# How the Natural & Anthropogenic Aerosol Plume over S. E. Asia caused the Millennium Drought

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**Abstract**

The Millennium Drought (Drought) from about 1997 to 2008 was one of if not the most severe drought in recorded Australian history. In 2006 River Murray inflows were 40% below the previous low. Nothing of this severity occurs without a cause, which must have the same time span, and the obvious challenge is to identify the culprit and explain how it caused the Drought. CAWCR Technical Report 26 discussed ENSO; the North West Shelf Sea Surface Temperature (SST); MSLP SE Australia; the SAM; and the Neighbouring Tasman Sea SST as possible causes and found that: local MSLP is the major influence; and ENSO's influence is created by "large-scale circulation changes". The literature and the Bureau of Meteorology (BoM) also link the positive phase of the Indian Ocean Dipole (IOD) to drought in Australia. Many researchers have tried to connect ENSO events to volcanic eruptions without success as their focus was on large eruptions which injected gases and tephra into the stratosphere. I include all eruptions in a restricted area, south east Asia (SE Asia), and show how they create ENSO events by reducing convection over the Maritime Continent and forcing the Trade Winds to relax. Simultaneously the volcanic plume moves the regional southern Hadley Cell south and creates the anomalous, persistent high pressure over south eastern Australia. Finally by intercepting the solar radiation by absorption and/or reflection, the volcanic plume cools the sea surface beneath it - the region where moisture which falls as rain in SE Australia evaporates - thereby reducing the available moisture in SE Australia and also creates IOD events. I show that SE Asian tectonic activity is highly variable and the level of volcanic tephra ejected during the Drought was treble the average for the 20th century and this was exacerbated by the anthropogenic aerosols in the same region which increased by 687% from 1979 to 2000 in September. Thus the Millennium Drought was caused by the increased levels of volcanic and anthropogenic aerosols over south east Asia which simultaneously: forced the circulation changes which created the anomalous high pressure over SE Australia; ENSO; and IOD events

# How the Natural & Anthropogenic Aerosol Plume over S. E. Asia caused the Millennium Drought

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## 1. Abstract

The Millennium Drought (Drought) from about 1997 to 2008 was one of if not the most severe drought in recorded Australian history. In 2006 River Murray inflows were 40% below the previous low. Nothing of this severity occurs without a cause, which must have the same timespan, and the obvious challenge is to identify the culprit and explain how it caused the Drought.

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Simultaneously the volcanic plume moves the regional southern Hadley Cell south and creates the anomalous, persistent high pressure over south eastern Australia. Finally by intercepting the solar radiation by absorption and/or reflection, the volcanic plume cools the sea surface beneath it - the region where moisture which falls as rain in SE Australia evaporates - thereby reducing the available moisture in SE Australia and also creates IOD events.

I show that SE Asian tectonic activity is highly variable and the level of volcanic tephra ejected during the Drought was treble the average for the 20th century and this was exacerbated by the anthropogenic aerosols in the same region which increased by 687% from 1979 to 2000 in September.

Thus the Millennium Drought was caused by the increased levels of volcanic and anthropogenic aerosols over south east Asia which simultaneously: forced the circulation changes which created the anomalous high pressure over SE Australia; ENSO; and IOD events.

## 2. The South East Asia aerosol Plume (SEAP)

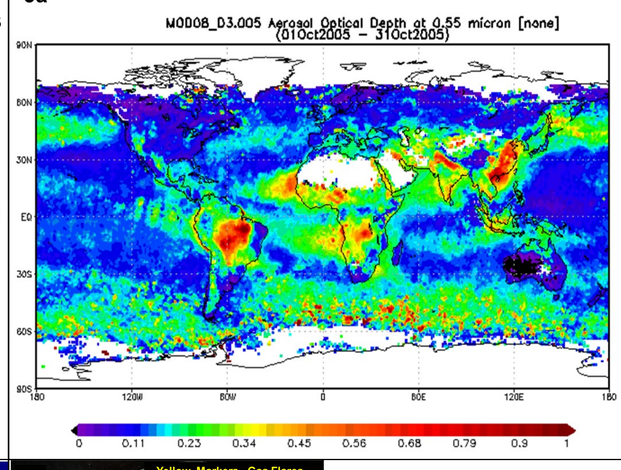
**The natural SEAP:** ***The SEAP Area (2d) is the most tectonically active area in the tropics*** with over 23% of the global volcanic eruptions occurring there. The figures below show the number of earthquakes (2a), volcanic eruptions and the volume of tephra ejected in the SEAP Area through the last century (2b) and it is clear that the level of activity varies hugely. Volcanoes eg Sangeang (2c) are the natural source of aerosols in the SEAP Area.

**The anthropogenic and recent SEAP:** Is one of eight, continental scale, aerosol, plumes (8 below) which now occur annually. It can be seen on the monthly mean AOD data from the NASA Giovanni System (3). Two areas: the SEAP Area, its location; & the Central SEAP (CSEAP) Area where it is most intense (2d) are used to describe 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.

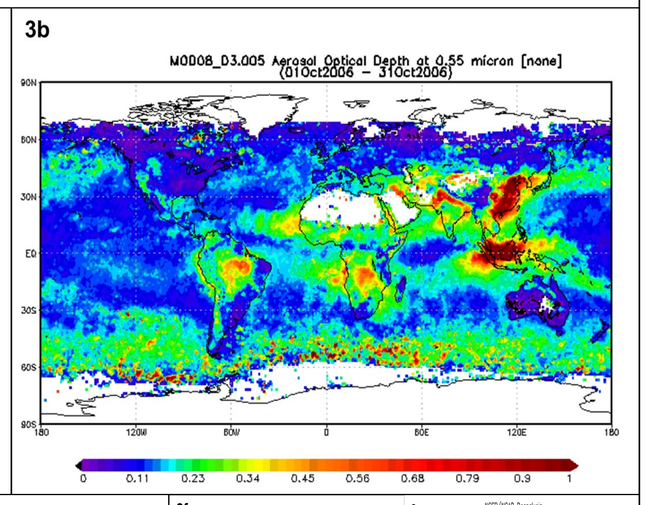
Figure 2e demonstrates the peak emission season is SON, the end of the SE Asian dry season and was very high in 1997, 02, 04, 06, 09, 14 & 15. From 1979 to 97 the increase in AI in September was 3.499%. 2f and 2g show the theoretical reduction in surface radiation caused by the SEAP and the anomalous high pressure over SE Australia. This paper focuses on SON (2f) because: the anthropogenic SEAP is at its most intense and will therefore have its greatest effect in this season when the grain crop in SE Australia is ripening and drought at this time is devastating.

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

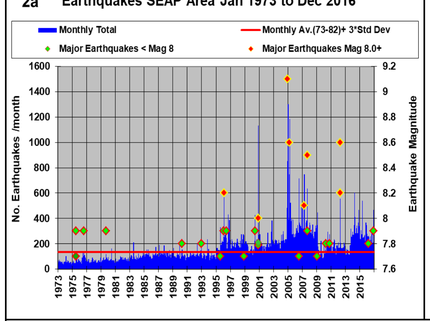
3a



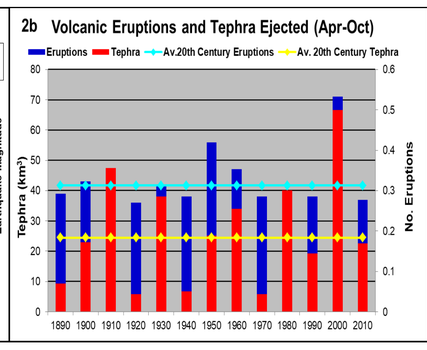

3b



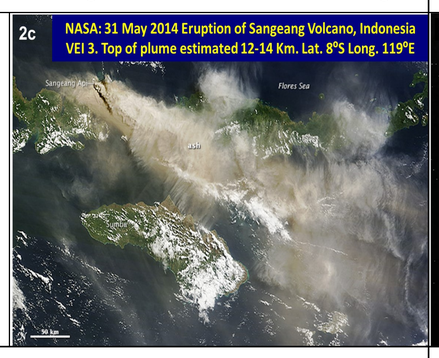

2a Earthquakes SEAP Area Jan 1973 to Dec 2016



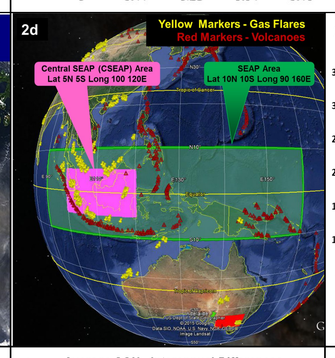

2b Volcanic Eruptions and Tephra Ejected (Apr-Oct)



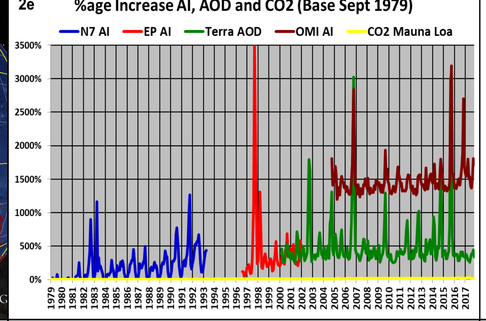

2c



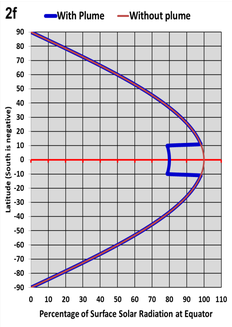

2d



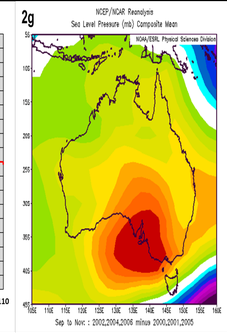

2e %age Increase AI, AOD and CO2 (Base Sept 1979)




2f




2g




## 4. The South East Asian Plume and Drought in South Eastern Australia

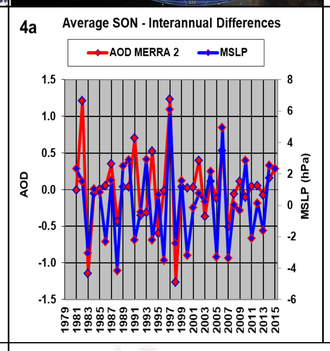
Both the natural and anthropogenic aerosol plumes over south east Asia correlate with drought in south eastern Australia as shown below in 7 a, b and c with graphical representations at 4 a, b and c and 10.

The CAWCR Technical Report 26 states that the changes in precipitation related to ENSO in SON are caused by circulation changes. The SEAP drives circulation changes by the mechanism shown in 2f (Hadley Cells) and 5a (Walker Circulation) which reduces convection under the plume and weakens the Trade Winds in the Walker Circulation and moves the convective arm of the southern regional Hadley Cell south creating anomalous and persistent high pressure over south eastern Australia (2g, 4a) - the greatest influence on rainfall CAWCR TR 26.

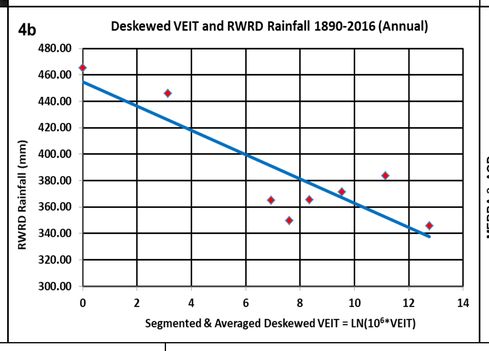
The correlations of the AI and AOD of the SEAP and the characteristics of drought in SE Australia are shown at 7.

**The 2006 SEAP (3b) resulted in the Vic, NSW & SA grain harvest falling by 67% cf '05 with losses of $2.3Bn.**

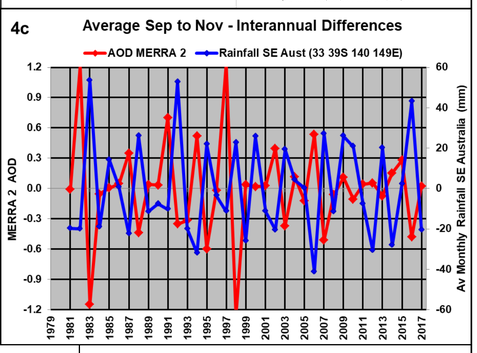
4a Average SON - Interannual Differences




4b Deskewed VEIT and RWRD Rainfall 1890-2016 (Annual)




4c Average Sep to Nov - Interannual Differences

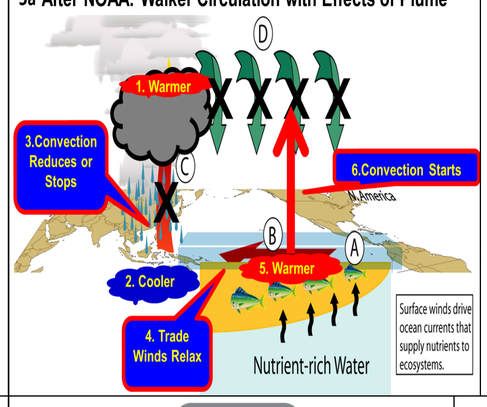



## 5. The South East Asian Plume and El Niño / ENSO Events

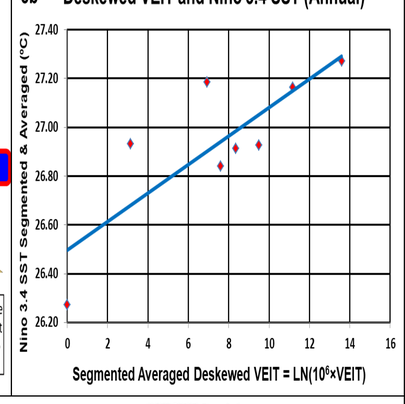
El Niño events are closely linked with changes in the Walker Cell - especially the Trade Winds. The literature, NASA, NOAA, the IPCC and the UK Met Office state in reports or on their websites that El Niño events start when the Trade Winds in the central and western Pacific Ocean relax or reverse. The Trade Winds form the lower limb of the Walker Cell 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 Cell is directly thermally driven, the heat must be applied ***at the Earth's surface in SE Asia*** - the SEAP Area - to drive the convection and as the variation in solar radiation at the top of atmosphere cannot explain the reduction in surface heating and the relaxation of the Trade Winds, the reduction in heat must be caused by aerosols in the atmosphere by the mechanism shown in 5a.

The correlations of the AI and AOD of the CSEAP Area and of volcanic tephra ejected in SE Asia with the indices used to monitor ENSO events highlighted in red are shown below in 7a, b and c. Graphs of the annually averaged Nino 3.4 SST and the SOI with segmented and averaged tephra are in 5b and 5c and of the SOI with AOD in 11.

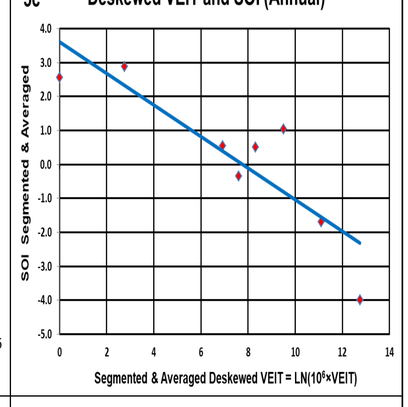
5a After NOAA: Walker Circulation with Effects of Plume




5b Deskewed VEIT and Nino 3.4 SST (Annual)




5c Deskewed VEIT and SOI (Annual)




## 6. The South East Asian Plume and the Indian Ocean Dipole

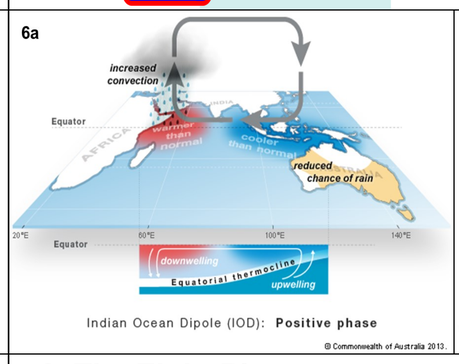
The IOD has also been linked in the literature and by the BoM to drought in south eastern Australia. The BOM states that "The IOD is one of the key drivers of Australia's climate and can have a significant impact on agriculture. This is because events generally coincide with the winter crop growing season".

As the correlations in 7 a, b and c and graph in 11 show there is a significant link between the SEAP and the IOD.

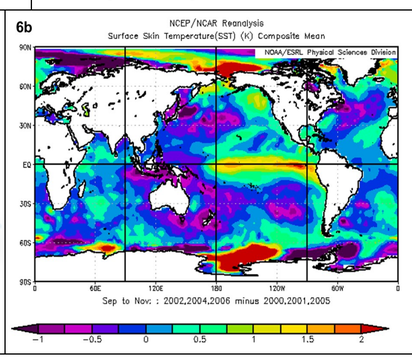
The SEAP creates an IOD event by reducing convection over south east Asia which forces the westerly winds flowing across the Indian Ocean to relax and cools the Sea Surface Temperature (SST) under the plume. These events cool the eastern Indian Ocean and warm the western Indian Ocean creating a positive IOD event 6a, b, c.

Simultaneously the SEAP creates drought in south eastern Australia as described above (4) and is the link between IOD events and drought in south eastern Australia.

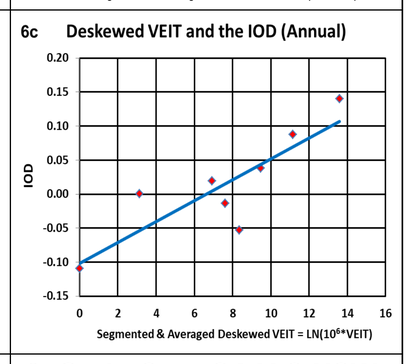
6a




6b




6c Deskewed VEIT and the IOD (Annual)




## 7. Correlations

7a 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 |
|---|---|---|---|---|---|---|---|---|
| | | 2000-17 | 1979-92 | 1996-01 | 2004 - 17 | 1979-01 | 1979-17 | 1980-17 |
| 1 | CSEAP Area Omega | 0.93 | 0.75 | 0.97 | 0.80 | 0.75 | 0.73 | 0.83 |
| 2 | SEAP Area SST | -0.84 | -0.89 | -0.88 | -0.60 | -0.87 | -0.81 | -0.74 |
| 3 | MSLP SE Australia | 0.77 | 0.40 | 0.78 | 0.72 | 0.56 | 0.56 | 0.54 |
| 4 | RWRD Rainfall | -0.55 | -0.66 | -0.30 | -0.22 | -0.31 | -0.24 | -0.48 ** |
| 5 | Rainfall SE Australia | -0.74 | -0.80 | -0.49 | -0.41 | -0.45 | -0.42 | -0.63 |
| 6 | Grain Harvest NSW Vic SA (To 2016) | -0.77 | -0.74 | -0.72 | -0.62 | -0.40 | -0.43 | -0.67 |
| 7 | SST Niño 3.4 | 0.85 | 0.71 | 0.97 | 0.73 | 0.79 | 0.74 | 0.81 |
| 8 | SST Niño 1 and 2 | 0.83 | 0.68 | 0.98 | 0.81 | 0.88 | 0.85 | 0.79 |
| 9 | SOI | -0.73 | -0.74 | -0.88 | -0.66 | -0.69 | -0.66 | -0.80 * |
| 10 | Indian Ocean Dipole | 0.86 | 0.82 | 0.98 | 0.74 | 0.92 | 0.89 | 0.79 |

7b 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 |
|---|---|---|---|---|---|---|---|---|
| | | 2000-17 | 1979-92 | 1996-01 | 2004 - 17 | 1979-01 | 1979-17 | 1980-17 |
| 1 | CSEAP Area Omega | 0.88 | 0.84 | 0.97 | 0.70 | 0.76 | 0.71 | 0.78 |
| 2 | SEAP Area SST | -0.71 | -0.34 | -0.55 | -0.36 | -0.51 | -0.46 | -0.57 |
| 3 | MSLP SE Australia | 0.66 | 0.56 | 0.07 | 0.46 | 0.42 | 0.60 | 0.65 |
| 4 | RWRD Rainfall | -0.69 | -0.48 | -0.78 | -0.53 | -0.42 | -0.41 | -0.64 ** |
| 5 | Rainfall SE Australia | -0.77 | -0.29 | -0.58 | -0.59 | -0.42 | -0.37 | -0.64 |
| 6 | Grain Harvest NSW Vic SA (To 2016) | -0.79 | -0.17 | 0.59 | -0.56 | -0.23 | -0.29 | -0.60 |
| 7 | SST Niño 3.4 | 0.75 | 0.68 | 0.86 | 0.67 | 0.69 | 0.68 | 0.77 |
| 8 | SST Niño 1 and 2 | 0.76 | 0.65 | 0.49 | 0.55 | 0.57 | 0.57 | 0.55 |
| 9 | SOI | -0.57 | -0.68 | -0.78 | -0.39 | -0.64 | -0.61 | -0.80 * |
| 10 | Indian Ocean Dipole | 0.66 | 0.58 | 0.80 | 0.48 | 0.75 | 0.70 | 0.66 |

7c Correlations of VEIT Data

| Index | Correlation Apr to Oct (Skew/Kurtosis) | Correlation Annual (Skew/Kurtosis) | VEIT Area | Period |
|---|---|---|---|---|
| Omega (CSEAP Area) | 0.99 (-0.38/-0.02) | 0.89 (0.15/-1.07) | 10S-1N; 102-151E | 1948 – 2016 |
| Rainfall RWRD | -0.78 (-0.05/-2.38) | -0.86 (1.69/2.54) | 10S-1N; 90-151E | 1890 – 2016 |
| Niño 3.4 SST | 0.80 (0.01/-2.47) | 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 |
| Indian Ocean Dipole | 0.88 (0.18/-2.31) | 0.85 (1.40/1.55) | 10S-0N; 90-150E | 1870 – 2016 |

7d Legend for all Correlation Tables

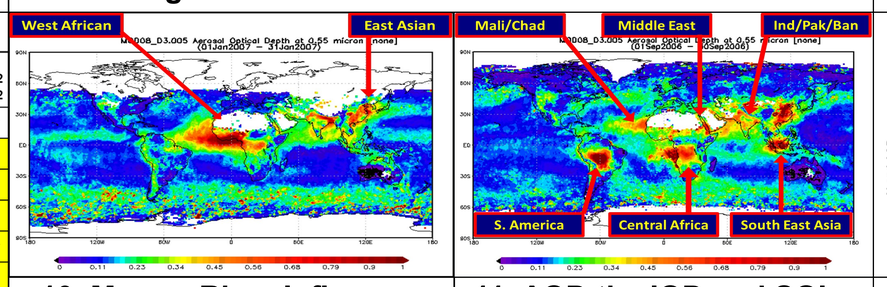
| Significance | < 0.10 | < 0.05 | < 0.02 | < 0.01 |
|---|---|---|---|---|

IPCC ENSO Indices

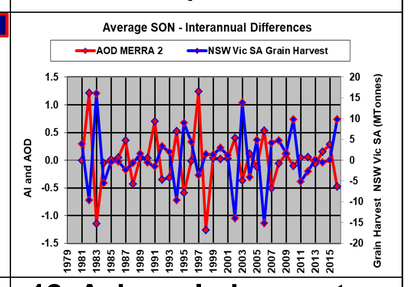
* The M2 SOI is derived from the MERRA-2 surface pressure around Darwin and Tahiti using the BOM formula available at: http://www.bom.gov.au/climate/glossary/soi.shtml

** The data in the MERRA-2 MERRA-2 (M2 M2) column in 7a and b is derived from the NASA MERRA-2 reanalysis dataset with one exception - the MERRA 2 RWRD rainfall correlation uses BoM rainfall data.

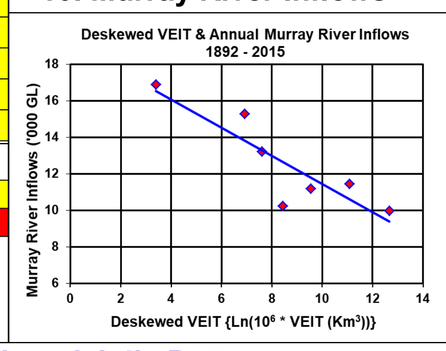
## 8. The Eight Plumes



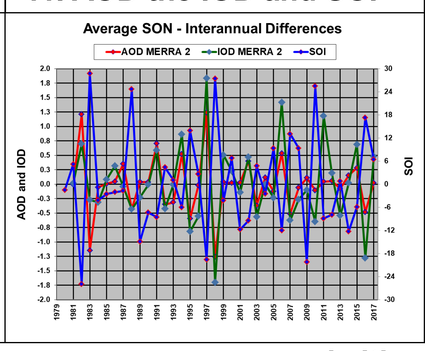

## 9. Grain Crop SA VIC NSW




## 10. Murray River Inflows




## 11. AOD the IOD and SOI




## 12. Acknowledgements

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- NASA: Analyses and visualizations used in this poster were produced with the Giovanni online data system using NASA satellite data and MERRA-2 reanalysis;
- National Oceanic and Atmospheric Administration;
- NOAA and the NCEP/NCAR reanalysis data set;
- IPCC Assessment Report 4 (AR4) and 5 (AR5);
- Mauna Loa observatory;
- Google Earth;
- ·Global Volcanism Program, Smithsonian Institution;
- US Geological Survey
- Australian Bureau of Meteorology;
- CAWCR (Centre for Australian Weather and Climate Research
- The UK Met Office
- Murray Darling Basin Commission

13. **The costs of this research, travel and registration were funded personally by Keith and Julie Potts.**

**www.keithpotts.net.au/publications**

## 14. Conclusions

1. **The Millennium drought was caused by aerosol regional dimming by apparitions of the volcanic and anthropogenic South East Asian aerosol Plume (SEAP), the levels of which increased substantially in frequency and severity during the Drought**
2. **The SEAP also created the ENSO and IOD events simultaneously**
3. **The correlations of volcanic eruptions for 127-147 years, four satellite datasets and the MERRA-2 reanalysis with SE Australian drought, ENSO and the IOD, where the source of the aerosols is known, means that the relationship of the SEAP to them is causal.**