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A new approach to detection of anthropogenic temperature changes in the Australian region

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With 6 Figures

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Summary

A new method has been applied for detecting a human influence on regional temperature changes in Australia over the last 50 years, including the whole of Australia, the southern half of Australia and the southeastern sector of Australia. There was a strong relationship between interannual variations of rainfall and temperature in different regions in Australia. The rainfall-related component of the temperature variations was removed using linear regression and the residual temperature variations were much smaller for maximum and mean temperature, and diurnal temperature range. Model simulations of regional temperature and rainfall variations agreed reasonably well with observations.

Trends in the residual variations of maximum, mean and minimum temperature over the last 50 years could not be explained by natural climate variations in all the regions considered and were consistent with the response to increasing greenhouse gases and sulphate aerosols in the climate models. This new approach has been able to enhance the signal-to-noise ratio for anthropogenic temperature change signals in the Australian region and to show that there is a clear anthropogenic warming signal in observed regional temperature trends, even for regions as small as the southeastern sector of Australia.

1. Introduction

Most studies of the possible causes of 20th century climate change have concentrated on global-scale patterns of temperature change (Mitchell et al, 2001). This is primarily because the magnitude of natural climate variability increases relative to any greenhouse-gas-induced climate change signal as the spatial scale of consideration is reduced (Stott and Tett, 1998). Recently, it has been shown that an anthropogenic climate change signal is detectable in continental-scale regions using surface temperature changes over the 20th century (Karoly et al, 2003; Stott, 2003; Zwiers and Zhang, 2003; Karoly and Braganza, 2005). Stott (2003) used simulations with the HadCM3 model to show that most of the observed warming over the last 50 years in six separate regions of the globe, including North America, Eurasia and Australia, was likely to be due to the increase in greenhouse gases in the atmosphere. In a similar study, Zwiers and Zhang (2003) used the Canadian climate model to assess the detectability of an anthropogenic climate change signal at different scales and showed that such a signal could be detected in the observed warming in North America and Eurasia over the 20th century. Neither of these studies considered regions smaller than continental scale. Both studies used the optimal fingerprint method, which seeks to enhance the signal-to-noise ratio by rotating the signal in a direction away from the largest natural variability.

Karoly et al (2003) and Karoly and Braganza (2005) used similar approaches to identify a significant human influence in recent temperature trends in the North American region and the Australian region, respectively. Several simple indices of area-average surface temperature variations were used from both observational data and climate model simulations. The mean warming in both regions could not be explained by natural climate variations and it was consistent with the climate response to increasing greenhouse gases and sulfate aerosols, as simulated by the climate models. Again, both these studies did not consider regions smaller than continental scale.

There has been a marked increase in observed Australian area-average mean temperature and a decrease in diurnal temperature range during the 20th century, with most of these changes over the last 50 years (Plummer et al, 1995; Torok and Nicholls, 1996; Della-Marta et al, 2004). Nicholls (2003) examined the relationship between observed Australian-average maximum temperature and rainfall variations and concluded that the increase in maximum temperatures is not associated with rainfall variations and is not likely to be due to natural climate variations alone. Power et al (1998) and Nicholls (2003; 2004) showed that a large fraction of the interannual variations of maximum temperature in several regions in Australia is associated with rainfall variations. Lower maximum temperatures are associated with increased rainfall, likely due to reduced solar heating due to increased cloud cover and reduced sensible heating due to increased soil moisture. Nicholls considered the residual maximum temperature variations, after removing the part associated with rainfall variations, and showed that the warming trend is much clearer as the interannual variability is substantially reduced.

Here, we apply a new method to detect a human influence on regional temperature changes in Australia over the last 50 years. Following Nicholls (2003; 2004), we reduce the natural variability of temperature by considering the residual temperature variations, after removing the part of the temperature variations that is associated with rainfall variations. We consider several different regions in Australia of different areas, including the whole of Australia, the southern half of Australia and the southeastern region of Australia. We focus on these regions as they are relatively heavily populated regions of the country and are important for agricultural production. The southern and southeastern regions are smaller than regions considered in previous climate change detection and attribution studies.

In the next section, the observational dataset and the climate model simulations are described. The model simulations represent the natural internal variability of climate as well as its response to human influences, including increases in atmospheric greenhouse gases and sulfate aerosols. Next, the variability of rainfall and temperature in the different regions in the model simulations is compared with that in the observations to evaluate the model simulations. The relationship between rainfall and temperature variations is assessed and used to determine the residual temperature variations. Finally, the trends in maximum, minimum and mean temperature over the last 50 years are considered, with and without removing the rainfall component, to show that a human influence can be detected in the residual temperature variations much more easily than in the full temperature variations.

2. Data

We use observed area-average Australian temperature anomaly and precipitation data from the Australian Bureau of Meteorology for the period 1910–2003, available online from *http://www.bom.gov.au/silo/products/cli_chg/*. The temperature data have been calculated using maximum and minimum temperature data from approximately 130 non-urban observing stations throughout the country. These stations are part of a high-quality temperature dataset, where adjustments have been made for discontinuities caused by changes in instrumentation and site location (Torok and Nicholls, 1996; Della-Marta et al, 2004). We consider annual-average anomalies of mean temperature (Mean), maximum temperature (Max), minimum temperature (Min), and diurnal temperature range (DTR). Since DTR is the difference between the maximum and minimum temperatures, it is expected to contain some information independent from mean temperature

(Braganza et al, 2004). The rainfall data are based on all available monthly rainfall totals from the Australian station network maintained by the Australian Bureau of Meteorology (Lavery et al, 1992; 1997). There is very good agreement between area-mean rainfall values determined using all available observations and values determined using the high-quality subset of rainfall stations (see *http://www.bom.gov.au/silo/products/cli_chg/ rain_timeseries.shtml* for details).

The station data have been gridded and then area-averaged into climatically-coherent regions defined by the Australian Bureau of Meteorology: northern, southern, eastern, southwest, and southeast. The analysis described below has been applied to all these regions but we only report the results for the whole of Australia, the southern region (south of 26° S) and the southeastern region (south of 33° S, east of 135° E), as they are typical of the other regions, and are of decreasing areas.

The observed climate variations in the 20th century are compared with simulations from three global coupled ocean-atmosphere climate models from:

- Canadian Center for Climate Modeling and Analysis (CGCM2),
- CSIRO, Australia (CSIRO Mk2),
- Hadley Centre, UK (HadCM2).

The horizontal resolutions for the atmosphere in the three models are: CGCM2 T32 ($3.8° \times 3.8°$), CSIRO Mk2 R21 ($3.2° \times 5.6°$) and HadCM2 ($2.5° \times 3.75°$). Details of these models and original references can be found in McAvaney et al (2001). All the models include representations of important physical processes in the atmosphere and the ocean, as well as sea-ice and land-surface processes. The models include adjustments of heat and fresh water fluxes at the surface to reduce climate drift in the coupled model simulations. Constant external forcing simulations ("control" runs) represent the natural internal variability of the unforced climate system. We have data from control runs for 200 years from CGCM2, 945 years from CSIRO Mk2, and 240 years from HadCM2.

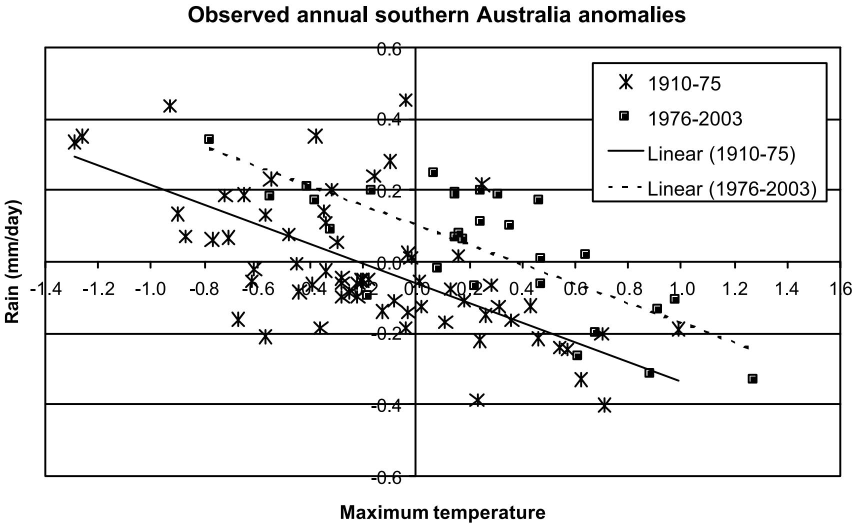
We also analyzed simulations with changes in anthropogenic forcing, including changing atmospheric concentrations of greenhouse gases and a representation of the effects of changing sulfate aerosols, to represent the human influence on climate ("GS" runs). The effects of changing sulfate aerosols were represented in these models using changes in surface albedo based on sulfate emissions. We have data from GS runs for 3 different ensemble members from 1900–2004 from CGCM2 (Flato and Boer, 2001), 3 different ensemble members from 1871–2004 from CSIRO Mk2 (Watterson and Dix, 2003), and 2 different ensemble members from 1861–2004 from HadCM2 (Tett et al, 1999).

The data from the models was area-averaged on the model grids for the same regions as the observational data; the whole of Australia, the southern half of Australia, and the southeastern region. For the southeastern region, this corresponded to 4 grid boxes in the CGCM2 model, 7 grid boxes in the CSIRO Mk2 model, and 6 grid boxes in the HadCM2 model, a much smaller area than considered in previous detection and attribution studies. The number of grid boxes depends on the model's land mask for this region, as well as its resolution, so the number of grid boxes is not directly proportional to the resolution.

3. Interannual variability in the observations and model simulations

In this section, the relationships between interannual variations of rainfall and variations of maximum, minimum and mean temperature and diurnal temperature range in the different regions in the observational data and in the model simulations are examined first. We also compare the variability of temperature and rainfall in the observations and models in the different regions to evaluate the model simulations.

Nicholls (2003) has shown that a large fraction of the observed interannual variations of maximum temperature in Australia are associated with rainfall variations but that the recent warming trend is independent of this relationship. This relationship is illustrated in Fig. 1, which shows a scatterplot between interannual variations of rainfall and maximum temperature for the southern Australian region from the observations and the HadCM2 model. There is a strong out-of-phase relationship between rainfall and temperature variations, with higher temperatures associated with reduced rainfall, in both the



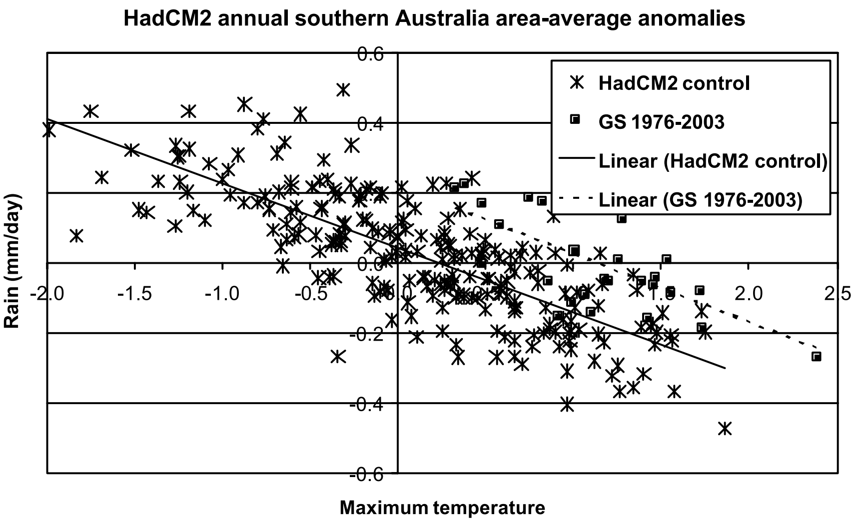


Fig. 1. Scatterplot of annual area-average rainfall and maximum temperature anomalies for the southern Australia region from observations (top) and the HadCM2 model (below). Asterisks show the values for the period 1910–75 from the observations and from the control simulation with the HadCM2 model, with the solid line being the best-fit straight line showing the relationship between rainfall and maximum temperature anomalies. The solid squares show the values for the period 1976–2003 from the observations and an anthropogenically-forced simulation with the HadCM2 model, with the dashed line being the line of best fit

observations and control model simulation, with a shift in this relationship to warmer temperatures when the period 1976–2003 is considered in either the observations or one of the GS forced model simulations.

A strong out-of-phase relationship between interannual variations of rainfall and diurnal temperature range in the southern Australian region is illustrated in Fig. 2 for both the observations and HadCM2 model. For diurnal temperature range, the relationship for the more recent period, 1976–2003, is very similar to that for the earlier period in the observations and for the control model simulations. This suggests that the observed changes in diurnal temperature range may be associated with changes in rainfall and not a change distinct from natural variability.

To evaluate the model simulations of the relationship between rainfall and temperature variations in the different regions, the observed annual mean area-average time series for each region are linearly detrended to remove any possible externally-forced monotonic climate signal. The results are insensitive to the order of the polynomial trend removed from the data, with more low frequency variability retained when a linear trend is removed. After detrending, the observed temperature variations may still include any response to variations of natural or anthropogenic external forcing on timescales less than about a century.

The correlations between interannual variations of rainfall and of maximum, minimum and mean temperatures and diurnal temperature range for the de-trended area-average observational data are compared with the model control runs in

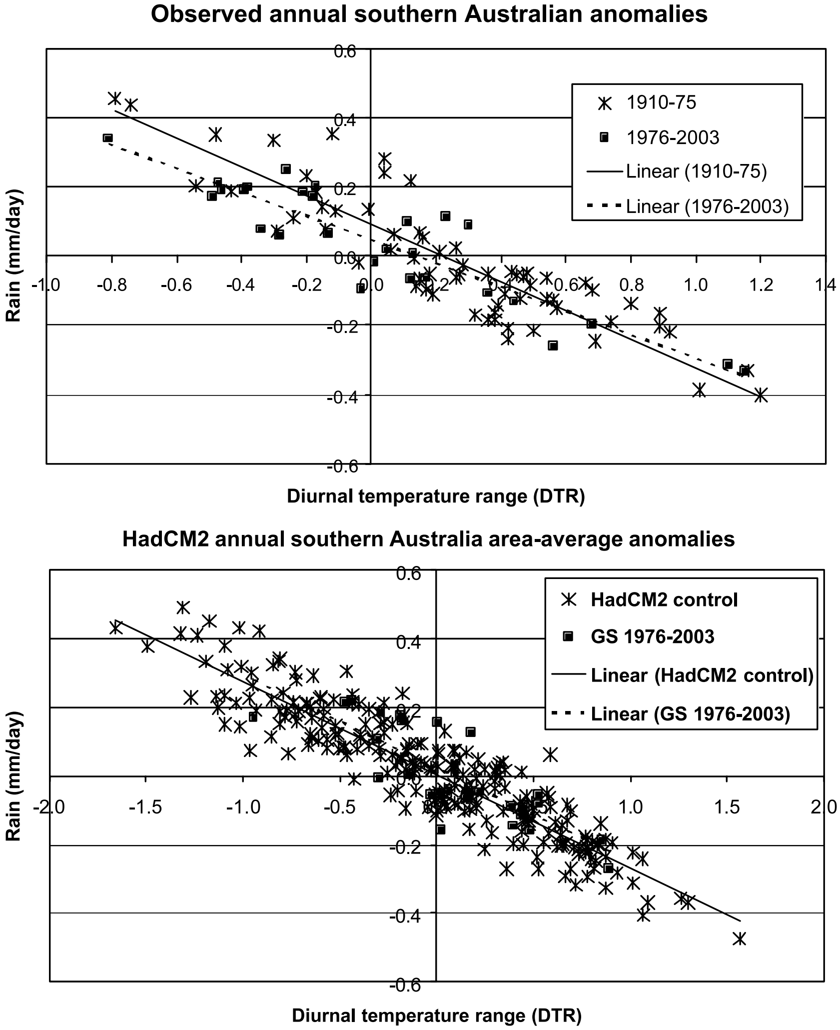


Fig. 2. As for Fig. 1, but for area-average annual rainfall and diurnal temperature anomalies in the southern Australia region. Note that the relationship during 1976–2003 is similar to that in the earlier period and is not shifted relative to the earlier period in both the observations and model simulation

Fig. 3. The correlations in the observational data are quite similar for the three different regions, with large negative correlations between rainfall and maximum temperature variations and between rainfall and diurnal temperature range variations in all three regions (as shown in Figs. 1 and 2 for the southern region), weaker negative correlations between rainfall and mean temperature variations and weak positive correlations between rainfall and minimum temperature variations. The opposite sign correlations between rainfall and maximum and minimum temperature variations are consistent with increased rainfall being associated with increased cloud cover, leading to reduced solar heating during the day and reduced longwave cooling at night.

In general, the model simulations show a reasonably similar structure for the correlations between rainfall and temperature variations in the three regions. However, there are some consistent differences between the modeled and observed correlations. These include larger negative correlations in the model simulations between rainfall and variations of maximum temperature, mean temperature, and diurnal temperature range, particularly for the whole Australian region and the southern Australia region. In addition, the correlations between rainfall and minimum temperature vary between the different models from weak negative correlations to positive correlations of around 0.4.

Next, we consider the interannual variability of temperature and rainfall, as shown by the standard deviations of annual anomalies in Fig. 4. As for Fig. 3, de-trended observational data are compared with results from control climate model simulations. The models show generally greater variability than observed for maximum temperature and DTR, similar variability for mean temperature and rainfall, and smaller variability for

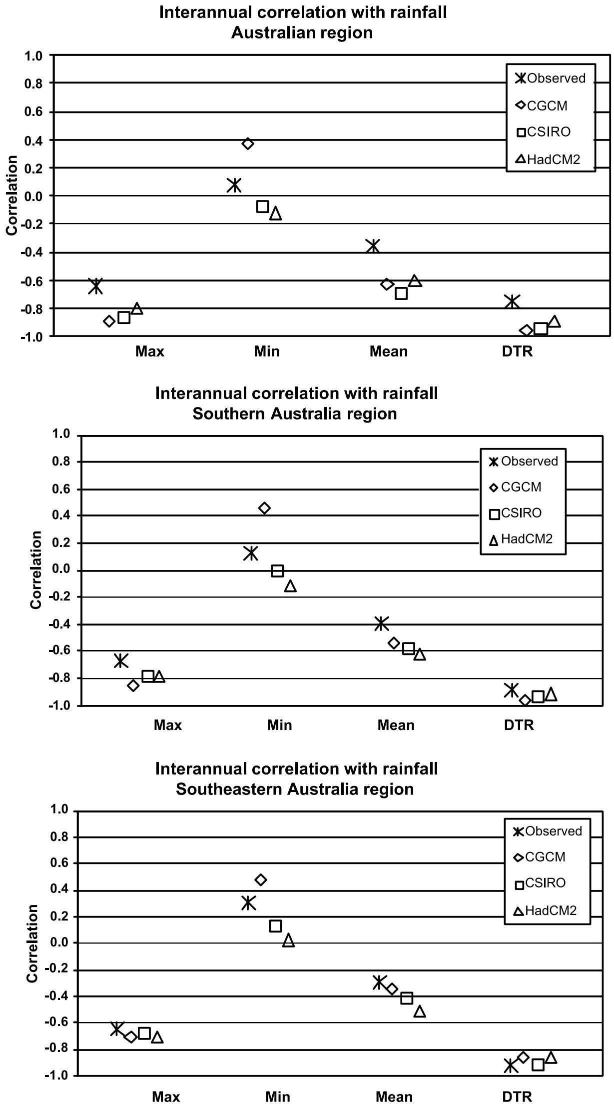


Fig. 3. Correlations of interannual variations of area-average anomalies of maximum temperature (Max), minimum temperature (Min), mean temperature (Mean), diurnal temperature range (DTR) with rainfall variations from de-trended observations and the control model simulations. Results for the Australian region are on top, while those for the southern and southeastern Australian region are below. In general, the models and observations show a very strong out-of-phase relationship between variations of rainfall and variations of both maximum temperature and diurnal temperature range in all regions, as shown in Fig. 1. However, the models generally show too strong a relationship between rainfall and mean temperature variations, associated with too large model variability of maximum temperature and sometimes too weak in-phase relationship of rainfall and minimum temperature variations

minimum temperature. This is consistent with reviews by Bell et al (2000) and Giorgi et al (2001) which note that simulations with climate models generally overestimate the variability of mean temperatures over continents. The CSIRO model generally shows less temperature variability than the other two models.

Following the approach of Nicholls (2003; 2004), the relationship between rainfall and temperature variations can be used to estimate the part of the temperature variations directly associated with the rainfall variations. We use linear regression to provide these estimates for maximum, minimum and mean temperatures, and DTR in each of the regions. Then we remove this rainfall-related component of the temperature variations and consider the residual temperature variations. The interannual variability of the residual temperature variations are shown in Fig. 4 also, using solid symbols for the models and "+" for the observations. The standard deviations of the residual variations are much smaller than those for the full variations of maximum temperature and DTR, associated with the large magnitude correlations of rainfall with each of these variables. For mean temperature, there is a small reduction of variance after removing the rainfall component, while there is negligible change in the standard deviation of minimum temperature, associated with the small correlations between rainfall and minimum temperature. In general, there is better agreement of the model-simulated internal variability of maximum temperature and diurnal temperature range with de-trended observations for the residual variations, after removing the rainfall related component, than for the full variations.

4. Trends over the last 50 years

In the previous section, it was shown that the control climate model simulations represent the interannual variability of temperature and rainfall in the three regions reasonably well. We now compare the observed temperature trends over the last 50 years with the range of 50 year trends simulated in the control model simulations and with the simulated trends over the last 50 years from the anthropogenically-forced (GS) model runs.

Results for the Southern Australian region are shown first in Fig. 5 for trends in area-average maximum, minimum and mean temperatures, diurnal temperature range (°C per 100 years) and rainfall (mm/day per 100 years). The trends

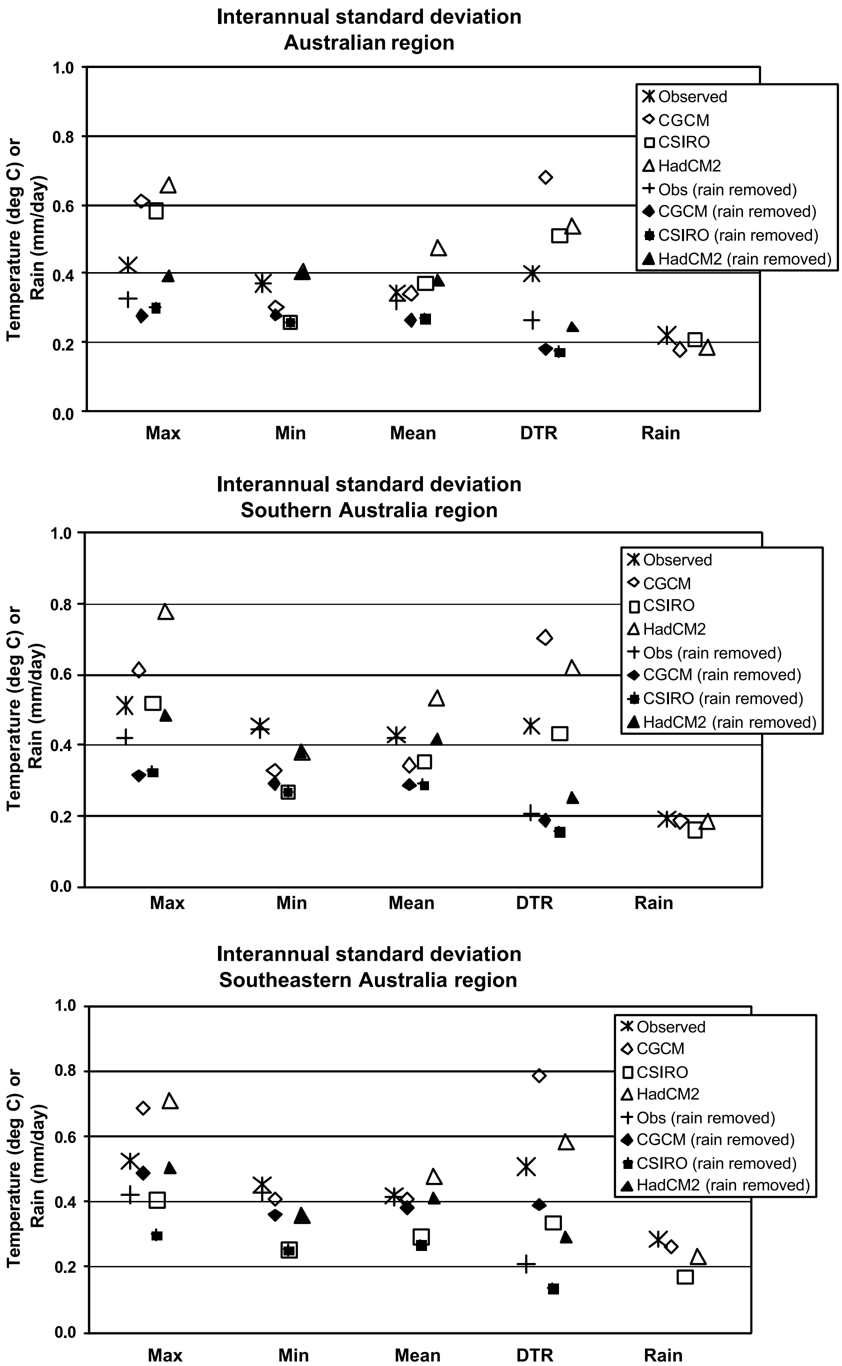


Fig. 4. Standard deviations of interannual variations of area-average anomalies of maximum (Max), minimum (Min), and mean temperatures, diurnal temperature range (DTR) and rainfall from de-trended observations and control model simulations. Results for the Australian region are on top, while those for the southern and southeastern Australian region are below. In general, the models overestimate the variability of maximum temperature and diurnal temperature range, but simulate the variability of mean temperature and rainfall reasonably well. The plus symbol for the observations and the filled symbols for the models show values after the variability linearly associated with interannual variations of rainfall has been removed. This leads to substantial reductions in the variability of maximum temperature and diurnal temperature range, with smaller reductions of variability in mean temperature and almost no reduction in variability of minimum temperature

shown in Fig. 5 are for the 50-year period 1954–2003. The results are not sensitive to the choice of end dates, with slightly smaller magnitude trends found for the period 1950–1999 (not shown). The error bar centred on zero at the location of the observed trends shows the 5%–95% confidence interval for natural variability of 50-year trends, as estimated from the control simulation with the HadCM2 model, which has the largest low frequency variability of the three models. If the observed trend is outside this confidence interval, then it is likely that the observed trend is not due to natural variability, as is the case for the mean and minimum temperature trends. The trends in maximum temperature, DTR and rainfall lie within the 5%–95% confidence interval for natural variability and hence can be explained by natural climate variations.

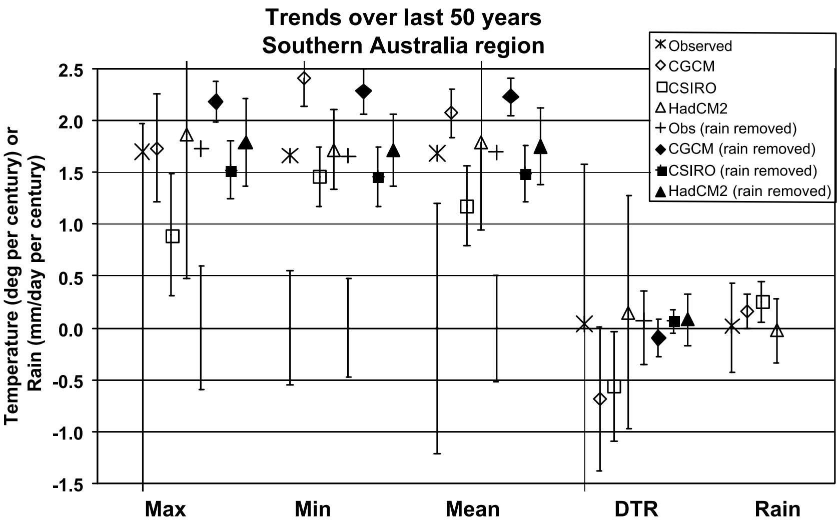


Fig. 5. Trends over the last 50 years (1954–2003) in area-average maximum, minimum and mean temperatures, diurnal temperature range (C per 100 years) and rainfall (mm/day per 100 years) for the southern Australia region from observations (*) and anthropogenically-forced model simulations (open symbols). The error bar centred on zero at the location of the observed trends shows the 5%–95% confidence interval for natural variability of 50-year trends, as estimated from the control simulation with the HadCM2 model, which has the largest low frequency variability of the three models. The model trends are based on the ensemble-mean values from the anthropogenically-forced simulations with each model. The error bars about the model trends show the 5%–95% confidence interval for the ensemble mean model trends due to internal variability of the model simulations. The plus symbols for the observations and the filled symbols for the models show trend values after the variability linearly associated with interannual variations of rainfall has been removed

The model trends are based on the ensemble-mean values from the anthropogenically-forced simulations with each model. The error bars about the model trends show the 5%–95% confidence interval for the ensemble mean model trends due to internal variability of the model simulations. All the model trends are consistent with the observed trends, indicating that the observed trends are consistent with the response to anthropogenic forcing.

The plus symbols for the observations and the filled symbols for the models show trend values after the variability linearly associated with interannual variations of rainfall has been removed. The trends in most of the variables are changed little by removing the rainfall-related component of the variability, although the trend in DTR is reduced to almost zero. However, removing the rainfall-related component of the temperature variations from the control model simulations substantially reduces the variability of the 50-year trends. This leads to much smaller 5%–95% confidence intervals for natural variability of the residual temperature trends, so that now the trends in maximum temperature, as well as in mean and minimum temperature are all significantly different from zero.

Results for the whole Australian region and for the southeastern Australian region are shown in Fig. 6. Very similar conclusions can be reached about the trends in these two regions as for the southern Australia region just discussed. The observed trends in mean and minimum temperature are significant but the trend in maximum temperature is not. After removing the rainfall-related variations, the natural variability of 50-year trends is substantially reduced, so that the trends in maximum, minimum and mean temperature are all significant. All the trends are consistent with the model-simulated response to anthropogenic forcing. Hence, even for the relatively small southeastern Australian region, the trends in residual temperature variations cannot be explained by natural climate variations. The residual trends in DTR are close to zero, suggesting that a large part of the observed trends in DTR in the different regions in Australia is associated with observed rainfall variations. This is consistent with the scatterplot for DTR and rainfall variations in Fig. 2, which shows that the relationship between rainfall and DTR over

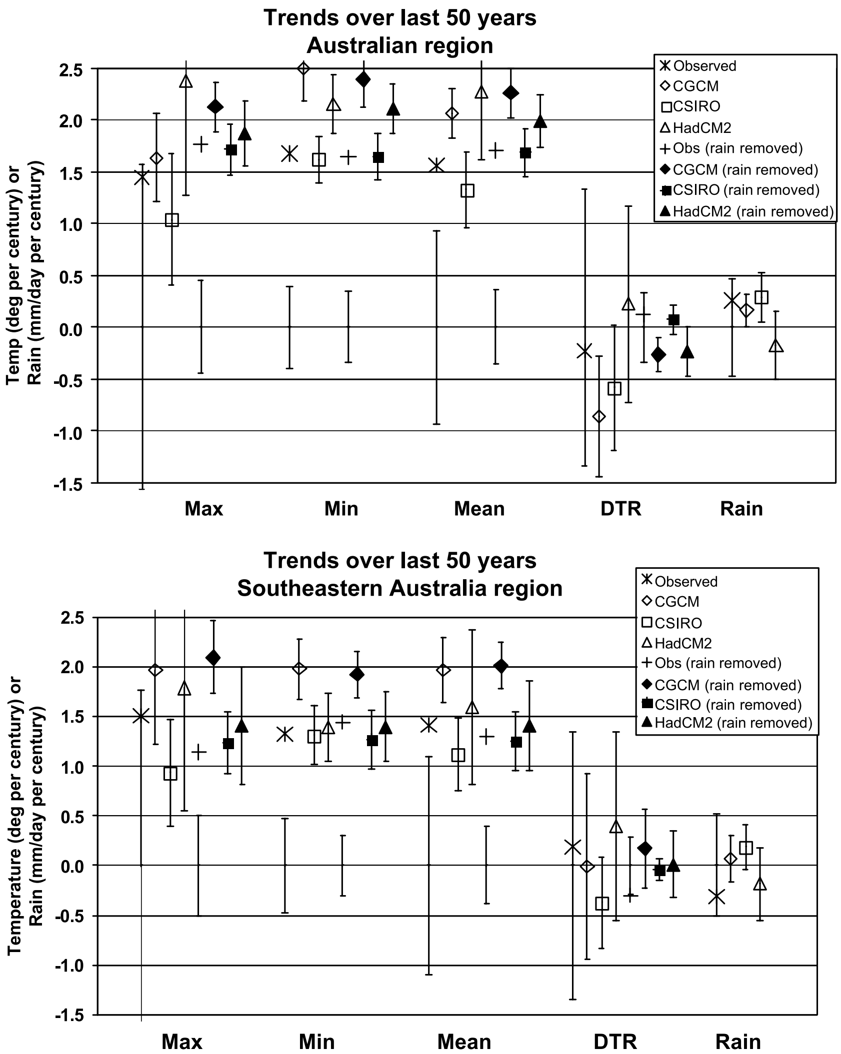


Fig. 6. As in Fig. 5, but for the Australian region and the southeastern Australian region

the recent period is no different to that over the whole century.

The analysis was repeated for the other climatic regions in Australia defined by the Bureau of Meteorology for their online observed area-average data, including the northern, eastern and southwestern regions. Very similar results were found for all these regions and they are not shown here.

It is interesting to note that the observed trend for maximum temperature in the Australian region is just within the 5%–95% confidence interval for natural variability, indicating that it is not significant here, while Karoly and Braganza (2005) reported a significant trend in area-average Australian maximum temperature. The difference from the previous analysis is that the HadCM2 model control simulation is used to provide the uncertainty range for natural variability and this model has larger low frequency variability than the multi-model estimate used by Karoly and Braganza (2005).

5. Conclusions

Previous climate change detection studies in different regions have found it difficult to distinguish the signal of anthropogenic climate change in regional temperature trends from natural climate variations except for continental scale regions. Here, we demonstrated that there is a strong relationship between interannual variations of rainfall and temperature in different regions in Australia. The rainfall-related component of the temperature variations was removed using linear regression and the residual temperature variations were much smaller for maximum and mean temperature, and diurnal temperature range. Model simulations of regional temperature and rainfall variations agreed reasonably well with observations.

Trends in the residual variations of maximum, mean and minimum temperature over the last 50 years could not be explained by natural climate variations in all the regions considered and were consistent with the response to increasing greenhouse gases and sulphate aerosols in the climate models. This new approach has been able to enhance the signal-to-noise ratio for anthropogenic temperature change signals in the Australian region and show that there is a clear anthropogenic warming signal in observed regional temperature trends, even for regions as small as the southeastern sector of Australia, corresponding to only four to seven grid boxes, depending on the model.

The approach used here is somewhat analogous to the optimal fingerprint detection approach, which rotates the climate change signal vector to be detected in a direction away from the natural climate variability to enhance the signal-to-noise ratio (see Mitchell et al, 2001, for a brief review and references therein). Here, the natural variability in the temperature variations is reduced by removing the rainfall-related component of the temperature variations and then seeking to detect any climate change signal in the residual temperature variations. As shown here, this also significantly increases the anthropogenic climate change signal-to-noise ratio.

We have confidence in the results as they are very similar for all the models, despite differences in the model formulations and in the representations of the anthropogenic forcings. However, we have not considered some other possible anthropogenic forcings, such as changes in land use and land cover, which may be more important in the Australian region than on global scales. In particular, Narisma and Pitman (2003) have shown that Australian land cover changes may have contributed to the observed increases in maximum temperatures in the south-east and south-west of Australia. However, they found very small contribution to Australian-average temperature changes due to land cover change.

While our approach has worked well in the Australian region, where there is a strong relationship between rainfall and temperature variations, it is not clear whether it will work as well in other regions of the globe. It is also not clear yet whether the approach can be extended to even smaller scales in the Australian region. Those questions are being considered in ongoing extensions of this study.

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