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Climate extremes during the 20th and 21st centuries simulated by the CSIRO Mk3.6 climate model with anthropogenic and natural forcings

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Abstract: Analyses of observed climate records around the world have shown a general trend over recent decades towards increases in the frequency of warm days and nights and decreases in the frequency of cold days and cold nights. In many regions, this has resulted in changes to the hydrological cycle. Studies have also shown that anthropogenic climate change will lead to more extreme events in many parts of the globe. However, it is unclear to what degree changes in radiative forcings, such as increased concentration of greenhouse gases, changed aerosol loading, solar variability and volcanic aerosols have contributed to the observed trends in climate extremes in various regions of the globe during the 20th century.

In this study, the CSIRO Mk3.6 coupled climate model was used to perform a number of attribution and experiments following the Coupled Model Intercomparison Project Phase 5 (CMIP5) experimental design. Results from these experiments were used to evaluate the relative impacts of various radiative forcings on climate extremes during the 20th century. These experiments include an ensemble of simulations with all forcings (anthropogenic and natural), natural forcings only, and all forcings with anthropogenic aerosols held constant at pre-industrial levels. Using the simulated daily data from these experiments, climate extreme indices defined by the Australian Government Bureau of Meteorology were computed for the 1851 to 2005 period. These include a number of temperature based indices, such as warm spell duration, hot days and warm nights, as well as a number of precipitation based indices, such as daily rainfall intensity, heavy precipitation days and consecutive dry days. This analysis quantifies the relative contributions of various radiative forcing factors to the simulated changes in extreme indices for the 1971 to 2005 period. Trends in the climate extreme indices were computed to show the simulated changes across the globe and in the Australian region during this period.

In addition, climate change projection experiments for the 21st century have been performed using the CMIP5 experimental design and several Representative Concentration Pathways (RCPs) with the same model. Results from these experiments were used to compute the set of climate extreme indices for the 2006 to 2115 period. Changes in these climate extreme indices in the Australian region for 30-year periods centered at 2030, 2050 and 2070 compared to baseline period (1971 - 2000) have been analysed.

Results from the analysis show that natural forcings cause only modest changes in the temperature and precipitation based extremes during the 20th century. Simulations with all forcings show statistically significant changes in the temperature based extremes over most land areas and these changes have greater magnitude than those due to natural forcings. Furthermore, the rates of increase of temperature based extreme indices are much greater in experiments accounting for anthropogenic forcings if only the greenhouse effect was considered without the cooling effect of anthropogenic aerosols. For example, the cooling impact of anthropogenic aerosols during the 1971 to 2005 period on the warming in global average mean screen temperature was 0.65°C.

Less significant changes can been seen for precipitation based extremes compared to temperature based extremes for all simulations. However, the analyses show that enhanced greenhouse gases may have suppressed the hydrological cycle in the Australian region during later part of 20th century, but this may have been counteracted by increased anthropogenic aerosols to varying degree.

Projections of temperature based extremes show continuing warming in the 21st century in the Australian region for all scenarios considered. These changes are consistent with the rate of increases in mean temperature. Projected changes in precipitation extremes show a strong tendency towards drying in the Australian region. However, extreme precipitation is projected to become more intense over tropical Australia.

Keywords: *Climate extremes, Climate change, CMIP5, Mk3.6, Natural, Anthropogenic, Aerosols*

1. INTRODUCTION

There is a great demand for robust information on projected changes in extreme events by decision makers and researchers working on assessing the impact of climate change on the economy, environment and society. Numerous studies have been published to address the effects of climate change on mean climate and climate extremes (IPCC, 2007). Based on these results, the Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change (IPCC) concluded that higher maximum and minimum temperatures, increased number of hot days, decreased number of cold days, and more intense precipitation have been observed in the second half of the 20th century in many parts of the world.

Simple climate extreme indices (Karl et al., 1999) are used to quantify the frequency, intensity and duration of significant departures from mean climate. These indices are able to capture more information on day-to-day variability than standard climate measures such as mean temperature and precipitation. Recent works (e.g. Alexander et al., 2006) have shown that there have been significant changes in the observed climate extreme indices during the 20th century. These include the temperature extremes such as frequency of hot days and duration of heat waves, as well as precipitation extremes such as rainfall intensity and duration of dry spells.

Statistical aspects of weather events and climate extremes can be derived from climate model simulations with projected changes in radiative forcings. Simulations using global climate models show that a gradual warming of the world due to anthropogenic climate change. This is accompanied by changes in the variability, intensity and frequency of extreme events, which is shown by changes in climate extreme indices.

Analysis of historical and projected extremes provides information on the extent of climate variability and likely changes in the variability in the future (Nicholls and Alexander, 2007). Previous studies indicate that climate model simulations contributing to CMIP3 are able to reproduce general trends in historical climate extremes observations (Tebaldi et al., 2006). However, the magnitude of the trends produced is less well reproduced (Alexander and Arblaster, 2009) and indicate that both observational data and models may have limitations and further research is warranted.

2. METHODOLOGY

The Climate Variability and Predictability (CLIVAR) Expert Team on Climate Change Detection and Indices (ETCCDI) has released a set of standard climate extreme indices for the investigation of climate change (Karl et al., 1999). The Australian Bureau of Meteorology adapted these climate extreme indices to Australian climate conditions (Australian Bureau of Meteorology, 2011). Details of these indices are shown in Table 1. These indices are calculated using daily maximum temperature, daily minimum temperature, daily mean temperature and daily precipitation at specified locations. It has been shown that Australia has experienced trends of increasing hot days and nights, and decreasing cold days (Alexander et al., 2007; Alexander and Arblaster, 2009).

The CSIRO Mk3.6 model (Rotstayn et al., 2010; Smith, 2009) has been used to complete a set of experiments following the CMIP5 experimental design (Taylor et al, 2011) for the 1851 to 2115 period. The model datasets analysed in this paper are from preliminary simulations used to test the climate model used in the joint CSIRO/QCCCE submission to the CMIP5 data archive (Collier et al., 2011). Extremes indices from these simulations were computed at the model ~2.9° × 2.9° horizontal resolution.

Results of analysis are presented using data from three sets of historical simulations for the 1851 to 2005 period, each consisting of an ensemble of 10 members, with all forcings (anthropogenic and natural), natural forcings only and all forcings with aerosol loading fixed at pre-industrial (~1850) levels. Simple attribution analysis has been undertaken to evaluate the relative roles of anthropogenic and natural forcings in simulated changes in trends of extremes during the 20th century. In addition, three sets of simulations for the 2006 to 2115 period using Representative Concentration Pathways (RCPs) for climate forcings during the 21st century have been analysed. These include the three RCP scenarios, namely the mid-range RCP4.5, high-range RCP8.5, and low-range RCP2.6 (Moss et al., 2010). Data from an ensemble of 21 members is used with each of these experiments to compute extreme indices.

In this study, percentiles of climate variables are calculated from the period of 1961 to 1990 where appropriate (see Table 1 for details). Changes within the experiment and differences between experiments are tested for statistical significance using non-parametric bootstrap methods. Statistical significance of trends is determined using Student's t-test. Changes and trends with 95% or higher significance level are shown in this paper.

Table 1: Australian Bureau of Meteorology Climate Extremes Indices

Very hot days	Count of days with daily maximum temperature > 40 °C	day
Hot days	Count of days with daily maximum temperature > 35 °C	day
Hot nights	Count of days with daily minimum temperature > 20 °C	day
Very hot nights	Count of days with daily minimum temperature > 25 °C	day
Warm days	Percentage of days with daily maximum temperature > 90th percentile (1961-1990)	%
Warm nights	Percentage of days with daily minimum temperature > 90th percentile (1961-1990)	%
Cool days	Percentage of days with daily maximum temperature < 10th percentile (1961-1990)	%
Cool nights	Percentage of days with daily minimum temperature < 10th percentile (1961-1990)	%
Highest maximum temperature	Maximum value of daily maximum temperature	°C
Highest minimum temperature	Minimum value of daily minimum temperature	°C
Lowest maximum temperature	Maximum value of daily minimum temperature	°C
Lowest minimum temperature	Minimum value of daily minimum temperature	°C
Warm spell duration	Count of days with at least 4 consecutive days of maximum temperature > 90th percentile	Day
Cold spell duration	Count of days with at least 4 consecutive days of maximum temperature < 10th percentile	day
Growing season length	Number of days between first span of 6 consecutive days with daily mean temperature > 15 °C and first span of 6 consecutive days with daily mean temperature < 15 °C	day
Wet days	Count of days with daily precipitation > 1 mm	day
Heavy precipitation days	Count of days with daily precipitation > 10 mm	day
Very heavy precipitation days	Count of days with daily precipitation > 30 mm	
Maximum 1-day precipitation	Maximum value of daily precipitation	mm
Maximum 5-day precipitation	Maximum value of 5-day accumulated daily precipitation	mm
Extremely wet day precipitation	Total precipitation on days where precipitation > 99th percentile	mm
Wet day precipitation	Total precipitation on wet days	mm
Simple daily intensity	Total precipitation divided by the number of wet days	mm/day
Consecutive dry days	Maximum number of consecutive days with daily precipitation < 1 mm	day
Consecutive wet days	Maximum number of consecutive days with daily precipitation ≥ 1mm	day

3. SIMULATED CHANGES IN EXTREMES FOR THE LATE 20TH CENTURY

Results for temperature and precipitation based extreme indices for the late 20th century are presented in this section. Due to space limitations, only selected results are shown.

3.1. Temperature based extreme indices

Figure 1 shows the time series of simulated global average annual screen temperature over the 1851 to 2005 period for the three ensembles of simulations with all forcings (natural, greenhouse gases and aerosols), natural forcings only and all forcings with anthropogenic aerosol loading at pre-industrial levels. The simulation with natural forcings shows little temperature change throughout the length of model integration, whereas the simulation with anthropogenic aerosols kept at pre-industrial level shows most warming. This warming is especially pronounced during the second half of 20^{th} century and reflects the increased emission of greenhouse gases. The difference in temperature between simulations with natural forcings and all forcings during the 1971 to 2005 period is 0.28°C.

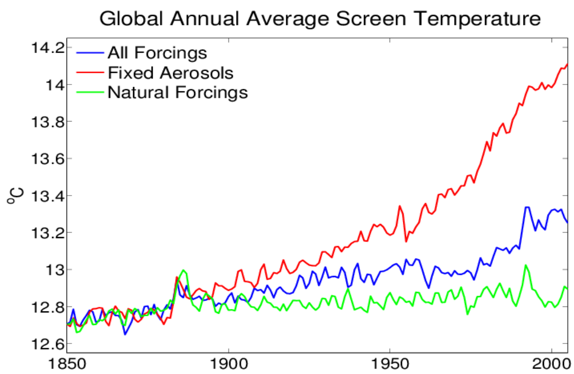

Figure 1: Global 10-member ensemble average annual screen temperature for the 1851 to 2005 period from simulations with all forcings, natural forcings, and all forcings with fixed aerosols

The rate of warming in simulation with natural forcings is much smaller than in the simulation with all forcings and fixed aerosols. This difference reflects the cooling impact of anthropogenic aerosols on simulated global mean screen temperature during the 1971 to 2005 period. Averaged over this period, the cooling effect of anthropogenic aerosols was 0.65°C.

Figure 2 shows the spatial trends in the frequency of warm days (percentage of year per decade) during the 1971 to 2005 period for the three simulations. Only trends that are significant at the 95% level using Student's t-test are shown (land areas in white are not statistically significant). The simulated trends in warm days are consistent with simulated changes in the global mean temperature (see Figure 1). The simulation with natural forcings shows relatively little change, whereas simulations with all forcings show greater statistically significant increases over the almost all land area. These trends are even more pronounced in the simulation with fixed aerosols. These results indicate that the rate of increase of temperature-based extreme indices would be much greater if only the warming impact of greenhouse gases was considered without the cooling effect of anthropogenic aerosols (Figure 2b,c).

The impact of anthropogenic aerosols on some temperature based extremes such as number of very hot days and warm spell duration is especially strong. The simulation with fixed aerosols shows a much stronger increase than the simulations with all forcings. On the other hand, the simulation with natural forcings shows few significant trends in those indices. For the other temperature based indices (not shown), there are similar widespread and coherent changes associated with anthropogenic forcings compared to natural forcings alone.

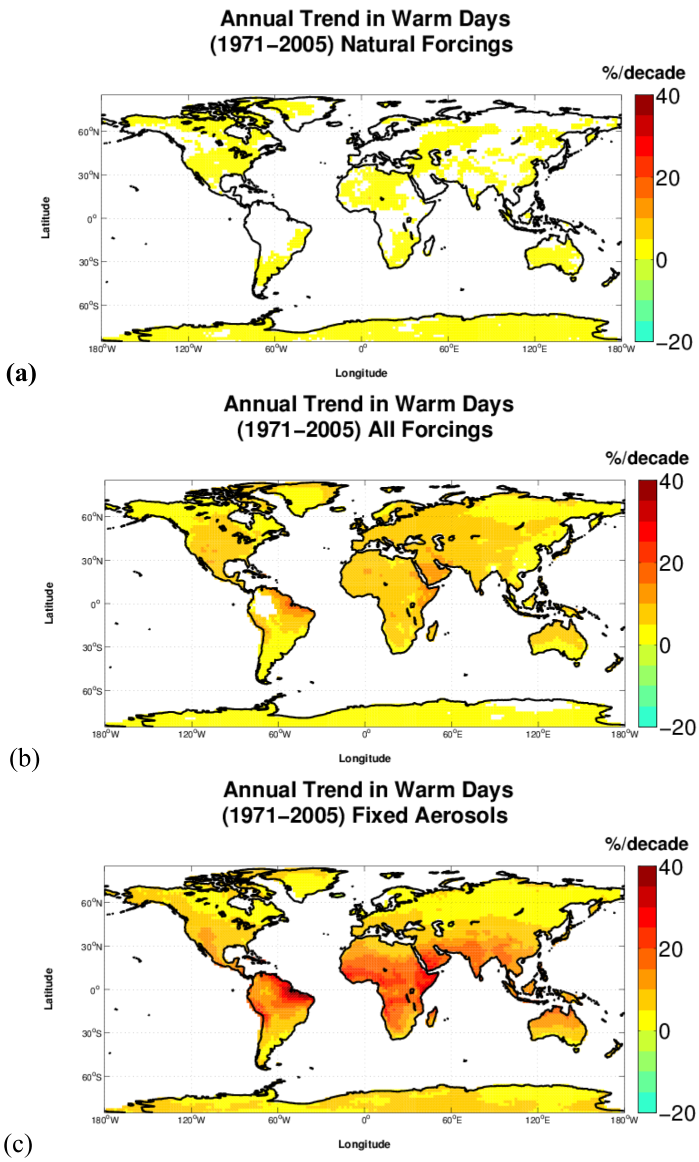

Figure 2: Simulated trends in annual warm days during the 1971 to 2005 period for simulations with (a) natural forcings (b) all forcings (c) all forcings with fixed aerosols (only statistically significant trends are shown).

3.2. Precipitation based extreme indices

Unlike temperature, the precipitation based indices show less significant changes. Figure 3 shows trends in annual wet days (number of days with precipitation more than 1 mm/day) for Australia over the 1971 to 2005 period from simulations with natural forcings (Figure 3a), all forcings (Figure 3b) and all forcings with fixed aerosols (Figure 3c). There are few statistically significant trends associated with the natural forcings results. On the other hand, there are statistically significant decreases around the southern fringe of the continent associated with the all forcings results, and significant decreases around northern and southern Australia associated with the fixed aerosols results. This indicates that greenhouse forcing acting alone would result in decreased frequency of wet days. Similarly, increased emissions of anthropogenic aerosols results in an increase in the number of annual consecutive wet days and an increase in the number of consecutive dry days (not shown).

From this analysis, it appears that the anthropogenic aerosols have acted to stimulate the hydrological cycle in the Australian region, whereas increased greenhouse gas emissions acted to suppress precipitation during the later part of the 20th century (Figure 3b,c). Figure 3d shows the difference in the number of annual wet days between simulations with all forcings and natural forcings only during the more recent 1991 to 2005 period, where the difference is marked than the 1971 to 2005 period. It indicates that, compared to natural forcings only, anthropogenic forcings resulted in decreases the number of wet days over South-West Western Australia, Victoria and Tasmania. These simulated changes are consistent with observed trends in precipitation in southern Australia during the recent decades and imply that increased greenhouse gas emissions are likely to have contributed to these observed changes.

4. PROJECTED CHANGES IN EXTREMES FOR THE 21ST CENTURY

This section describes simulated results of changes in temperature and precipitation based extremes during the 21st century from different forcing scenarios. Projected changes in mean global annual screen temperature are as shown in Figure 4. For the period 2106 to 2115 relative to 2006 to 2015, global average annual screen temperature would increase by 4.9°C for RCP8.5, 2.0°C for RCP4.5 and over 1.0°C for RCP2.6. Projected changes in mean precipitation also indicate a strong tendency towards drying over Australia during the course of the 21st century (not shown).

Projected changes for temperature based extremes are consistent with the changes in mean temperature. Changes in the number of annual warm days with respect to the base period of 1970 to 2000 are shown in Figure 5a,b,c for three 30-year periods centered at 2050, 2070, 2100 under RCP8.5, which represents the strongest greenhouse forcings among the three scenarios.

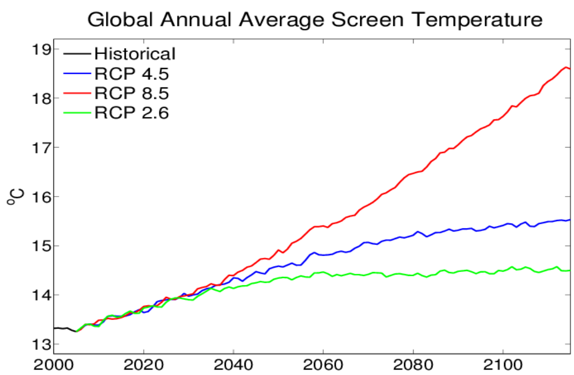

Figure 4: Global 21-member ensemble average annual screen temperature for the 2000 to 2115 period from simulations with RCP2.6, RCP4.5 and RCP8.5.

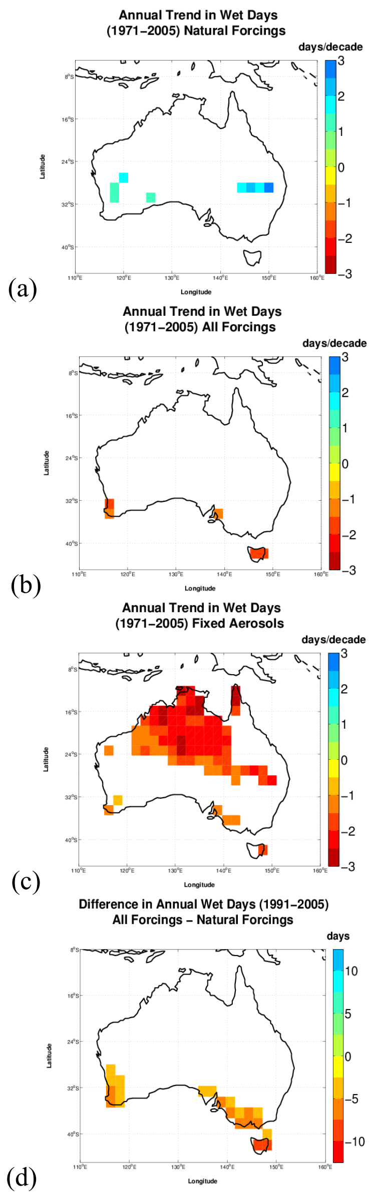

Figure 3: Simulated trends in annual wet days for the 1971 to 2005 period with (a) natural forcings; (b) all forcings; (c) all forcings with fixed aerosols ; (d) Simulated differences in the number of wet days for the 1991 to 2005 period between all forcings and natural forcings (only statistically significant trends are shown).

There are progressive increases in the occurrence of warm days over the whole of Australia during the 21st century, with greatest increases in northern Australia.

The number of annual wet days (number of days with rainfall > 1 mm/day) for the same periods under RCP8.5 show widespread tendency towards decreases in numbers of wet days during the 21st century. (Figure 5d,e,f). Strongest decreases occur over northern Australia, South-West Western Australia and South-East Australia (Victoria, Tasmania and parts of South Australia). These changes are largely consistent with the projected changes in temperature based indices (see Figure 5a,b,c) and indicate continuing drying in the subtropics. These changes are also consistent with previous findings with CMIP3 models focusing on the analysis of the dynamical drivers of changes in hydrological cycle during the 21st century (Vecchi and Soden, 2007).

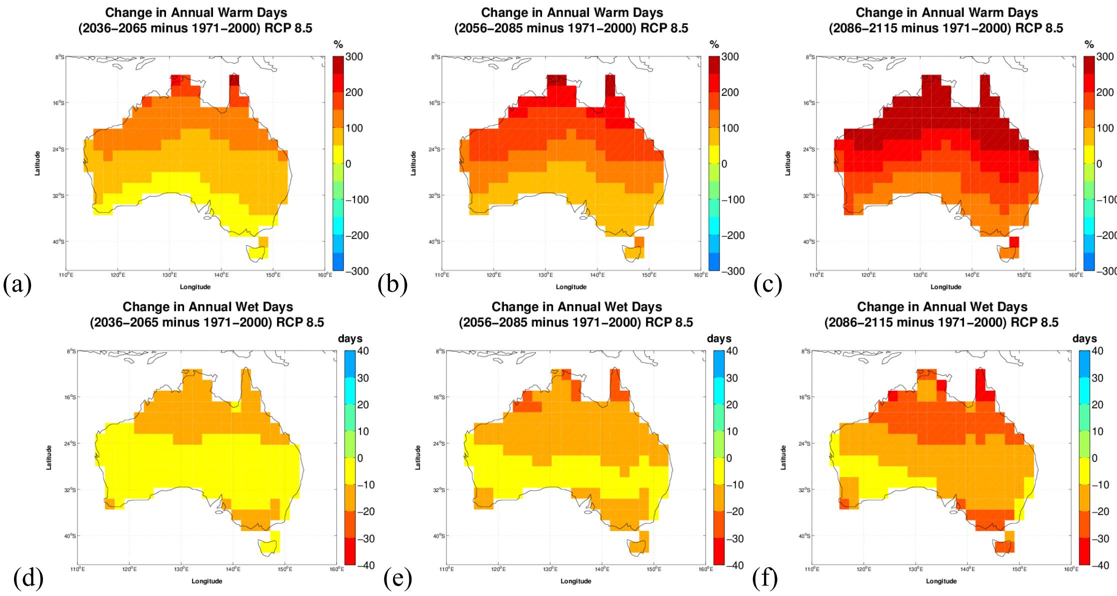

Figure 5: Projected changes in (a,b,c) annual percentage of warm days; (d,e,f) number of wet days around 2050, 2070 and 2100 from simulations with RCP8.5 (only statistically significant trends are shown).

Similar changes are also projected for extremely wet day precipitation (total precipitation on days where precipitation > 99th percentile) for most of Australia, especially during the second half of 21st century. Figure 6 shows the projected changes in annual precipitation on extremely wet days for simulations with RCP4.5 with moderate greenhouse forcings, under which the contribution of anthropogenic aerosols is still substantial. Consistent decreases in over most of Australia can be seen, with the exception of northern and southern fringes of Australian continent, where the model shows significant increase in extreme precipitation. These changes are similar to that described by Held and Soden (2006, Figure 7) and Vecchi and Soden (2007), where results from multi-model analysis based on CMIP3 simulations have been presented. The projected increases in extreme precipitation in the tropics and decrease in sub-tropics have been linked to changes in large scale circulation reflected in changes in overturning Hadley cell circulation (Lu et al., 2007; Previdi and Liepert, 2007). These changes appear to be result of projected changes in the increasing concentration of greenhouse gases and decreasing emissions of anthropogenic aerosols during the 21st century.

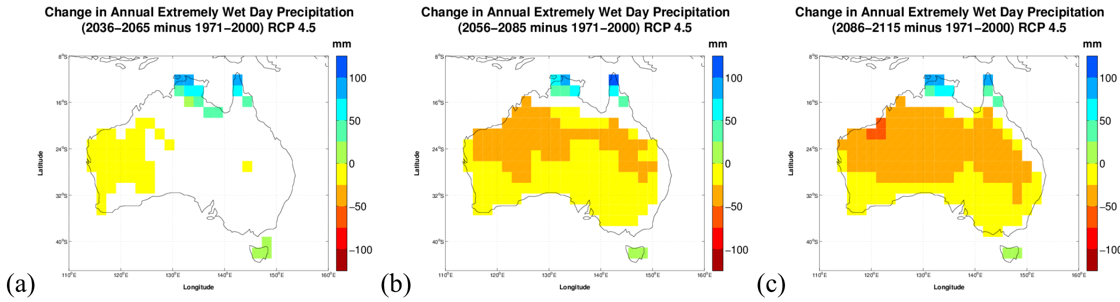

Figure 6: Projected changes in annual amount of extremely wet day precipitation around (a) 2050; (b) 2070; (c) 2100 from simulations with RCP4.5 (only statistically significant trends are shown).

5. CONCLUSION

Analysis of climate extremes using climate data from a suite of simulations using the CSIRO Mk3.6 coupled climate model has been undertaken and selected results have been described in this paper. Results of the analysis show that natural forcings caused relatively modest changes in temperature and precipitation based extreme indices during the 20th century. Simulations with all forcings with aerosols fixed at pre-industrial levels show the largest changes in temperature based extremes over the most of the land area compared to either natural forcings only and all forcings. This implies that the rate of increase of temperature based extremes without the cooling effect of anthropogenic aerosols would be much greater. The cooling impact of anthropogenic aerosols during the 1971 to 2005 period is estimated to have reduced global warming by 0.65°C. Precipitation based extremes show less significant changes than temperature based extremes for all simulations and all indices. The results also imply that greenhouse gases tend to suppress the hydrological cycle, while anthropogenic aerosols tend to stimulate it, offsetting the negative impact of greenhouse forcings on precipitation based indices. Simulations from projection experiments suggest continuing warming during the 21st century in simulations for all Representative Concentration Pathways (RCPs). They also indicate a strong tendency towards drying in the Australian region. However, extreme precipitation is projected to increase over tropical Australia for the medium range RCP4.5 scenario, possibly due to the effect of anthropogenic aerosols. It should be noted that the results presented in this paper are from one model, although the ensemble size is much larger than previously available. Multi-model analysis of results from CMIP5 project would be required to more robustly assess the response of climate extremes to different forcing factors during the 20th and 21st centuries.

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