Have Australian Rainfall and Cloudiness Increased Due to the Remote Effects of Asian Anthropogenic Aerosols?

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This talk is based on a paper under review at JGR.
• **Background and motivation**
  § Aerosols and how they can affect tropical circulation and rainfall
  § Observed Australian rainfall and cloudiness trends (especially the intriguing “northwest” pattern of rainfall increase)

• **The CSIRO Mk3A GCM**
  § Similar to Steve’s Mk3L, with Aerosols

• **Experiments**
  § 20th century “transient” runs with and without aerosol forcing

• **Results and comparison with observed trends**
  § Need (Asian) aerosol forcing in the model to get the right sign for Australian rainfall and cloudiness trends

• **Conclusions and implications**
Cai’s “three-headed dog” represents the major modes of variability affecting Australian rainfall.

- **Cerberus**
- **Indian Ocean Dipole**
- **Southern Annular Mode**

**ENSO**

**Indian Ocean Dipole**

**Southern Annular Mode**
Atmospheric aerosols

- An aerosol is a haze of fine particles or droplets, e.g. sulfate, carbonaceous, dust. Usually, these are “internally” mixed.
- Main anthropogenic sources: burning of fossil fuel and biomass.
- Aerosols have direct and indirect effects on solar radiation.
Global-mean indirect aerosol forcing could have larger magnitude than CO$_2$ forcing.

- First indirect aerosol effect: smaller cloud droplets increase cloud albedo
- IPCC 4$^{th}$ Assessment is likely to include a best estimate for this effect
- Spatial variations? Stronger in Northern Hemisphere (NH)
GCMs show a southward shift of tropical rainfall in response to aerosol forcing

From Rotstayn et al. (GRL, 2000): Rainfall response of AGCM + mixed-layer ocean to indirect effects of sulfate aerosol (mm/day)

- The NH cools relative to the SH, so the ITCZ shifts southward
- Several GCMs have since obtained similar results in response to indirect or direct + indirect aerosol forcing
- Rotstayn & Lohmann (J. Clim., 2002) argued that aerosols may have contributed to the 1970s and 1980s Sahelian droughts via this mechanism
Direct aerosol effects are more important than suggested by the global-mean TOA forcing.


Even in the global mean, direct aerosol atmospheric heating is probably larger than that due to GH gases!
In regions not far from Australia, aerosol forcing is much stronger than GH-gas forcing


- Aerosols tend to cool the surface and stabilize the boundary layer
- Indian Ocean SSTs are known to strongly influence Australian rainfall variations
- In June 2002, I showed this figure and suggested a possible link to Australian tropical rainfall trends
Observed rainfall trends since 1950 show a pattern of increasing rainfall over NW and central Australia.

1951-1996 annual rainfall trends (mm/century). Light (heavy) stippling shows points significant at 1% (10%) using a two-sided t-test on the 46 annual means. Data are from CRU TS 2.1 (Mitchell & Jones, Int. J. Climatol. 2005)

Most greenhouse-forced transient GCM runs have not captured the increasing rain over NW Australia (e.g., Whetton et al., Clim. Res., 2001)

Q: Is the northwest-central rainfall increase due to Asian aerosol forcing?
The CSIRO Mk3A global climate model

- Based on the Mk3 AGCM (at R21 horizontal resolution) and the Mk2 OGCM (as is Steve Phipps’ “Mk3L” version)
- Misses some of Steve’s improvements, but has other good stuff
- Includes a new interactive aerosol treatment and radiation scheme
- Interactive aerosols are sulfate, organic carbon, black carbon, mineral dust and sea salt (11 prognostic variables, diagnostic sea salt)
- Also new is prescribed stratospheric aerosol from volcanic eruptions
- Updated radiation scheme via Joyce Penner at U. Michigan
  - Shortwave from Grant & Grossman at LLNL
  - Longwave from M.-D. Chou at GSFC
- Shortwave radiation scheme includes effects of above aerosols
- First & second indirect aerosol effects included in cloud scheme
The low-resolution GCM captures the broad features of Australian seasonal rainfall. The model tends to be too dry rather than too wet.
The modelled aerosol optical depth using emissions for 2000 shows a low bias

- Satellite composite from Kinne et al., ACPD, 2005
- They give an estimate for global and annual-mean clear-sky AOD of 0.135 to 0.15 (cf. model 0.093)
- Main reasons for low bias are:
  - sea salt unintentionally set to zero above the marine boundary layer (an NEC compiler bug!)
  - carbonaceous aerosol emissions on the low side
- An updated model version agrees better with the satellite retrievals (but not yet used for climate-change runs)
Our new 20th century transient runs have several forcings not included in the standard Mk3 model.

The eight-member **ALL ensemble** (1871-2000) is forced by:

- Long-lived GH gases (not just “equivalent” CO$_2$) (Hansen et al., 2002)
- Ozone (Kiehl et al., 1999)
- Solar variations (Lean & Rind, 1998)
- Time varying sulfur emissions (extended from Smith et al., 2001)
- Time varying carbonaceous aerosols (BC and OC) (Ito & Penner, 2005)
- Simple BC effect on snow albedo (Hansen & Nazarenko, 2004)
- Volcanic aerosol (Sato et al., 1993)
- Wind-driven feedbacks of dust and sea salt
- No land-use changes as yet

The eight-member **AXA ensemble** is identical, but holds the sulfur and carbonaceous-aerosol emissions at their 1870 levels.
Global-mean aerosol emissions mostly increase during the 20th century.

![Graph showing annual emission (TgS or TgC) over years from 1880 to 2000. The graph includes lines for sulfur, POM, and BC emissions.](image)
The ALL ensemble gives a better simulation of global-mean temperature change after 1950.

Near-surface temperature change relative to 1871-1900 mean. Observations are from HadCRUT2 (Jones and Moberg, 2003; Rayner et al., 2003)
Trends in anthropogenic aerosol optical depth are dominated by the NH (and especially Asia)

We analyse the period 1951-1996 (to maximise the effect of Asian aerosols)
The ALL ensemble and observations show increasing rainfall and cloudiness over Australia.

Observed and modelled trends in Australian rainfall, cloudiness and diurnal temperature range (DTR) during 1951-1996. Significance at 10% (1%) is denoted by bold (italic bold) font.

<table>
<thead>
<tr>
<th></th>
<th>annual rainfall (mm/century)</th>
<th>cloudiness (%/century)</th>
<th>DTR (K/century)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observed (CRU)</td>
<td>38</td>
<td>10.9</td>
<td>−2.43</td>
</tr>
<tr>
<td>Observed (BoM)</td>
<td>68</td>
<td></td>
<td>−0.78</td>
</tr>
<tr>
<td>ALL ensemble mean</td>
<td>92</td>
<td>3.1</td>
<td>−1.03</td>
</tr>
<tr>
<td>AXA ensemble mean</td>
<td>−35</td>
<td>−4.6</td>
<td>0.21</td>
</tr>
</tbody>
</table>

- The AXA ensemble (no aerosols) gets the sign wrong for rainfall, cloudiness and DTR.
Inclusion of aerosol forcing increases the cloudiness trend everywhere over Australia.

Cloudiness trends in %/century.
The annual rainfall trend pattern is also strongly affected by inclusion of aerosol forcing in the GCM.
The summertime rainfall trend pattern is much improved in the ALL ensemble.

DJF seasonal rainfall trends in mm/century
The regional $T_s$ trend patterns are a first step towards understanding the different dynamical responses.

Near-surface temperature ($T_s$) trends in K/century
Over the Indian Ocean, the ALL ensemble shows a shift of convection towards NW Australia during 1951-1996.

Warm colours denote a trend of increasing subsidence, cool colours increasing ascent (Pa/s/century). Divergent winds at 220 hPa in m/s/century.

This behaviour resembles the negative phase of the Indian Ocean Dipole (linked to increased rainfall over Australia).
Aerosol forcing makes the simulated monsoonal winds over the Indian Ocean flow more towards Australia.


- This effect is present in both DJF and JJA seasons (not shown)
- Should also be seen in $T_s$ and SLP trends
The zonal-mean observed $T_s$ trends over the Indian Ocean sector tend to support the model.

Meridional $T_s$ gradient is similar in observations and ALL ensemble.

× ALL ensemble underestimates warming in this region (and SH overall)
The modelled SLP trends are dynamically consistent with basic monsoon theory...
But it is difficult to conclude anything from the observed SLP data sets.

(a) NCAR/NCEP SLP trend 1951-1996
(b) ERA-40 SLP trend 1958-1996
(c) HadSLP2 SLP trend 1951-1996
(d) Smith-Reynolds SLP trend 1951-1996

hPa/century
A sensitivity test confirms that Asian aerosols cause the northwest-Australian rainfall increase (in the model :)

The (eight-member) ASIA ensemble is like the ALL ensemble, but it holds anthropogenic aerosol emissions outside Asia fixed at their 1870 levels.
Large differences among the members of the ALL ensemble point to natural variability

- Shown are annual rainfall trends from the individual runs (mm/century)
- This low-resolution model may overestimate interdecadal variability
Changes in ocean dynamics contribute to the SST trends in the Indian and Pacific Oceans (averaged over 0 to 240 metres depth)

ALL minus AXA trends in near-surface ocean currents in m/s/century
Caveats

• Only one model used; desirable to repeat with others
• R21 model underestimates ENSO-like variability
• ALL ensemble tends to underestimate warming in SH
• Aerosol treatments are subject to gross uncertainty
• The model shows aerosols giving increased rainfall over NE Australia too, which is not observed
• Differences between runs remind us of the importance of natural variability
• Some support for SST trends in HadCRUT2 observations, but SLP trends are poorly known
Subject to the caveats on the previous slide

• Our results suggest that Asian anthropogenic aerosols have increased Australian rainfall and cloudiness, especially in the northwest

• Aerosols tend to suppress the hydrological cycle over Asia, but compensating circulation changes may enhance it over Australia

• The effect of aerosol forcing resembles the negative phase of the Indian Ocean Dipole

• There is also an indication that aerosols make the Pacific SST trend pattern more like La Nina (not shown today)
Implications

• Aerosols should not be neglected when modelling past or future Australian climate change

• If Asian aerosols have caused the increase in northwest-Australian rainfall, then decreasing these aerosols during the 21st century could augment existing Australian drying trends

• We now have a framework to attribute Australian rainfall trends to anthropogenic forcing and/or natural variability in the three key ocean basins:
  
  § Pacific Ocean (ENSO)
  
  § Southern Ocean (Southern Annular Mode)
  
  § Indian Ocean (Indian Ocean Dipole)
That old three-headed dog again...

- **Cerberus**
- **Southern Annular Mode**
- **Indian Ocean Dipole**
- **ENSO**