PROJECT 2.1: OBSERVED AND MODELLED CLIMATE FOR THE NORTH-WEST

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As shown in Figure 1, rainfall has increased significantly over north-western Australia in recent decades. Climate simulations forced by increasing greenhouse gases have mostly been unable to reproduce this trend (Christensen et al. 2007). An exploratory study with a low-resolution version of the CSIRO climate model suggested that this rainfall increase may be caused in part by the massive Asian haze, which consists mainly of fine particles (aerosols) of human origin (Rotstayn et al. 2007; see this reference and Shi et al. 2008 for the model's limitations).

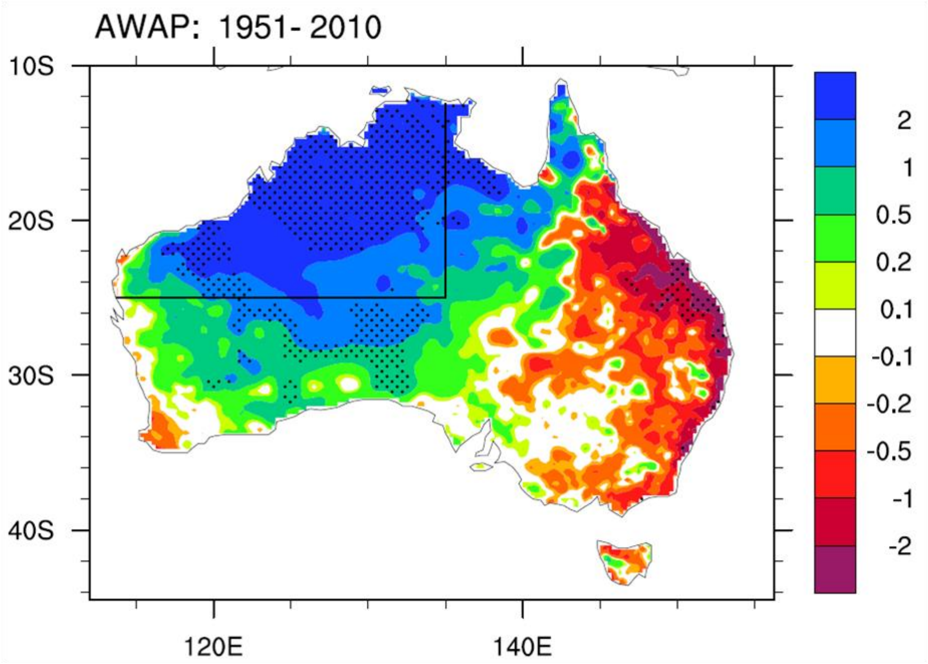

Figure 1: Observed December–March rainfall trends from the Australian Water Availability Project (AWAP; Jones et al., 2009) in mm per day per century for 1951–2010. Stippled trends are significant at 5%, meaning there is only a 5% probability of obtaining that result by chance. The area enclosed by the black lines (land only) denotes the region referred to as north-western Australia in the text.

IOCI3 investigators further evaluated this possibility using an improved climate model (CSIRO Mark 3.6; Rotstayn et al. 2012). They also considered other possible causes of increased rainfall in the north-west, such as changes in greenhouse gases, ozone or natural climate variability.

Few other studies have systematically attempted to attribute the cause of the north-west rainfall increase; see Rotstayn et al. (2012) for an overview. Cai et al. (2011) analysed model output from the Coupled Model Intercomparison Project Phase 3 and grouped models according to whether they included aerosol effects, but were unable to detect a clear aerosol signal. This may reflect the very crude aerosol treatments of these earlier models. An interesting hypothesis suggested by Lin and Li (2012) links the north-west rainfall increase to ascending motion induced by an increase of sea surface temperature (SST) in the tropical Atlantic. Note that, if found to be correct, this also raises the question of what has ultimately caused increased SST in the tropical Atlantic.

Why is it important to understand the cause of rainfall changes in the north-west? Aerosols from Asia are expected to be reduced over the next few decades, in response to concerns about human health and other adverse effects of aerosol pollution. If aerosols have substantially caused the observed rainfall increase, then the rainfall trend would be expected to reverse. Other possible causes, such as Antarctic ozone depletion or natural variability, are also relatively short-term drivers, whereas increasing long-lived greenhouse gases (GHGs) are much longer term. The required policy response may differ, depending on whether the cause is long-term or short-term.

Aerosols tend to exert a cooling effect on climate, effectively “masking” the effects of increasing greenhouse gas concentrations. Sources of human-generated aerosols include industry, motor vehicles and vegetation burning. Australia has relatively low levels of aerosols but is just across the Equator from the planet's highest concentration of human-generated aerosols. Figure 2 shows a calculation of the radiative forcing due to human-generated aerosols, with negative numbers denoting a cooling effect. The strongest such effects are in the south-east Asian region. Figure 2 also shows that aerosol forcing is highly variable in space, implying that aerosols have a strong ability to induce changes in wind patterns (Rotstayn and Lohmann 2002); this may include the monsoonal winds that carry moisture towards Australia's North-West in summer.

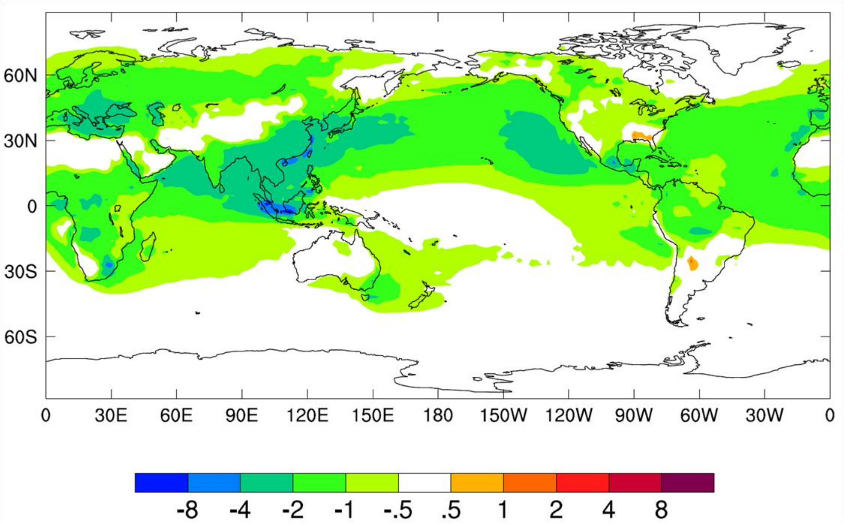

Figure 2: Radiative forcing due to human-generated aerosols from the CSIRO Mark3.6 global climate model (in Watts per square metre). Not that the cooling effect of aerosols (green through blue areas) is most pronounced in south-east Asian region, just across the equator from Australia.

Modelling results: aerosols and greenhouse gases

IOCI3 investigators from CSIRO collaborated with the Queensland Climate Change Centre of Excellence to carry out modelling simulations. These simulations are a subset of more than 150 simulations that comprise an Australian submission to the Coupled Model Intercomparison Project Phase 5 (CMIP5, Taylor et al., 2012). This project will provide the climate modelling input to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. A special focus of the Australian submission (described by Collier et al. 2011) was the inclusion of a large number of "single-forcing" simulations, which enable separation of the effects of increasing long-lived GHGs from those of aerosols and other forcing agents.

They carried out 10-member ensembles with different forcing assumptions for the historical period (1850 – 2010), and projections for the 21st Century (2011 – 2100). The reason they used substantial (10-member) ensembles for each forcing scenario is that this enables a better separation of the effects of the forcing agent from the effects of random noise, sometimes referred to as chaos. IOCI3 investigators focussed mainly on the 10-member ensembles listed in the following Table:

HIST	Standard historical ensemble with "all forcings", namely, long-lived GHGs, ozone, human-generated aerosols, and natural forcing.
NO_AA	Same as HIST, but with human-generated aerosols fixed at 1850 levels.
GHGAS	Historical run forced only by changes in long-lived GHGs.
RCP4.5	Projection for 2011 to 2100 based on Representative Concentration Pathway 4.5, in which total radiative forcing is stabilized before 2100 at roughly 4.5 Watts per square meter (Clarke et al. 2007). This pathway is strongly driven by increasing long-lived GHGs, reinforced by the effects of decreasing aerosols.

The effect of human-generated aerosols in a warming climate is calculated from the difference of HIST minus NO_AA. Further details of the simulations are given by Rotstayn et al. (2012).

Figure 3 compares ensemble-mean summer rainfall trends for the historical climate simulated by HIST (1951 – 2010) and projected future climate simulated under RCP4.5 (2011 – 2100). HIST, which includes increases in human-generated aerosols, shows modest increases over some areas, but these are mostly not significant. In contrast, RCP4.5 shows substantial, statistically significant decreases in rainfall over most of Australia, especially the North West.

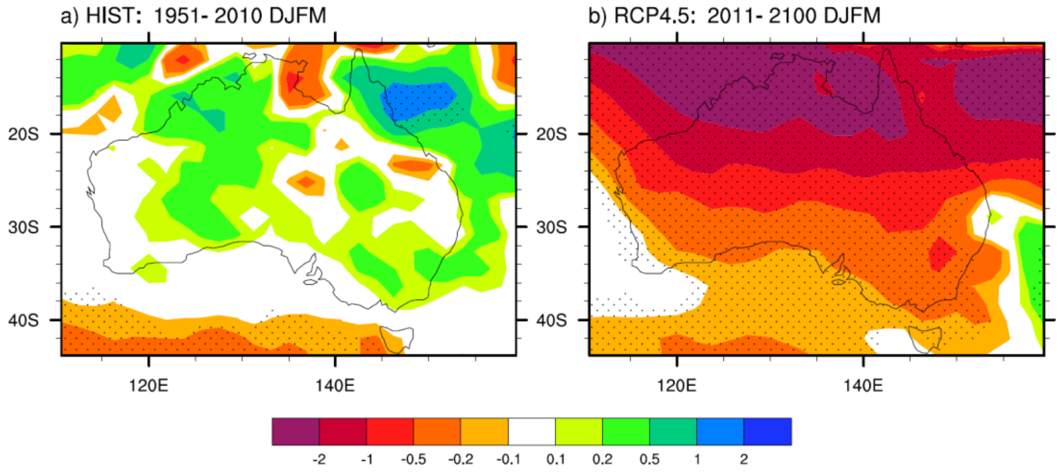

Figure 3: Simulated December–March rainfall trends (mm per day per century), from (a) HIST (1951–2010), (b) RCP4.5 (2011–2100). Stippled trends are significant at 5%. In (a), which simulates the historical effects of all forcings including aerosols, the effects of GHGs are masked by aerosol induced increase in rainfall. In 3(b) the simulation of

21st century rainfall is strongly influenced by increasing GHG forcing, reinforced by decreasing aerosols, resulting in drying (yellow to red areas).

How do we reconcile the fact that projected future rainfall changes under runs such as RCP4.5 differ so dramatically from historical rainfall changes simulated by runs such as HIST?. Figure 4 sheds some light on this question. When models are used to simulate historical rainfall trends using only long-lived GHGs as forcings (Figure 4a), the result resembles a weaker version of 21st Century projected trends (Figure 3b) in runs such as RCP4.5, which are strongly driven by GHG forcing. However, in the simulation of historical rainfall changes from HIST (Figure 3a), the effects of increasing long-lived GHGs are substantially masked by an aerosol-induced increase of rainfall, which is largest over the north-west (Figure 4b).

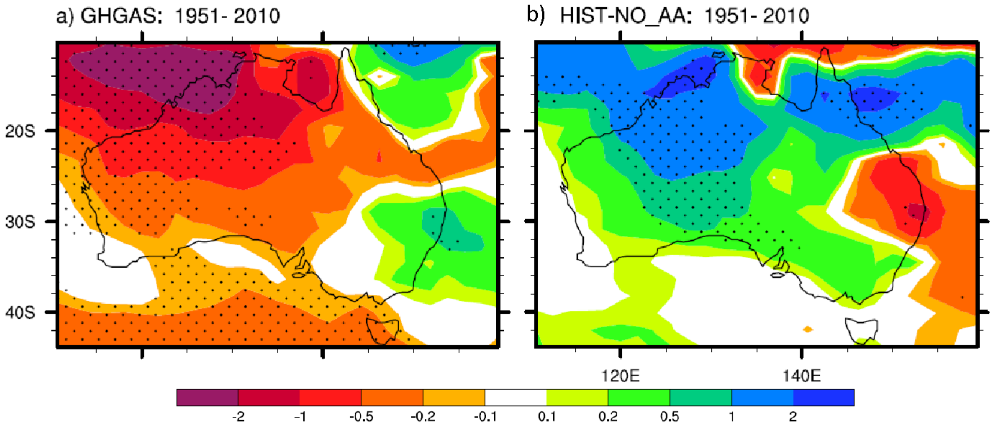

Figure 4: Simulated historical (1951–2010) December–March rainfall trends (mm per day per century), from (a) GHGAS, (b) HIST minus NO_AA. Stippled trends are significant at 5%. Models that simulate historical trends using only GHGs as in (a) produce weaker versions of future trends projected by models strongly driven by GHG forcing (see 3{a} above). In (b), which simulates the historical effects of aerosols, the effect of GHGs is masked by the aerosol-induced increase in rainfall.

Simulations also showed a similar, but smaller masking effect due to changes in ozone (Rotstayn et al. 2012). This is broadly consistent with another recent modelling study which indicated that Antarctic ozone depletion has caused an increase of summer rainfall across the low latitudes of the Southern Hemisphere (Kang et al. 2011).

Possible Mechanism for Aerosol Effect on WA Rainfall

To increase scientific confidence in such results, it is necessary to: (1) explain the physical mechanism in the model and in observations; and (2) compare results across a range of global climate models. Rotstayn et al. (2012) discussed the mechanism in the CSIRO Mark 3.6 model by which human-generated aerosols contribute to increasing rainfall, and increasing long-lived GHGs contribute to decreasing rainfall in the north-west. The key aerosol-induced feature is a cyclonic (clockwise) circulation trend off the coast, which strengthens the monsoonal winds, and carries more moisture towards the north-west from the Indian Ocean; the opposite occurs in response to forcing from increasing GHGs. This mechanism is also seen in data from reanalyses. We have also proposed specific processes that may explain the connection between aerosol forcing and the cyclonic circulation trend (Rotstayn et al., 2012). Further work is needed to establish the veracity of the proposed mechanism, and the extent to which these findings are model-dependent.

Discussion & Knowledge Gaps

Climate models can be used explore possible causes and effects of rainfall changes by turning on one forcing at a time. Single-forcing simulations with the CSIRO Mark 3.6 global climate model suggest that increasing GHGs tend to cause a decrease of rainfall over the north-west, whereas human-generated aerosols tend to cause an increase. They also suggest that future rainfall trends may look very different from recent trends: future trends will be driven by increasing concentrations of long-lived GHGs, and an unmasking of the effects of GHGs if aerosol levels decrease as expected.

The 10-member ensemble averages used were designed to capture the forced response to changes in aerosols or long-lived GHGs by averaging out the effects of decadal variability. Even in the case that isolates the aerosol forcing, these ensemble averages were unable to capture the large magnitude of the observed rainfall trend over the north-west (the region defined by the black lines in Figure 1). The observed rainfall trend is 2.72 mm per day per century, whereas the ensemble-mean trend in HIST minus NO_AA is 0.95 mm per day per century. This suggests that the observed trend includes both a forced and an unforced component. In other words, the model suggests that some of the observed trend is likely to be associated with natural variability.

Results based on one climate model, like those presented here, should be treated as a hypothesis. Going forward, CMIP5 will provide a valuable opportunity to compare results from a range of models. These models have been subject to intense scrutiny by climate analysts. Although it is currently uncertain how many modelling groups will contribute “single-forcing” simulations to the CMIP5 data base, a recent and concerted effort to encourage other groups to submit simulations will enable isolation of the effects of human-generated aerosols (Boucher et al. 2011).

The focus of this IOCI3 investigation was mean rainfall, but it should be noted that much of the rainfall in the north-west is associated with tropical cyclones or other extreme rainfall events. The connection between different forcing agents, mean rainfall and such high-impact events is an important topic for future research. Another area of further investigation is the possible underlying mechanism by which aerosols and GHGs may influence rainfall in north-west Australia (Rotstayn et al. 2012).

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