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

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Milestone 2.1.3: Report on attribution of observed rainfall changes, based on historical climate model runs

1. Background and Progress

Observations show increasing rainfall in the north-west of Australia, but climate simulations forced by increasing greenhouse gases have generally not reproduced this trend. An exploratory study with a low-resolution version of the CSIRO climate model suggests that a possible cause of the rainfall increase is the massive Asian haze, which consists mainly of fine particles (aerosols) of human origin (Rotstayn et al., 2007). The aim of Project 2.1 is to further evaluate this hypothesis using an improved climate model, while also considering other possible causes of increased rainfall in the north-west (e.g., greenhouse gases or natural variability).

Because this IOCI3 project is too small to be viable independently, we decided in early 2009 that the climate simulations for this project need to "piggy back" on a larger project funded by the Queensland Climate Change Centre of Excellence (QCCCE). The QCCCE-funded project aims to perform the full set of simulations required for the Coupled Model Intercomparison Project Phase 5 (CMIP5), from which the modelling input to the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change will be drawn. Linking this project to the AR5 simulations will give the IOCI3 work more credibility and a higher profile, and IOCI3 also benefits from the resources provided by QCCCE (e.g., access to their supercomputer and programming support). However, it also contributed to delays in the IOCI3 timelines, in part because we are now conducting a much larger and more complex set of simulations than originally planned. These delays were in addition to those incurred due to a lack of supercomputing capacity at CSIRO in the early stages of IOCI3, and limited funding of Project 2.1 (only 0.25 staff members in total).

With colleagues in Queensland, we completed a large set of coupled atmosphere-ocean historical runs and future projections, intended for submission to CMIP5. In late 2010, analysis of these runs commenced. In January, 2011, we found an error in the treatment of volcanic forcing in the CSIRO Mk3.6 climate model, which disrupted our work program for several weeks while we assessed the effects of the error. We found that, in all historic runs that include natural forcing, we had inadvertently set the negative shortwave component of volcanic forcing to zero, leaving a smaller, positive longwave forcing due to volcanic eruptions. Although this is a relatively small forcing compared to, e.g., human-generated greenhouse gases and aerosols, we decided that the heavy scrutiny applied to CMIP5 means that we needed to rerun all affected simulations. This entails a delay of several months for the Mk3.6 CMIP5 effort, although the existing runs still have scientific value. These runs have been used in a paper submitted to an international journal (Rotstayn et al., 2011), and also form the basis for the analysis in the following sections.

In Sections 2 and 3, we show how historic runs with "individual forcings" can be used to improve the understanding of the relationship between recent and projected climate change in the Indo-Pacific region, This is very relevant to north-western Australia, because this is a region where recent projected trends have generally been different, which raises questions about the veracity of the projections. By introducing results from future projections here, we are slightly extending this report beyond the original scope; we feel this is merited because of the insights that can be gained by looking at the historic and projected changes together.

2. Simulations

We used the CSIRO Mark 3.6 (Mk3.6) Global Climate Model (GCM), which has recently been described by Rotstayn et al. (2010). Mk3.6 primarily differs from its predecessors by inclusion of an interactive aerosol scheme, which treats sulfate, organic carbon, black carbon, dust and sea salt. As well as direct radiative effects of these species, the model treats the "indirect" effects of aerosols on clouds. We included CMIP5-recommended data sets for solar irradiance and concentrations of long-lived greenhouse gases (GHGs) and ozone (http://cmip-pcmdi.llnl.gov/cmip5/), as well as emissions of sulfur, organic carbon and black carbon needed by the aerosol scheme (Lamarque et al., 2010). With our aerosol treatments, net top-of-atmosphere anthropogenic aerosol forcing from 1850 to 2000 is −1.4 W m^{-2}. This is a little larger in magnitude than the best estimate of −1.2 W m^{-2} from Forster et al. (2007), though it is well within the large uncertainty range.

As well as future projections, we have performed a set of 10-member historic ensembles (for 1850 to 2005), designed to explore the effects of changes in GHGs, aerosols, ozone and natural (solar and volcanic) forcing. Here we focus on the following 10-member ensembles:

1. **HIST**: Standard historic run with "all forcings", namely, long-lived GHGs, ozone, anthropogenic aerosols, and natural forcing.
2. **NO_AERO**: Same as HIST, but with anthropogenic and biomass-burning aerosol emissions fixed at 1850 levels. (We hereafter refer to these emissions collectively as "anthropogenic".)
3. **GHGAS**: Historic run forced only by changes in long-lived GHGs.
4. **RCP4.5**: Projection for 2006 to 2100 based on Representative Concentration Pathway 4.5, in which total radiative forcing is stabilized before 2100 at roughly 4.5 W m^{-2}.

As mentioned above, the historic runs that include natural forcing (HIST and NO_AERO) are affected by an error, in that the shortwave component of volcanic forcing is zero. Thus, our runs should not be used to draw inferences about the role of natural forcing. It should still be valid to compare two experiments that both omit this shortwave effect.

3. Results and Discussion

Teleconnections are driven by sea-surface temperature (SST) anomalies relative to the low-latitude ocean (Xie et al., 2010; Watterson, 2010), so it is useful to compare trends in near-surface temperature (T_s) relative to the mean low-latitude (30°S to 30°N) trend from each ensemble. We compare 50-year trends from the historic period (1956 – 2005) with 95-year trends from RCP4.5 (2006 – 2100). Figure 1 shows that two of the historic runs (GHGAS and NO_AERO) qualitatively share many features with the strong GHG-driven pattern in RCP4.5:

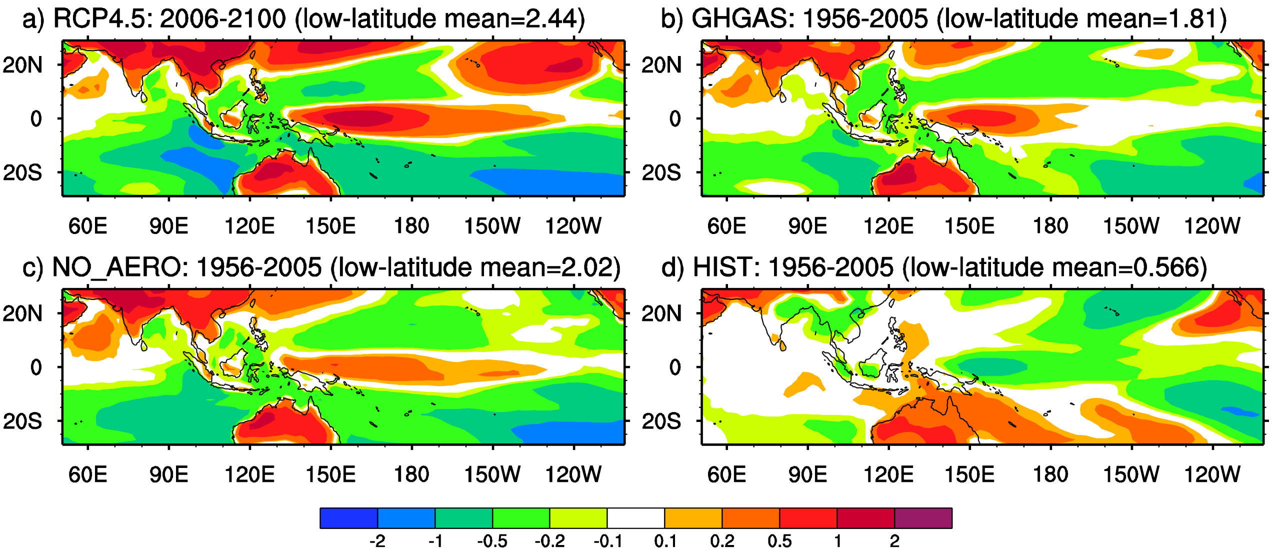

Figure 1: Ensemble-mean trends of T_s relative to the low-latitude (30°S to 30°N) mean T_s trend, from (a) RCP4.5 (2006–2100), (b) GHGAS (1956–2005), (c) NO_AERO (1956–2005), (d) HIST (1956–2005). The low-latitude mean T_s trend for each ensemble (which is subtracted from the trend at each grid point to generate each plot) is shown in its header (K/century).

1. Enhanced warming over continental areas, a result typical of the response of GCMs to increasing GHGs (Meehl et al., 2007).
2. Enhanced warming in the western and central equatorial Pacific (DiNezio et al., 2009).
3. Relatively less warming in the tropical Indian Ocean (IO) and in much of the South Pacific Ocean. The response in the IO resembles a positive Indian Ocean Dipole, with relative cooling in the east and warming in the west (Saji et al., 1999).
4. Less warming in the Southern Hemisphere than in the Northern Hemisphere, consistent with the multi-model mean shown by Meehl et al. (2007).

In contrast, the HIST run, which differs from NO_AERO solely by inclusion of anthropogenic aerosol forcing, differs in many respects from the above runs:

1. Over South and East Asia there is relatively less warming, due to negative forcing by anthropogenic aerosols.
2. In the equatorial Pacific, there is relatively less warming instead of enhanced warming.
3. In the Southern Hemisphere, the pattern is very different, with enhanced warming over much of the Pacific Ocean, and no sign of the reduced warming seen in the tropical eastern IO in the other runs.

There are strong positive correlations, of order 0.8 or more, between the SST trend patterns in RCP4.5, GHGAS and NO_AERO (not shown). This confirms that increasing GHGs are the dominant forcing in these runs. However, the SST trend patterns in HIST are (weakly) negatively correlated with those in RCP4.5, GHGAS and NO_AERO. We focus on SSTs because of their importance in driving tropical atmospheric circulation, although the correlations are not dramatically different when land points are included.

How is atmospheric circulation affected by the different SST trend patterns seen in the four experiments? Figure 2 shows trends of velocity potential and divergent wind vectors at 220 hPa; with the sign convention used here, cool (warm) colours denote centres of increasing (decreasing) upper-level divergence and ascending motion. GHGAS and NO_AERO show similar patterns, with increasing upper-level divergence over the tropical western Pacific, and decreasing upper-level divergence over a region centred near Indonesia. The pattern in RCP4.5 resembles a more intense version of that seen in GHGAS and NO_AERO, consistent with the relative SST trends shown in Fig. 1. However, the trend pattern in the HIST run is very different, with decreasing upper-level divergence over the equatorial central and western Pacific and increasing upper-level divergence over a wide area further west.

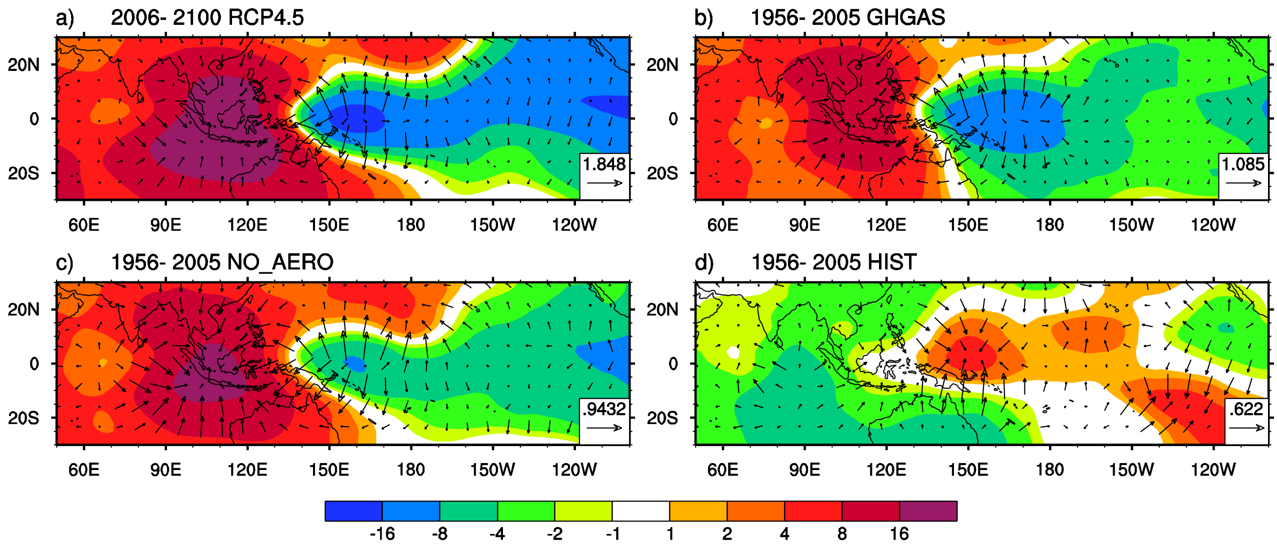

Figure 2: As Figure 1, but showing ensemble-mean trends of velocity potential ($10^5 m^2/s$/century) and divergent wind vectors (m/s/century) at 220 hPa. The largest vector is shown in the lower-right corner of each panel.

The results in Fig. 2 suggest that the enhanced equatorial Pacific warming and relative cooling in the equatorial eastern IO are central to the response of the Mk3.6 GCM in the Indo-Pacific region. The dynamic response of our model to GHG forcing (Fig. 2a) is qualitatively similar to that shown, in terms of changes in 500-hPa vertical velocity for an ensemble of GCMs forced by increasing GHGs, by Vecchi and Soden (2007). They related these changes to a weakening of the tropical circulation (and especially the Walker circulation), consistent with an increase in lower-tropospheric water vapour in a warmer climate (Held and Soden, 2006). A weaker Walker circulation gives weaker convergence of near-surface zonal winds over the Indonesian region. In the Pacific, there is a weakening of the equatorial easterly winds and associated oceanic upwelling. Over the eastern IO, anomalous equatorial easterlies occur, with an increase in upwelling and a shallowing thermocline. Further, a weakening Indonesian Throughflow, in response to weakened equatorial Pacific easterlies, tends to contribute to a shallower eastern IO thermocline in GCMs forced by increasing GHGs (Alory et al., 2007). The enhanced equatorial warming in the Pacific was studied by DiNezio et al*.* (2009), who found that ocean dynamical changes act to reduce (enhance) the net heating in the east (west). This explains why models simulate enhanced equatorial warming, rather than El-Niño-like warming, in response to a weaker Walker circulation.

These changes in low-level equatorial winds are also seen in our model in response to GHG forcing (not shown). The GHG-forced runs (NO_AERO, GHGAS and especially RCP4.5) show weakening 850-hPa easterly winds over the equatorial central and western Pacific. The HIST run has a very different response, with enhanced equatorial-Pacific easterlies. Taken together, these results suggest that anthropogenic aerosol forcing has substantially "masked" the model's dynamic response to GHG forcing in the Indo-Pacific region.

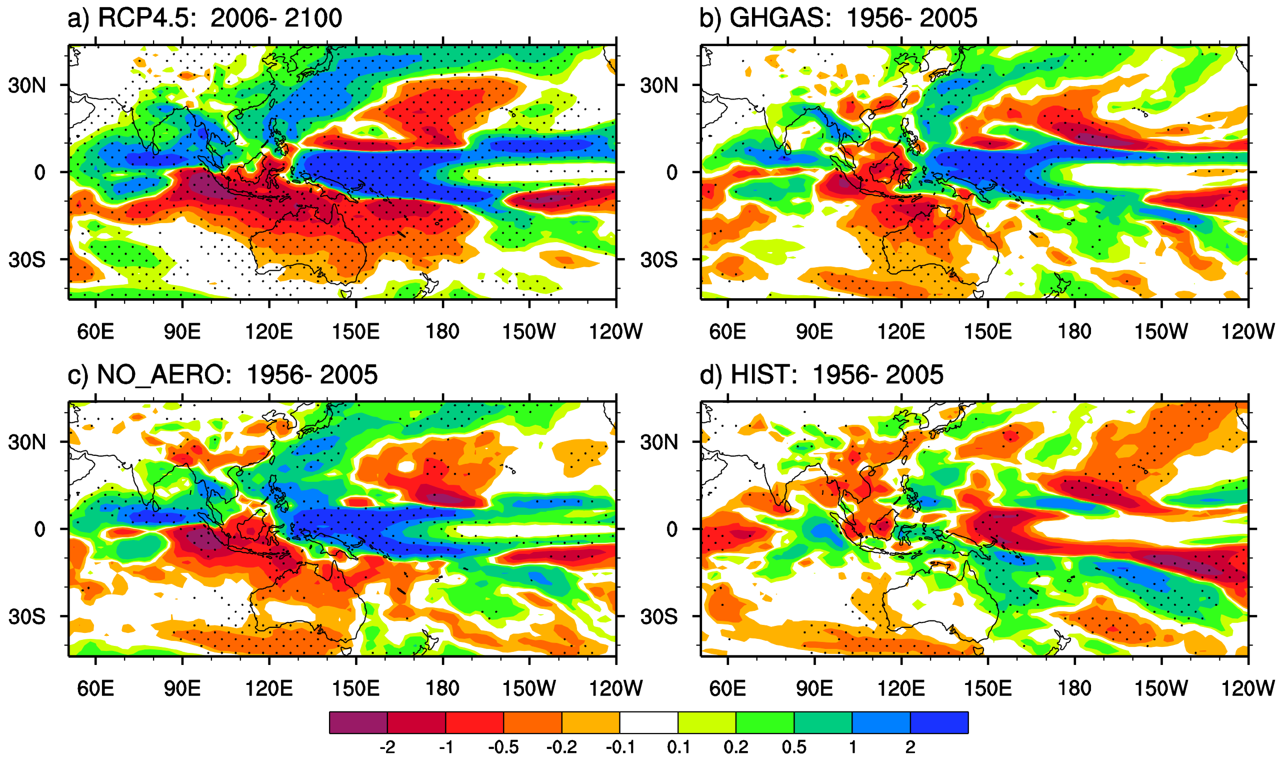

Figure 3. As Figure 1, but showing ensemble-mean rainfall trends (mm/day/century). Stippling shows trends that are significant at 5%.

Figure 3 shows annual rainfall trends from the same four ensembles. Statistical significance at each grid point was assessed using a two-sided *t* test, taking the 10 individual trend values as independent data points. In the runs dominated by GHG forcing (RCP4.5, GHGAS and NO_AERO), prominent features are the areas of increasing rainfall centred over the equatorial western Pacific, and decreasing rainfall centred over the equatorial eastern IO. These are collocated with regions of enhanced surface warming and relative cooling respectively (Fig. 1). The decreasing rainfall trend centred over the equatorial eastern IO also extends to Australia, especially over tropical regions. Rainfall trends in HIST are generally smaller, consistent with the weaker trends seen in Figs. 1d and 2d. Decreasing rainfall over Australia in RCP4.5 is consistent with Watterson (2011), who compared 21st Century simulations from 23 GCMs and found that changes in simulated Australian rainfall correlated strongly with changes in a "Pacific-Indian Dipole index", similar to the equatorial SST trend pattern seen in our runs dominated by GHG forcing.

It is recognised that projected decreases in anthropogenic aerosol concentrations will unmask the effects of increasing GHGs on global-mean temperature (Kloster et al., 2010). However, the implications for regional circulation have not received much attention. Our historic runs suggest that, in the Australian region, anthropogenic aerosols may have substantially delayed GHG-induced changes in low-latitude atmospheric circulation and associated rainfall changes. Our 21st Century ensemble suggests that future climatic trends may look very different from trends over the last few decades. In our historic runs, an important effect of anthropogenic aerosols is that they delay the weakening of the Walker circulation, which is driven by increasing lower-tropospheric water vapour in a warmer climate (Held and Soden, 2006; Vecchi and Soden, 2007). We have not specifically discussed the role of "Asian" aerosols in this report, but another set of simulations (not shown) suggest that the response of the Mk3.6 model over Australia is not driven by Asian aerosols in isolation, but by anthropogenic aerosols more broadly (of which Asian aerosols are a subset).

4. Conclusions and Further Work

We have shown that, in the CSIRO Mk3.6 GCM, anthropogenic aerosols have delayed the response of atmospheric circulation and rainfall to increasing GHGs in the Indo-Pacific region, including north-western Australia. In this model, increasing GHGs tend to drive a decrease of rainfall over most of Australia, with a "centre of action" to the north-west of Australia. This effect has been delayed, or "masked" by anthropogenic aerosols. However, aerosol emissions are projected to fall rapidly in the next few decades, suggesting that the effects of increasing GHGs will be augmented by decreasing effects of aerosols.

There are several uncertainties regarding our results. Possibly the most substantial is the large uncertainty in anthropogenic aerosol forcing. The HIST ensemble slightly underestimates the observed global-mean warming relative to the base period of 1850–1879, and this underestimate would likely be increased if shortwave volcanic forcing had been included. This suggests that our anthropogenic aerosol forcing of -1.4 W m^{-2} may be too large in magnitude, so it is possible that the impacts of these aerosols are overestimated. More generally, the response of our model is physics-dependent, and it would be desirable to extend the analysis to include a wider range of models. This may be possible in a future project. More work is required to explore the mechanisms that relate to north-western Australian rainfall changes, both in the Mk3.6 model and in observations. Thus far, Project 2.1 has mainly comprised a laborious technical phase (i.e., configuring and running the model, and processing the outputs). In the final year of IOCI3, we intend to focus more on analysis of the mechanisms, and we hope to have the opportunity to extend and deepen the analysis in a future project.

The issues that need to be considered are complex. Some of these are as follows. The individual runs that comprise our 10-member ensembles show large internal variability, suggesting that an unambiguous attribution of rainfall trends in the North-West may be difficult to achieve. A pessimistic view was taken recently by Cai et al. (2011), who argued that future projections of rainfall over the north-west are strongly correlated with biases in the simulation of ENSO, which affect all GCMs to some extent. However, another recent study gives some cause for optimism (Li et al., 2011). Although these authors were mainly focused on the decrease of rainfall over north-eastern Australia, their analysis helps to explain the mechanism underlying the negative correlation between rainfall variations over the north-eastern and north-western regions (referred to a "flip-flop" by Rotstayn et al., 2010), and the relationship of Australian tropical rainfall trends to SSTs off the north-west coast. Another important aspect is to better understand the effects of aerosols on the Hadley (north-south) circulation as opposed to the Walker (east-west) circulation (e.g., Ming and Ramaswamy, 2011). Our current analysis suggests that the effect on the Walker circulation may be more crucial in the Australian region.

Due to the unexpected delay in the Queensland-funded Mk3.6 CMIP5 project, on which Project 2.1 depends, this report is based on provisional results, rather than from our CMIP5 submission as originally planned. However, based on the tests we carried out after the volcanic-forcing problem was discovered in late January, we do not anticipate that the revised simulations will show dramatically different rainfall trends. For our final report on Project 2.1 (in 2012), we intend to analyse the revised simulations in more detail than has been possible with the current set of runs.

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Summary of new linkages to other IOCI 3 Projects

We now have a large set of global climate simulations, which could be used to drive dynamical or statistical downscaling models.

Summary of new research opportunities

The collaboration with QCCCE has increased our capacity to perform sensitivity studies of this type with the CSIRO Mk3.6 climate model. There is scope to systematically explore the effects of different anthropogenic climate forcings (long-lived greenhouse gases, aerosols, ozone and land-use change).

List of publications accepted and submitted

Rotstayn, L. D., S. J. Jeffrey, J. I. Syktus, M. A. Collier, S. M. Dravitzki, A. C. Hirst, and K. K. Wong (2011), Have anthropogenic aerosols delayed greenhouse gas-induced changes in Indo-Pacific regional circulation and rainfall?, Atmos. Sci. Lett., submitted.

IOCI-related presentations

Rotstayn, L. D . "The CSIRO Mk3.6 GCM: An Australian Contribution to CMIP5", Australia - New Zealand Climate Forum, Hobart, October 2010.

Rotstayn, L. D . "Different forcings: land cover, greenhouse gases, ozone and aerosols", CMIP5 Science Workshop, Melbourne, April 2011.