1 and 2	0.80	0.64	0.43	0.61	0.56	0.57	0.55
5	SOI	-0.57	-0.68	-0.78	-0.39	-0.64	-0.61	-0.85 **
6	Oceanic Niño Index	0.53	0.63	0.62	0.47	0.58	0.59	0.55
7	SST SEAP Area	-0.71	-0.34	-0.55	-0.36	-0.51	-0.46	-0.57
8	Rainfall CSEAP Area	-0.63	-0.78	-0.73	-0.51	-0.63	-0.54	-0.77
9	NOAA Interpl'd OLR	0.84	0.90	0.87	0.63	0.68	0.70	0.76



5c Correlations of VEIT Data

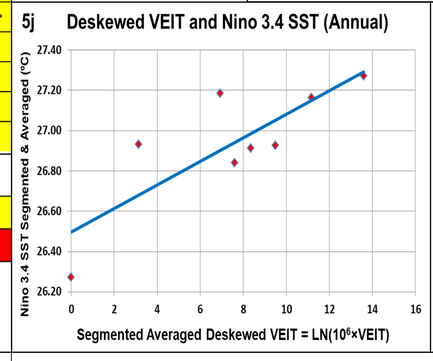
Index	Correlation Apr to Oct (Skew/Kurtosis)	Correlation Annual (Skew/Kurtosis)	VEIT Area	Period
Niño 3.4 SST	0.80 (0.01/-2.46)	0.83 (1.76/2.98)	10S-1N; 90-151E	1870 – 2016
SOI	-0.82 (-0.23/-1.41)	-0.87 (0.04/-0.82)	10S-1N; 110-160E	1876 – 2016
HADCRUT4 Global Temp Anomaly	0.87 (1.47/1.48)	0.90 (1.54 / 2.29)	10S-10N; 115-160E	1880 – 2016
Omega (400 hPa) (CSEAP Area)	0.99 (-0.37/-0.02)	0.89 (0.15/-1.07)	10S-1N; 102-151E	1948 – 2016

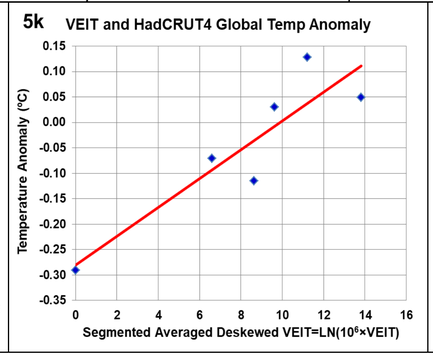
5d Legend for all Correlation Tables

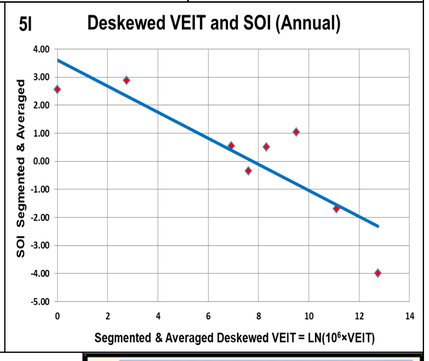
Significance	< 0.10	< 0.05	< 0.02	< 0.01
IPCC ENSO Indices				

* MERRA-2 Easterly Wind Component normally negative with positive change during ENSO cf Trade Wind Index which is normally positive with negative change during ENSO

** SOI from MERRA-2 surface pressure Darwin and Tahiti from the BOM formula available at: http://www.bom.gov.au/climate/glossary/soi.shtml







6. Mechanism

The SEAP absorbs, reradiates and reflects solar radiation as the correlations of AI/AOD with OLR and air temperature at 650hPa show. 6a (IPCC AR5) shows volcanic aerosol plumes and states that the effect on the lower atmosphere and therefore the surface is "Cooling because reduction of sunlight overwhelms any increased downward energy emitted by volcanic cloud". This reduction in surface solar radiation (***aerosol regional dimming***) reduces the energy available to drive convection in the CSEAP Area (5a, 5b (9a and 9b page 2)). Omega, measured in Pa/s, is negative for rising air and the AI/AOD correlations are positive as an increase in AI/AOD reduces convection.

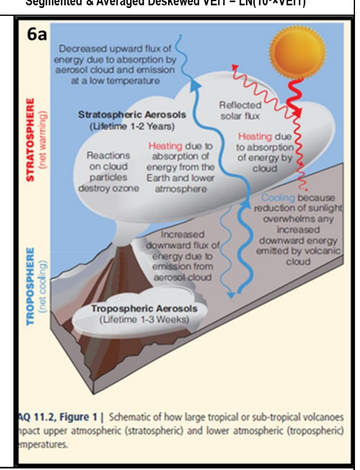
The reduced convection then forces the Walker Circulation to relax and reduces the Trade Wind speed as with lower or no convection over the SEAP Area there is no 'exit' for the Trade Winds into the Walker and Hadley Circulation. The relaxation of the Trade Winds causes the SST to rise in the Niño areas as there is a strong negative correlation (-0.90/-0.94 (ρ < 0.01) annual average/interannual difference) between the Trade Wind speed and SST in the Niño 3.4 area.

The reduction of convection in the SEAP area reduces rainfall in the region and this is reinforced by the weaker Trade Winds which transport less water vapour into the region.

This creates: conditions conducive to forest fires in the SEAP Area; a denser aerosol plume; and positive feedback driving the climate more deeply into an El Niño which only ends with the start of the SE Asian monsoon in November.

The other effects during El Niño events are created by changes in the global circulation and wind systems which all arise from the reduction in convection over the SEAP Area (the maritime continent) and the relaxation of the Trade Winds. For example, drought in SE Australia (SEAus) is also caused by the SEAP.

An estimate of the surface radiative forcing of the SEAP is shown at 10 on page 2 where a reduction of 20% of the radiation without the plume is shown. It is clear that the greatest surface radiation now falls at the edges of the plume and that these regions will now drive the Hadley Circulation. This forces the regional sub-tropical high into an anomalous position which perturbs the storm tracks in that hemisphere around the globe.



AQ 11.2, Figure 1 | Schematic of how large tropical or sub-tropical volcanoes impact upper atmospheric (stratospheric) and lower atmospheric (tropospheric) temperatures.

7. Conclusions

1. **All El Niño/ENSO events are triggered and sustained by aerosol regional dimming by the South East Asian aerosol Plume (SEAP).**
2. **The correlation of volcanic eruptions for over 140 years, extensive anthropogenic aerosols from four satellite datasets and the MERRA-2 reanalysis with ENSO, where the aerosol source is known, means that the SEAP to ENSO relationship is causal.**

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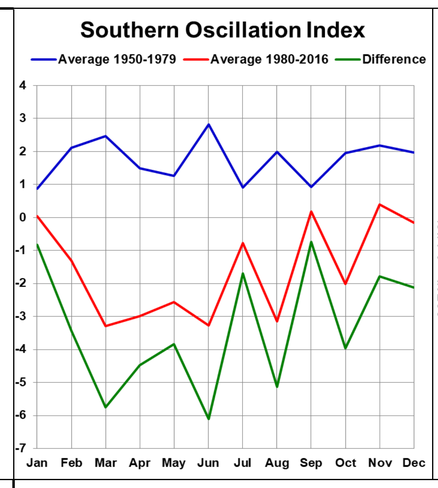
8. The Southern Oscillation Index and SST in the Niño 3.4 Area

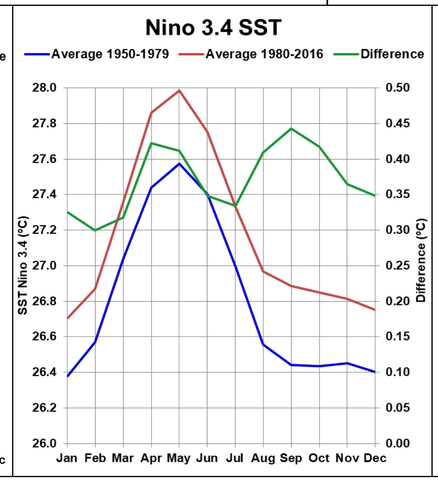
The Southern Oscillation Index is defined by the Australian Bureau of Meteorology as:

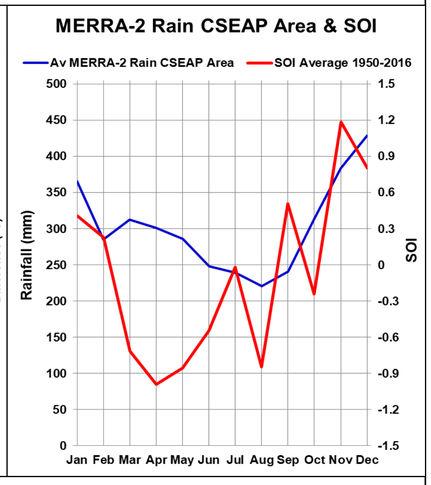
*"The **Southern Oscillation Index**, or SOI, gives an indication of the development and intensity of El Niño or La Niña events in the Pacific Ocean. The SOI is calculated using the pressure differences between Tahiti and Darwin.*

Sustained negative values of the SOI lower than −7 often indicate El Niño episodes …
Sustained positive values of the SOI greater than +7 are typical of a La Niña episode…"

The graphs show the changes in the averages of the SOI and SST in the Niño 3.4 area from 1950 to 1979 and from 1980 to 2016. Changes in the SOI can only be caused by either the pressure in Darwin increasing or the pressure in Tahiti falling or both occurring simultaneously as in an ENSO event. Changes in the SST in the Niño 3.4 area must be driven by a relaxation of the Trade Winds. These significant changes are indicative of a move to a more 'ENSO prone' period and this is entirely consistent with the increases in both the natural and anthropogenic elements of the SEAP described at section 4 on page 1. The third graph shows the seasonal relationship between the SOI and rainfall in the CSEAP Area which is also consistent with the SEAP causing ENSO events.

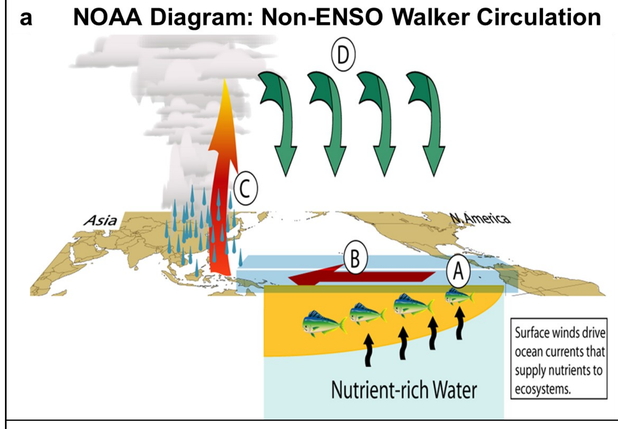




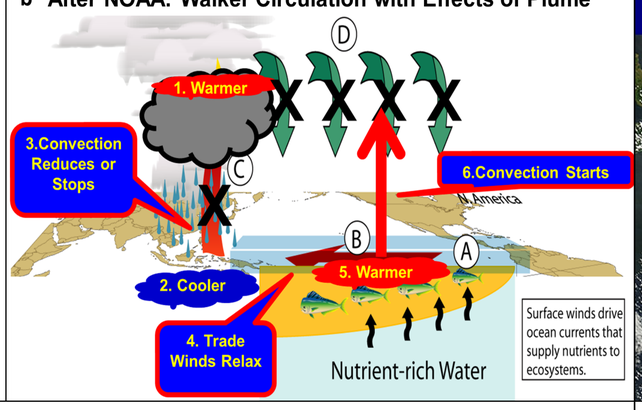


9. The Seven Stages of an ENSO Event (With apologies to Shakespeare)

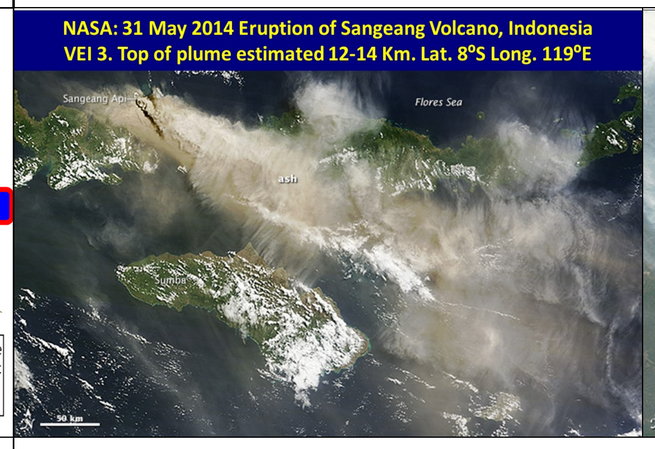
a NOAA Diagram: Non-ENSO Walker Circulation

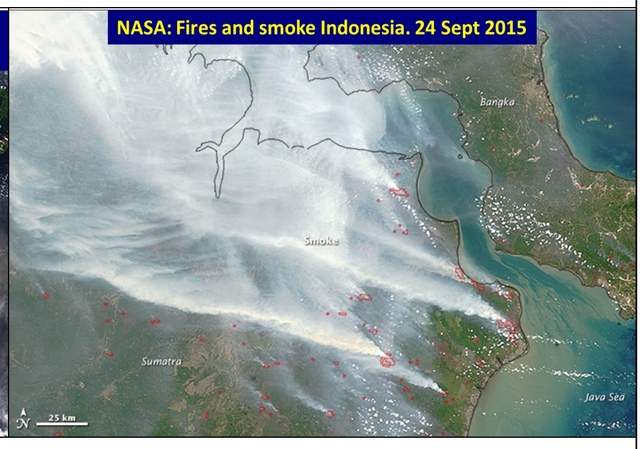


b After NOAA: Walker Circulation with Effects of Plume

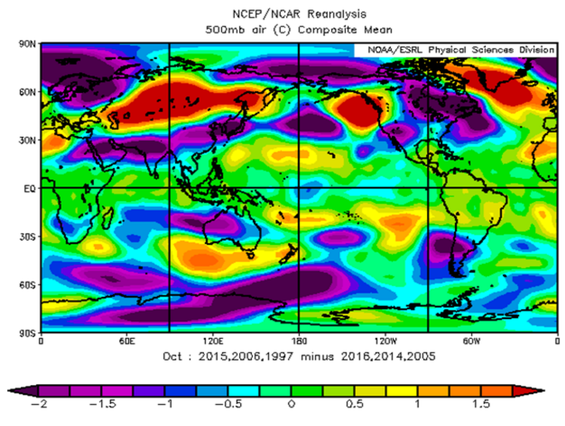


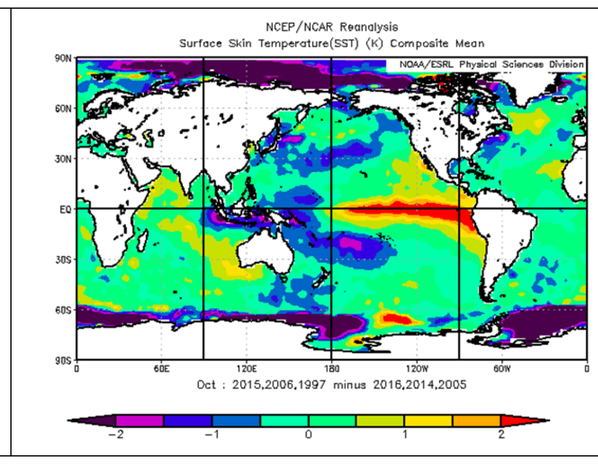
9.1 The volcanic and/or anthropogenic South East Asian Plume commences



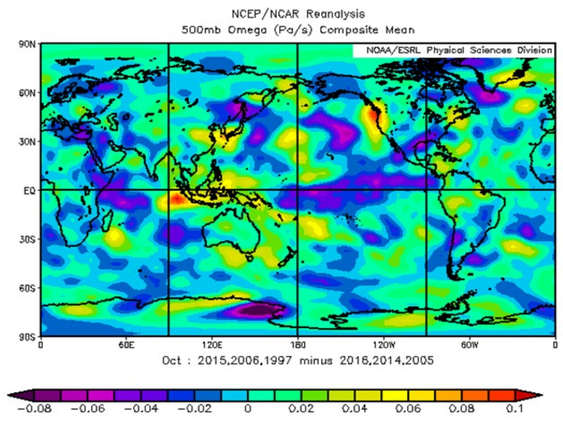


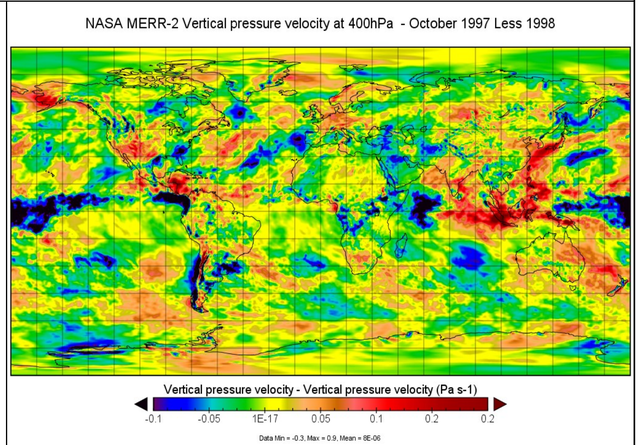
9.2 The SEAP intercepts solar radiation warming the atmosphere and cooling the surface - creating a temperature inversion



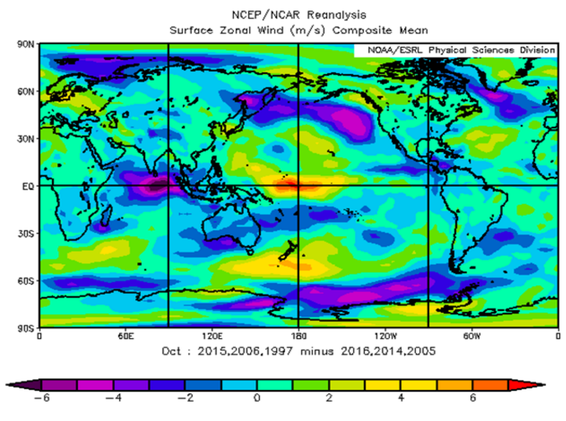


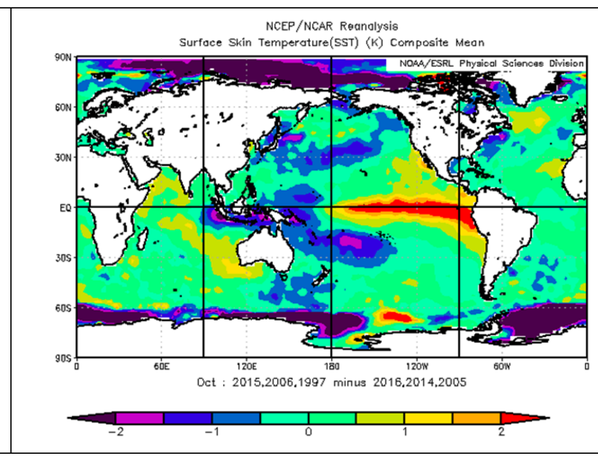
9.3 The temperature inversion reduces convection. (Darwin 131ºE, Tahiti 148ºW)



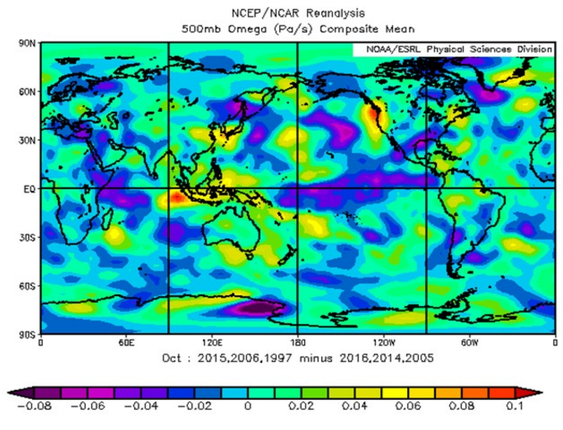


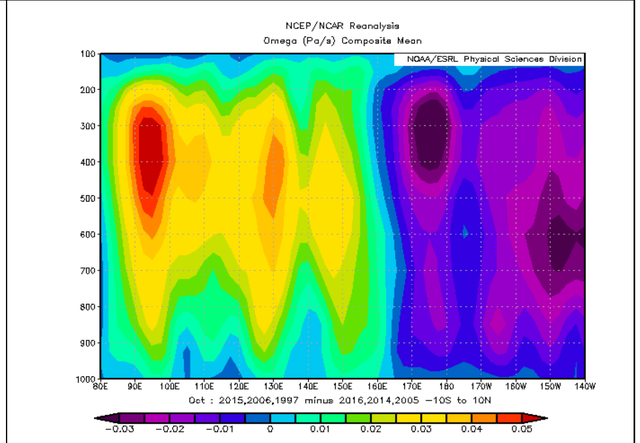
9.4 The reduced convection forces the Trade Winds to relax which causes the SST in the central Pacific Ocean to rise



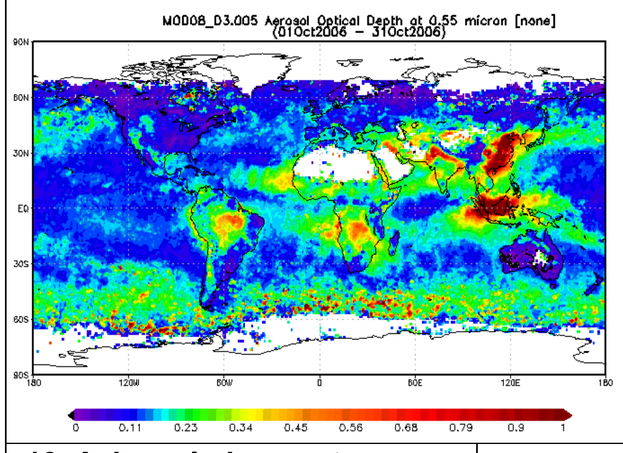


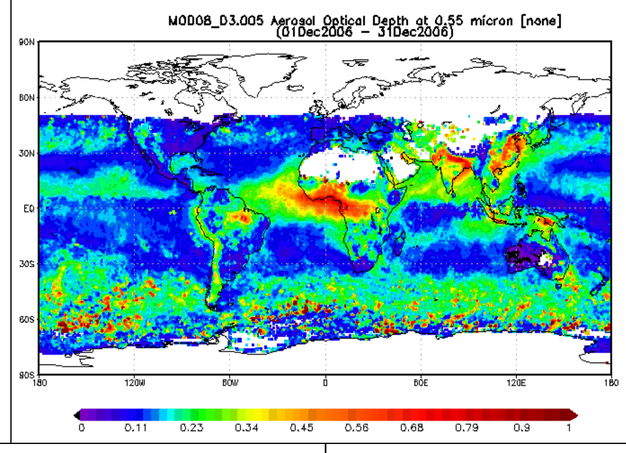
9.5 The higher SST creates convection in the central Pacific and further weakens or reverses the Trade Winds and Walker Circulation establishing an ENSO event



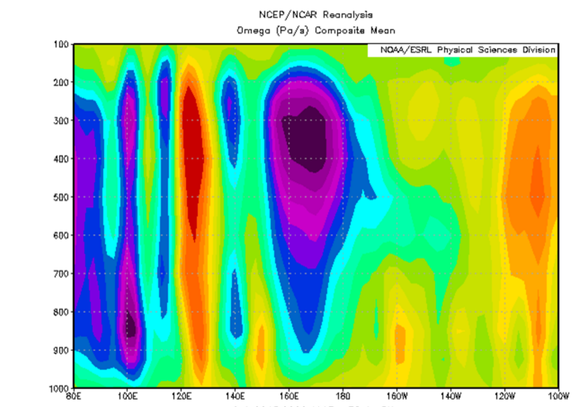


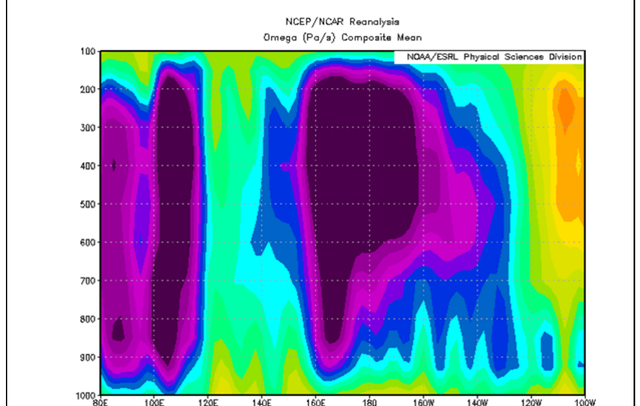
9.6 The SEAP collapses at the onset of the SE Asian Monsoon in November - December which enables convection to be re-established





9.7 The 'normal' Walker Circulation is re-established forcing the Pacific warm pool west again and the ENSO event ends





10. Acknowledgements

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- NOAA and the NCEP/NCAR reanalysis data set;
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AI / AOD Aerosol Index / Aerosol Optical Depth
OLR Outgoing Longwave Radiation
SON September, October and November
SST Sea Surface Temperature

Presented at
AGU Fall Meeting
New Orleans 11th to 15th December 2017

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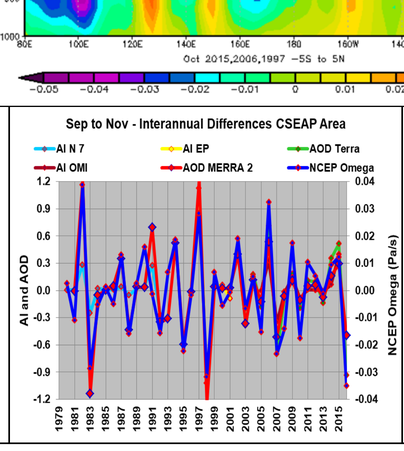

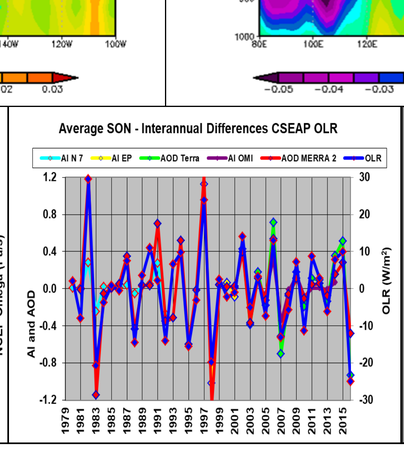

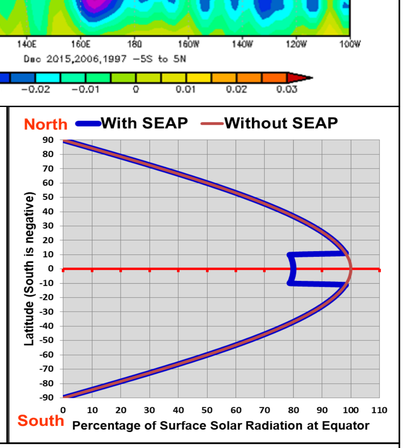

11. Conclusions

1. **All El Niño/ENSO events are triggered and sustained by aerosol regional dimming by the South East Asian aerosol Plume (SEAP).**
2. **The correlation of volcanic eruptions for over 140 years, extensive anthropogenic aerosols from four satellite datasets and the MERRA-2 reanalysis with ENSO, where the aerosol source is known, means that the SEAP to ENSO relationship is causal.**

For more information on aerosol plumes: www.keithpotts.net.au