Have Australian Rainfall and Cloudiness Increased Due to the Remote Effects of Asian Anthropogenic Aerosols? (A study with the CSIRO GCM)

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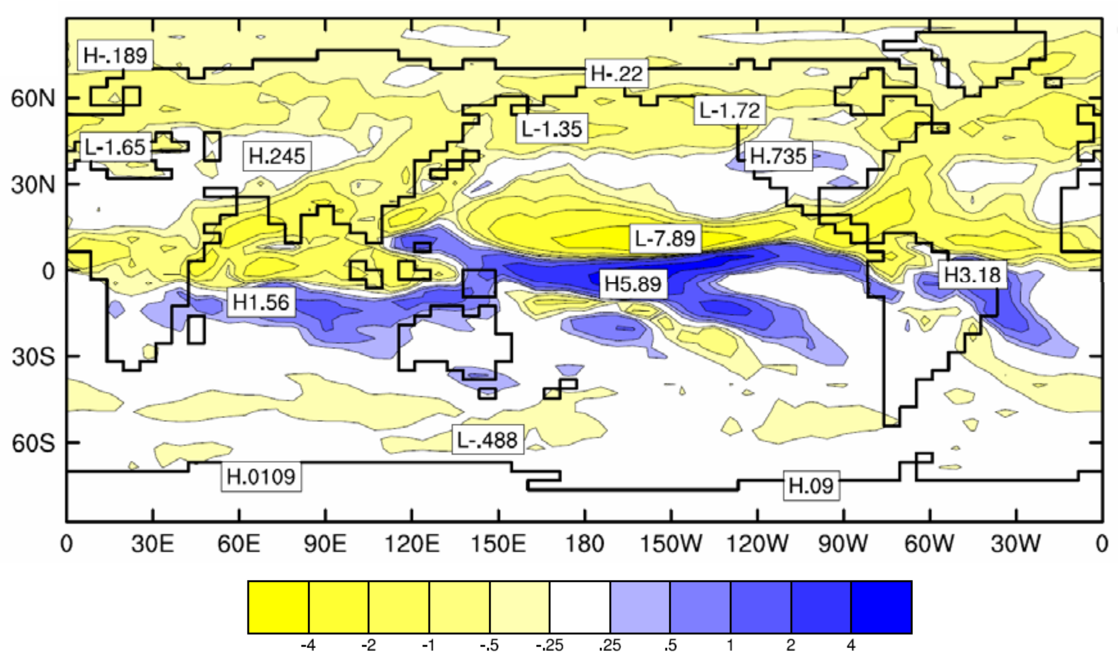
CSIRO

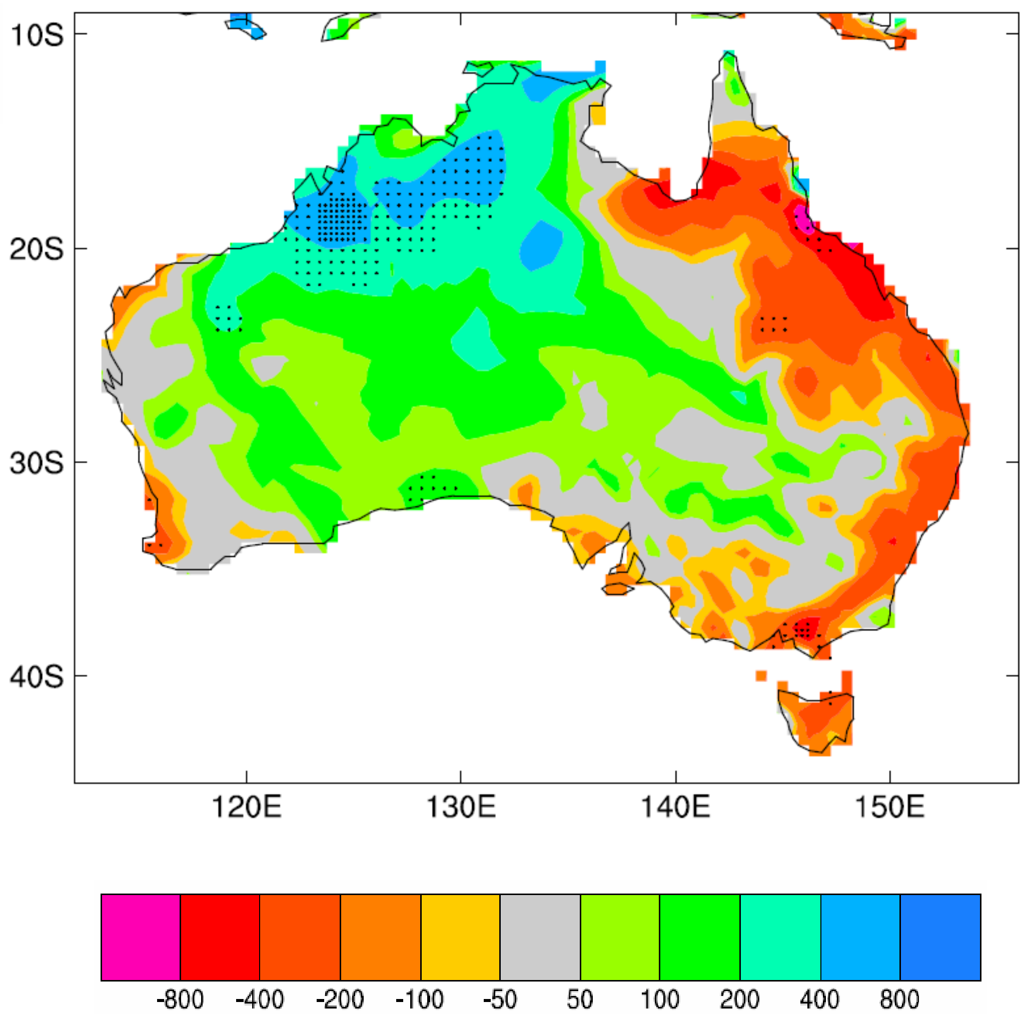
Aerosols vary in space (so they are not just some kind of “negative greenhouse gas”)

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



- **The Northern Hemisphere (NH) cools relative to the Southern Hemisphere (SH), so tropical rainfall shifts southward**
- **Several other GCMs have since obtained broadly 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**

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

- Low resolution version of the Mk3 AGCM (18L, spectral R21: 5.6^{o} x 3.2^{o})
- 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)
    - sulfur cycle (Rotstayn & Lohmann, 2002; Feichter et al., 1996)
    - carbonaceous aerosol (Cooke et al., 1999)
    - mineral dust (Ginoux et al., 2004)
- Prescribed stratospheric aerosol from volcanic eruptions (Sato, updated)
- 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 in (Rotstayn, 1997) cloud scheme

With these treatments, the total global-mean TOA anthropogenic aerosol forcing is -1.2 W m^{-2}

Calculated as the difference between fixed-SST runs with 1870 and 1990 emissions (and using the method of Hansen et al., 2005, to adjust for the effects of “feedbacks”):

- Direct aerosol forcing is -0.39 W m^{-2}
- Total indirect aerosol forcing is -0.8 W m^{-2} (fairly conservative)
- The latter is especially uncertain; we parameterize N using a “tuned” version of the empirical scheme of Menon et al. (2002):

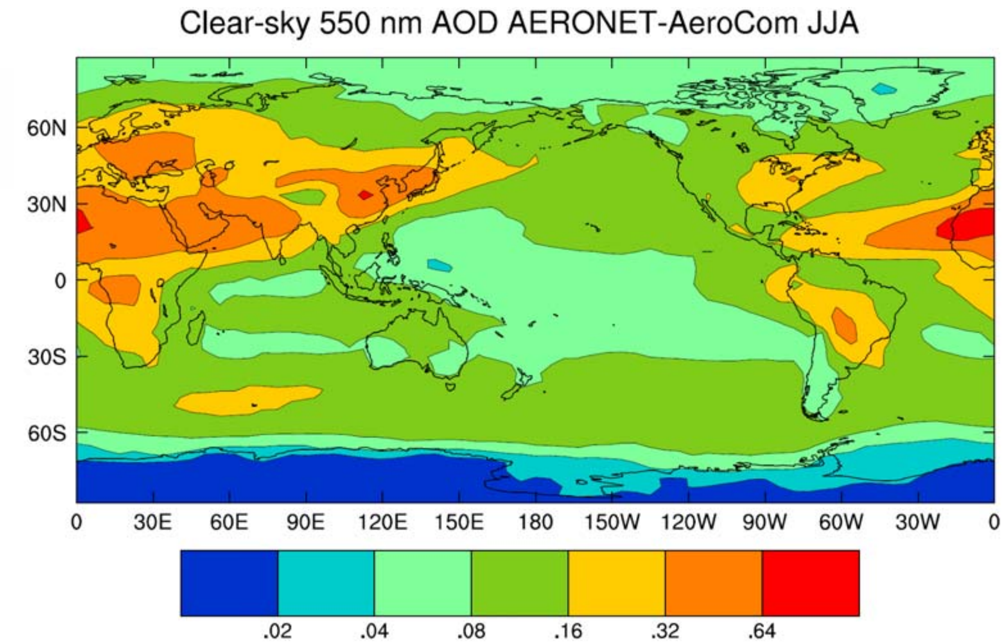
$$N_{\text{ocean}} = 10^{2.41+0.50\log(\text{SO4})+0.13\log(\text{OM})+0.05\log(\text{SS})} \quad (1)$$

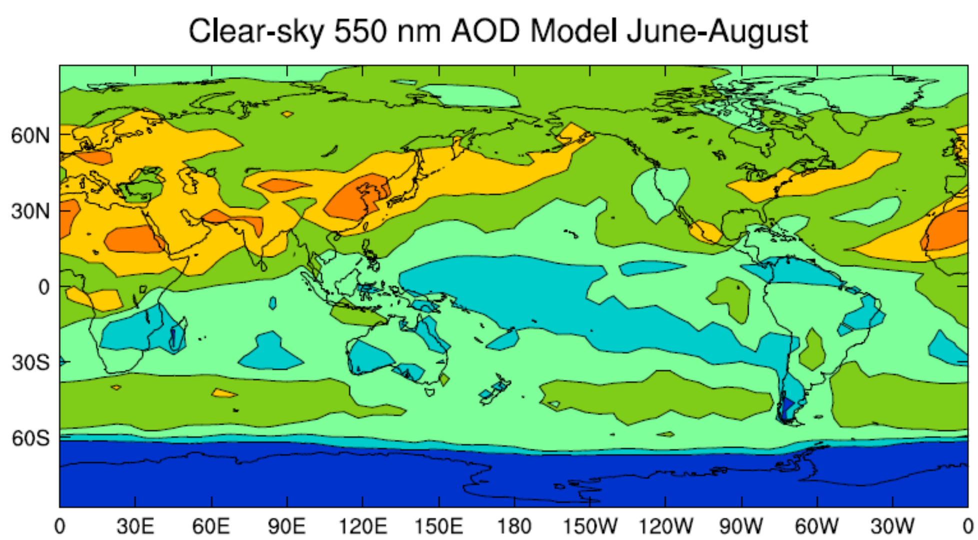
$$N_{\text{land}} = 10^{2.41+0.50\log(\text{SO4})+0.13\log(\text{OM})}, \quad (2)$$

where we reduced the coefficient of SO4 in (2) from 0.5 to 0.26 (following Boucher & Lohmann, 1995)

- “Dispersion” effect on droplet size distribution is included in 1st and 2nd indirect effects (Rotstayn & Yangang Liu, 2003, 2005)

The modelled aerosol optical depth using emissions for 2000 shows a low bias





- AERONET-AeroCom AOD composite from Stefan Kinne (submitted to Atmos. Environ., 2006)
- The "climatology" suggests a global, annual-mean clear-sky AOD of ~ 0.13 (cf. 0.096 in the GCM)
- Satellite retrievals tend to overestimate AOD due to cloud contamination, making the GCM look worse than it is
- Main issues in GCM: sea-salt restricted to MBL, and low-ish carbonaceous aerosol emissions
- GCM looks better for SSA than AOD (not shown today)

Our 20th century transient runs include most of the "forcings" that are thought to be important

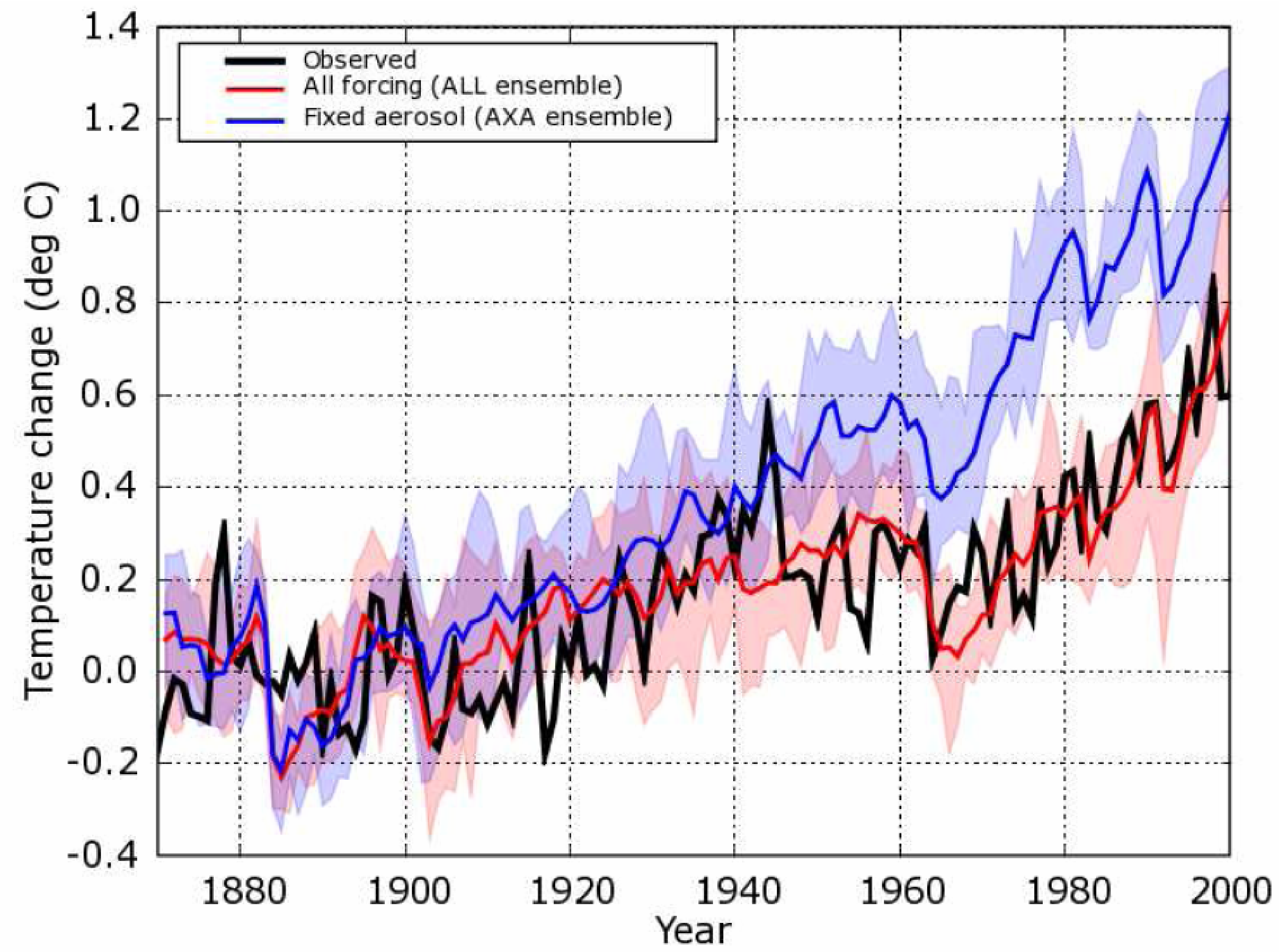
The eight-member ALL ensemble (1871-2000) is forced by

- 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 (Smith et al., 2001, 2004)
- Time varying carbonaceous aerosols (BC and OC) (Ito & Penner, 2005)
- Simple BC effect on snow albedo (Hansen & Nazarenko, 2004)
- Volcanic aerosol (updated from Sato et al., 1993)
- 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.

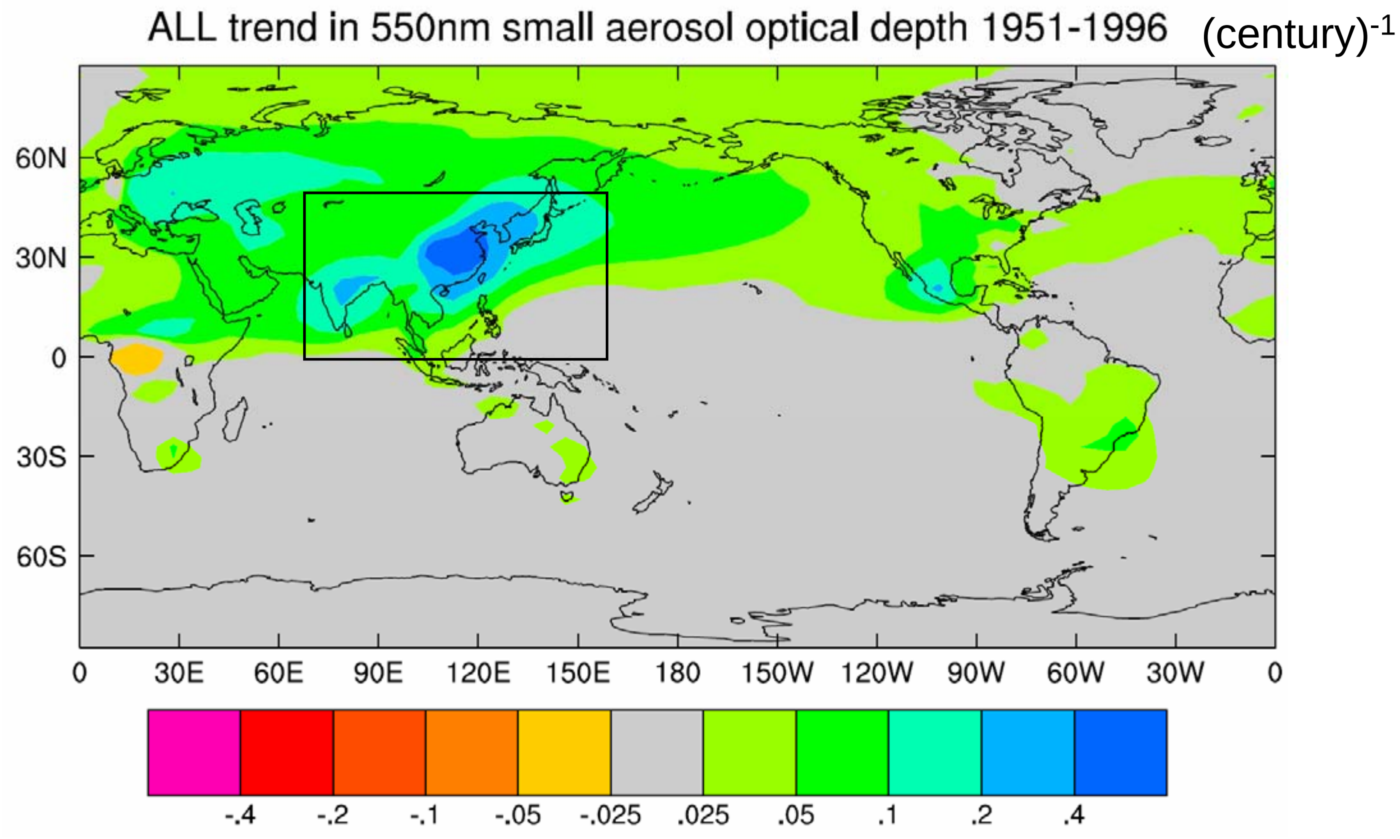
We also did an ensemble in which only "Asian" anthropogenic aerosols were allowed to change from their 1870 levels (ASIA ensemble)

The ALL ensemble gives a better simulation of global-mean temperature change after 1950



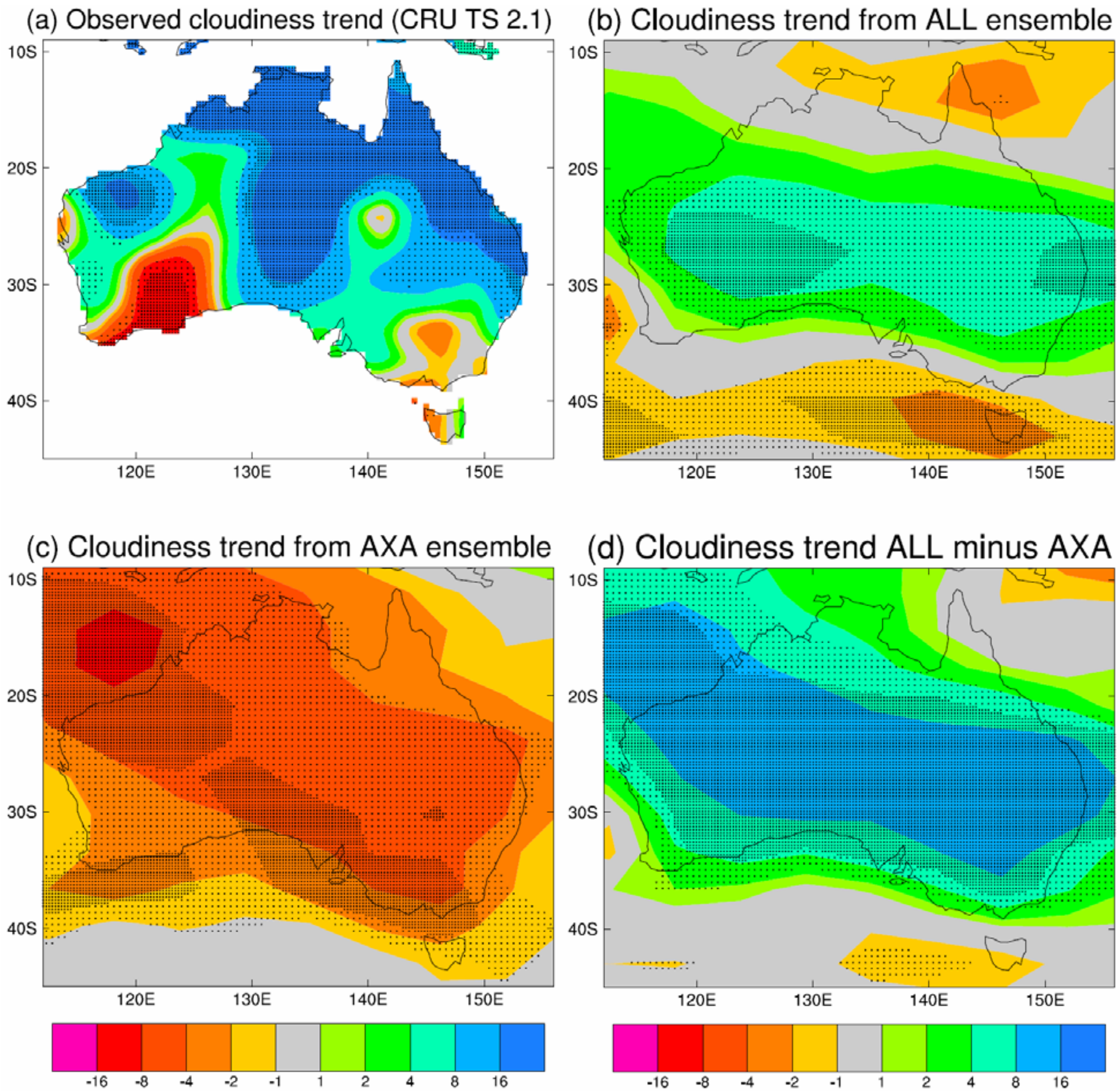
Near-surface temperature change relative to 1871-1900 mean. Observations are from HadCRUT2 (Jones and Moberg, 2003; Rayner et al., 2003)

Trends in anthropogenic aerosol optical depth are dominated by the NH (and especially Asia)



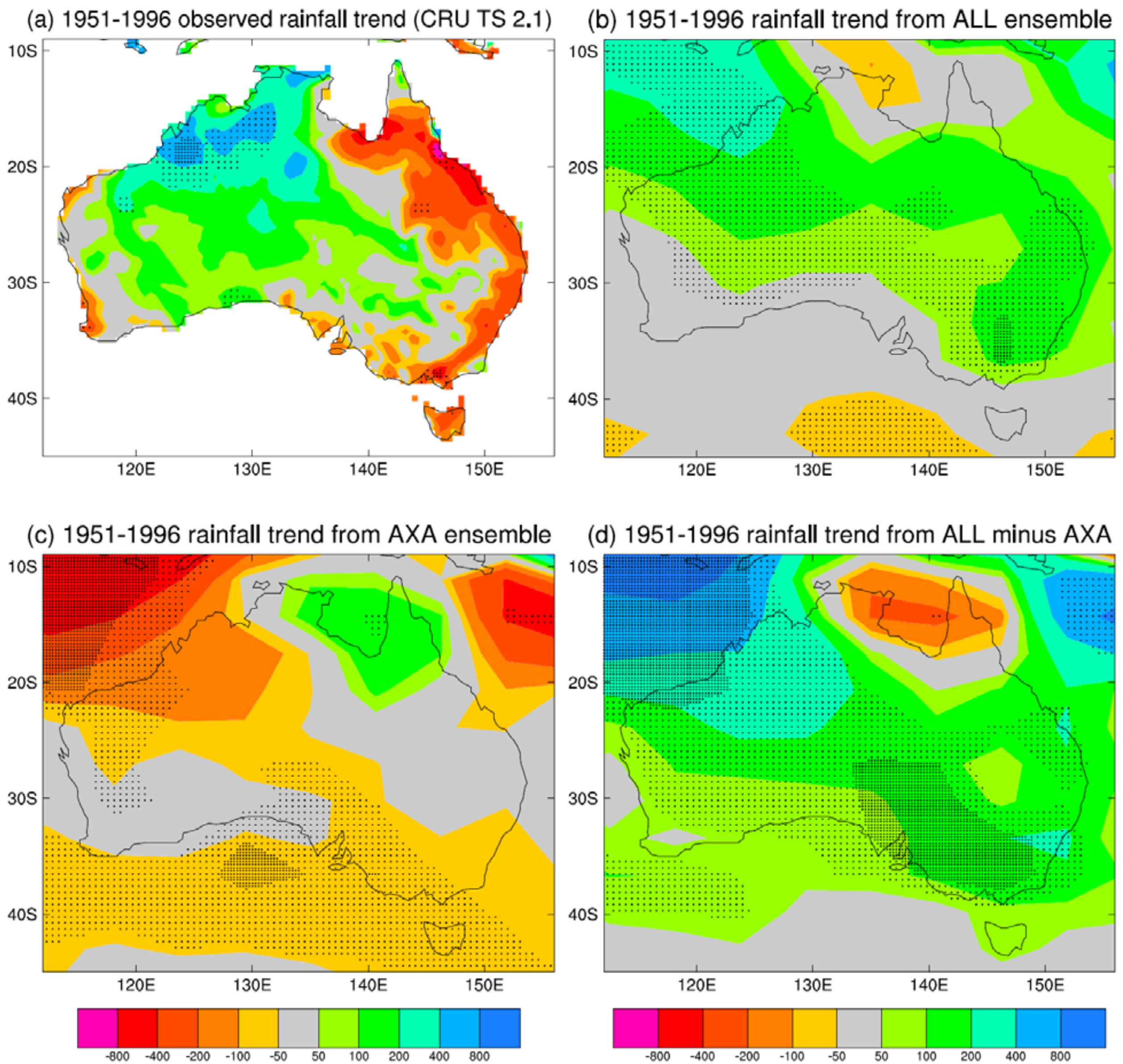
We analyse the period 1951-1996 (to maximise the effect of Asian aerosols)

Inclusion of aerosol forcing increases the cloudiness trend everywhere over Australia



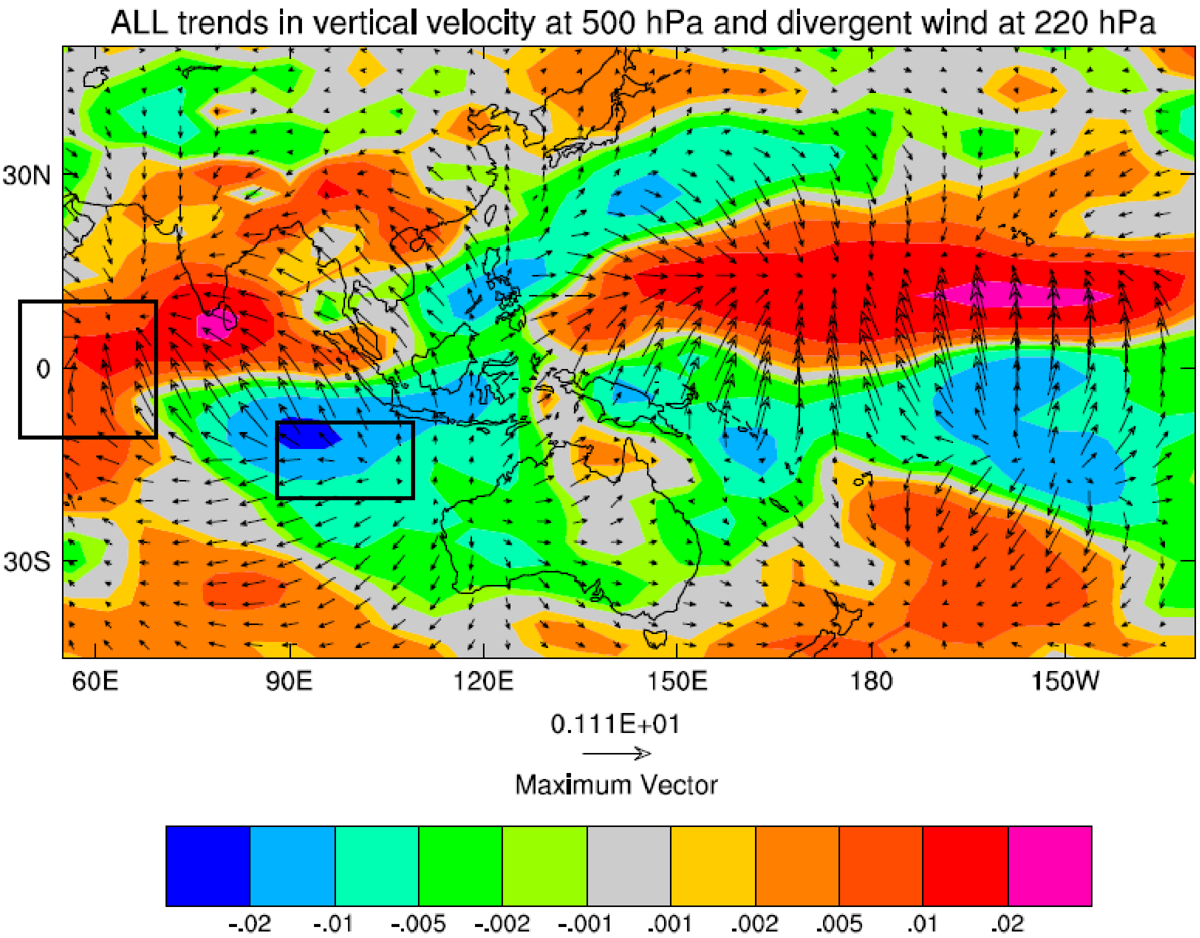
Cloudiness trends in %/century

The annual rainfall trend pattern is also strongly affected by inclusion of aerosol forcing in the GCM



Annual rainfall trends in mm/century

Over the Indian Ocean, the ALL ensemble shows a shift of convection towards NW Australia during 1951-1996

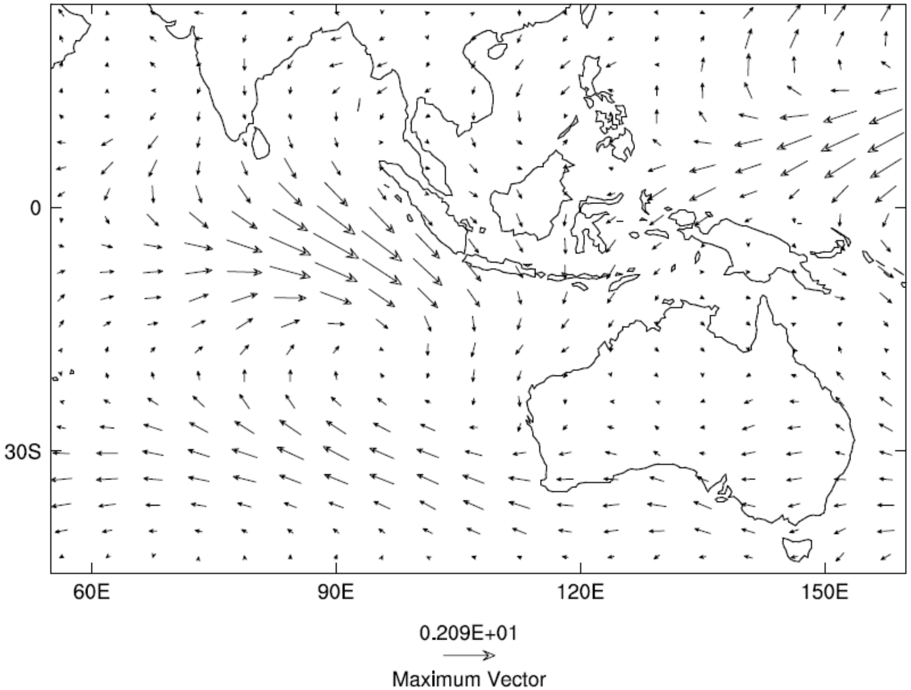


Warm colours denote a trend of increasing subsidence, cool colours increasing ascent (Pa/s/century). Divergent winds at 220 hPa in m/s/century.

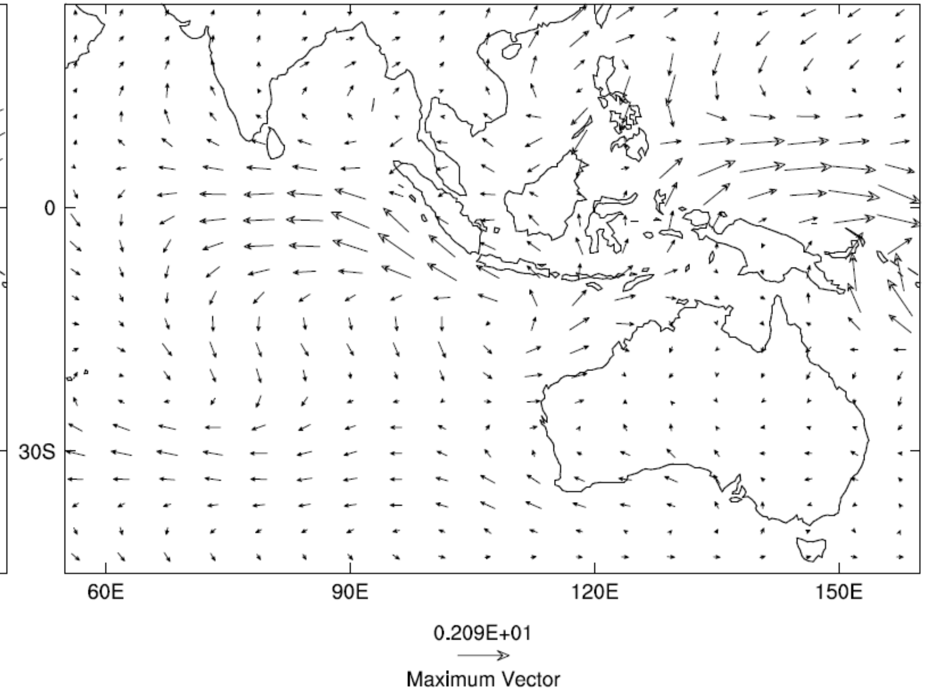
This behaviour resembles the negative phase of the Indian Ocean Dipole (linked to increased rainfall over Australia)

Aerosol forcing makes the simulated monsoonal winds over the Indian Ocean flow more towards Australia

ALL ensemble-mean trends in near-surface winds



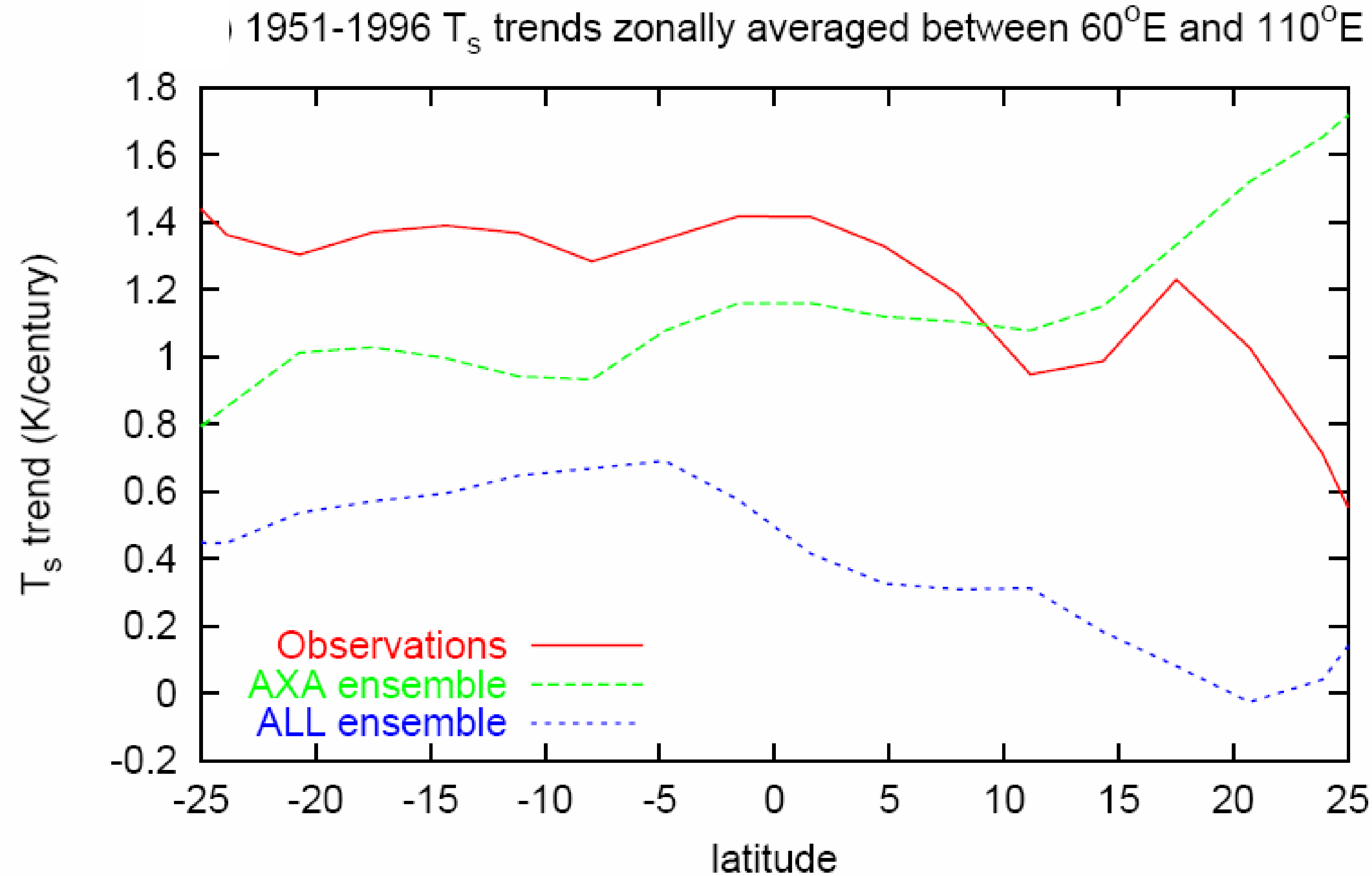
AXA ensemble-mean trends in near-surface winds



1951-1996 near-surface wind trends in m/s/century.

- **This effect is present in both DJF and JJA seasons (not shown)**
- **Should also be seen in T_s and SLP trends (60^oE to 110^oE)**

The zonal-mean observed T_s trends over the Indian Ocean sector tend to support the model

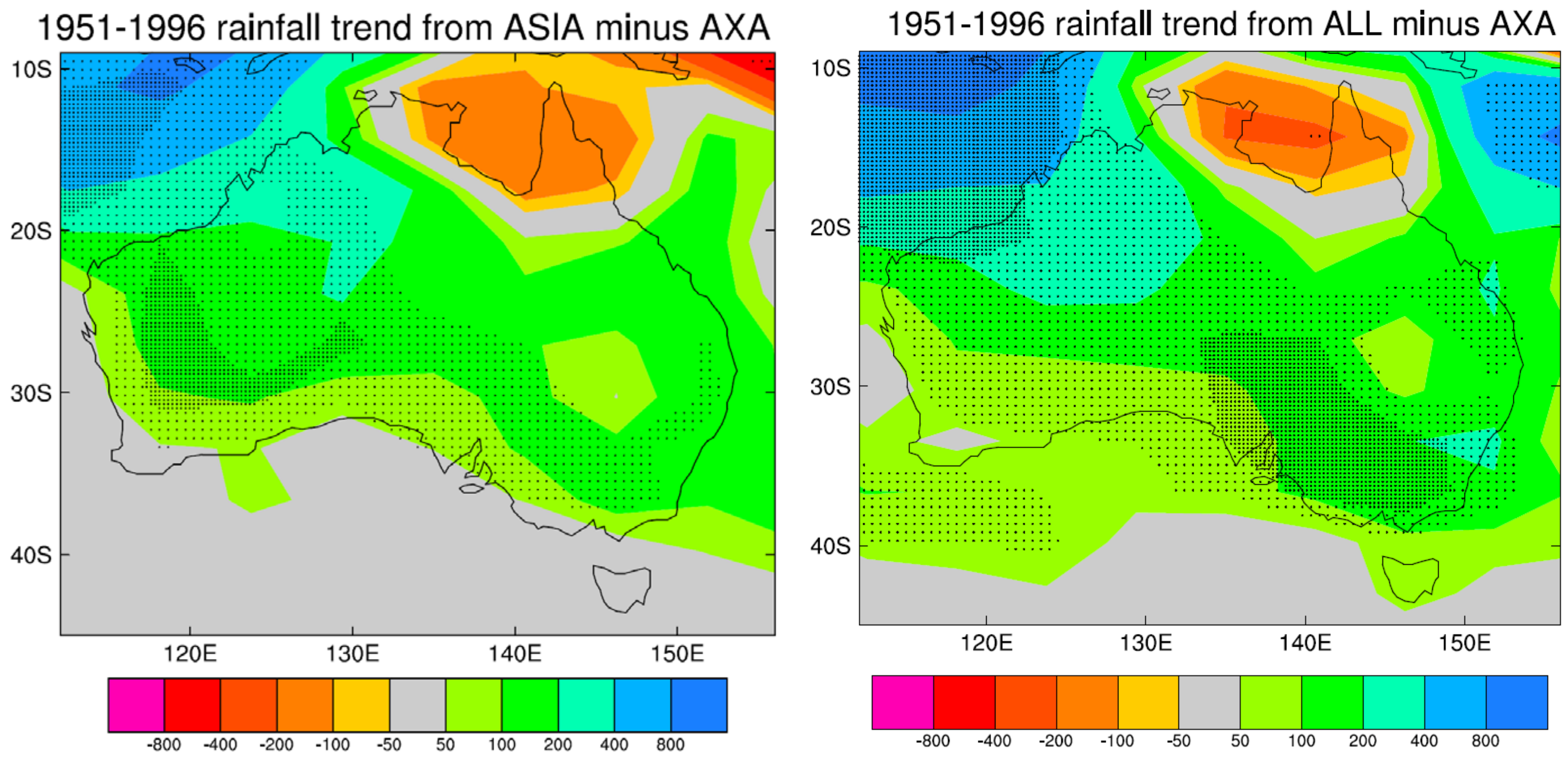


✓ Meridional T_s gradient is similar in observations and ALL ensemble

× ALL ensemble underestimates warming in this region (and SH overall)

✓ SLP gradients are also dynamically consistent in GCM

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

Caveats

- Only one model used; desirable to repeat with others
- Coarse-resolution model has limitations (esp. OGCM)
- Aerosol treatments are subject to gross uncertainty, and much more work is needed to reduce this
- Other GCM physics (e.g., convection) is also uncertain
- The model shows aerosols giving increased rainfall over NE Australia too, which is not observed
- Differences between ensemble members remind us of the importance of natural variability (not shown today)
- Some support for SST trends in HadCRUT2 observations, but SLP trends are poorly known

Conclusions

- Our results suggest that Asian anthropogenic aerosols may have increased Australian rainfall and cloudiness, especially in the northwest
- More robustly: Aerosols should not be neglected in future modelling of Australian climate change!
- The effect of aerosol forcing in the GCM 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)
- Thus, aerosol forcing may be important for understanding climate change in the whole Indo-Pacific region
- More work is needed to quantify these effects

Reviewer #3

This is a substantial paper that is reasonably well written and shows evidence of careful thought on this fascinating topic. The effort may be likened to an attempt to scale Mount Everest with equipment and supplies of unknown quality. The reviewer is left with the difficult task to assess from a distance whether he / she believes that the attempt has been successful or not. Of course, this assessment is impossible to make as the reviewers do not have the means to verify the authors' claims at success. Inevitably the reviewer will then have to evaluate the 'equipment' as well and judge whether the authors may have had sufficiently sophisticated tools to accomplish the attempt. (Think Mallory and Irvine). I hope the authors can forgive me this simile, but it points to what I believe to be the main issue with this paper: The claim that aerosol patterns can affect large-scale circulations is highly contentious, perhaps even outrageous and the state of development of GCM's is hardly good enough to even make such a claim. [And Mallory and Irvine did not come back to tell the tale.]

I confess that I have great reservation about this type of work which is highly ambitious and speculative, but uses modeling tools that are not yet up to the task of providing results with sufficient accuracy. Nevertheless [and undeniably so] the authors show so many little pieces of 'evidence' that even a very skeptical reviewer might find in his conscience a sliver of acceptance of the claims of the authors. With this in mind, in my own judgment, the paper should probably be published with some extra revision but that the claim remains unproven just as in Mallory and Irvine's case.