Attribution of recent temperature changes in the Australian region

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Submitted to *J. Climate*

January 2004

Abstract

Variations of Australian-average mean temperature and diurnal temperature range are used to investigate climate variations during the 20th century. The observed interannual variability of both is simulated reasonably well by a number of climate models but they do not simulate the observed relationship between the two. Comparison of the observed warming and reduction in diurnal temperature range with climate model simulations shows that Australian temperature changes over the 20th century were very unlikely to be due to natural climate variations alone. It is likely that there has been a significant contribution to the observed warming during the second half of the century from increasing atmospheric greenhouse gases and sulfate aerosols.

Introduction

The Synthesis Report of the IPCC Third Assessment (IPCC, 2001) concluded that one of the key uncertainties regarding attribution of climate change was "relating regional trends to anthropogenic climate change". 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 relative to any greenhouse-gas-induced climate change signal increases 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 large regions using surface temperature changes over the 20th century (Karoly et al. 2003; Stott, 2003; Zwiers and Zhang, 2003). 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. While these two studies used the optimal fingerprint method, Karoly et al. (2003) identified a significant human influence in recent North American climate change using several simple indices of surface temperature variations.

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. 2003). Nicholls (2003) has 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.

Here, we investigate the causes of these changes in Australian-average temperatures by comparing simulations performed by six different global climate models with observed climate variations. Australia is a good place to test regional climate change attribution as it has a relatively good observational network for most of the 20th century and it has coherent large-scale

climate variations over much of the country. The climate model simulations represent the natural internal variability of climate as well as its response to human influences, such as increases in atmospheric greenhouse gases and sulfate aerosols. Natural external influences (changes in solar irradiance and volcanic aerosols) are also included in some simulations. This is a significant extension of other regional climate change attribution studies as we use the results from six different models and we consider both mean temperature and diurnal temperature range for a smaller region than most other studies. Stott (2003) considered Australian temperature changes and concluded "it is not possible to reliably attribute Australian temperature changes" in his analysis because "the level of agreement between observed Australian temperature changes and anthropogenic forced model simulations was not as good as for other regions". Here, we further investigate the attribution of recent Australian temperature changes using a different approach from Stott (2003), a number of different climate models and a slightly different observational database.

Data

We use observed Australian-average temperature anomaly data from the Australian Bureau of Meteorology for the period 1910-2002 (http://www.bom.gov.au/climate/change/amtemp.shtml). These 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. 2003). 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. This is a different dataset than that used by Stott (2003).

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

CSIRO, Australia (CSIRO Mk2)

Geophysical Fluid Dynamics Laboratory, USA (GFDL R30);

Hadley Centre, UK (HadCM2 and HadCM3);

Max-Planck-Institute fur Meteorologie, Germany (ECHAM4);

National Center for Atmospheric Research, USA (PCM).

Details of these models, including their resolution in the ocean and atmosphere, 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. Four of the models (CSIRO Mk2, GFDL R30, HadCM2 and ECHAM4) include adjustments of heat and fresh water fluxes at the surface to reduce climate drift in the coupled model simulations. The other two models (HadCM3 and PCM) have no flux adjustments and maintain stable global-mean climates when external forcings are not varied. Maximum and minimum temperature and diurnal temperature range data were not available from the HadCM3 model and the GFDL model does not include a diurnal cycle of solar radiation.

The constant external forcing simulations ("control" runs) represent the natural internal variability of the unforced climate system. We also analyzed simulations with changes in anthropogenic forcing, including changing atmospheric concentrations of greenhouse gases, ozone and sulfate aerosols, to represent the human influence on climate (GS), and simulations with changes in natural external forcing, including changing solar irradiance and volcanic aerosol amounts in the stratosphere, to represent the climate response to natural external forcings (NAT). A summary of the simulations with the different models and the different forcings is given in Table 1.

Comparison of model simulations with observations

The observed variability of the de-trended Australian-average temperatures on interannual and decadal timescales is compared with the variability in model control runs in Table 2 to evaluate the quality of the simulations of natural internal climate variability. Simple linear de-trending was used to attempt to remove any possible anthropogenic signal in the observed indices. The results are insensitive to the order of the polynomial trend removed from the data. After detrending, the observed temperature variations may still include any response to variations of natural external forcing on timescales less than a century. The standard deviations of the temperatures are used as a measure of the variability. On interannual timescales, the models

show generally greater variability than observed for maximum temperature, mean temperature and DTR, and smaller variability for minimum temperatures (Table 2(a)). 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. On decadal timescales, the simulations agree better with the observations, and there are no significant differences between the models and the observed decadal variability of mean temperature (Table 2(b)). However, most of the models still overestimate the decadal variability of maximum temperature and DTR, and underestimate minimum temperature variability.

The relationship between Australian-average DTR and mean, maximum and minimum temperature variations is assessed in Table 3, which shows the correlations between interannual variations. The observed correlation between DTR and mean temperature is close to zero, indicating that they are nearly independent for natural climate variations. Observed DTR has a significant positive correlation with maximum temperatures and negative correlation with minimum temperatures, consistent with it being the difference of two variables with similar variance. However, the model simulations do not agree well with the observations for these relationships. All the models show a significant positive correlation between DTR and mean temperature, associated with too strong a relationship of DTR with maximum temperature and too large variability of maximum temperature. While the models do not simulate well the observed relationship between DTR and mean temperature, they do not underestimate their interannual and decadal variability.

Next, the observed linear trends in the Australian-average temperatures over the second half of the 20th century, as well as the whole century, are compared with anthropogenically-forced (GS) model simulations in Fig. 1. We use the observed trends starting in 1910 and 1913 to estimate the sensitivity of the 90-year observed trend to small changes in the initial year, and starting in 1950 and 1953 for the 50-year trends. The uncertainty in the forced model response is reduced by using the ensemble-mean response for each model (See Table 1 for the number of members in each ensemble). The ensemble mean model trends are used starting in 1910 and 1950, as data from some of the model simulations was not available past 1999. The model trends were not sensitive to the starting date, as they were averaged over the different members of the ensemble,

reducing the impact of internal climate variations. The probability distribution of 50-year and 90-year trends due to internal climate variability is estimated from the long control simulations with the CSIRO and PCM models.

Over the period 1950-99, there were significant increases in the observed Australian area-average mean, maximum and minimum temperatures (since the observed trends are outside the 90% confidence intervals for natural internal variability, shown in Fig. 1a). The observed trends over 1953-99 are slightly smaller than over 1950-99 because of cooler Australian temperatures averaged over 2000-2002, compared with the previous 3 years. The largest impact is on the DTR trend, which is half the magnitude of the trend over 1950-99, but neither are outside the range of natural internal variability. The observed trends in maximum temperature and diurnal temperature range during 1950-99 are consistent with the response to anthropogenic forcing (GS) in all the models. By consistent, we mean that the observed trend lies within the 90% confidence interval obtained by combining the uncertainty for the ensemble-mean forced model trend with the uncertainty for an individual realization estimated from control runs. However, the CSIRO and PCM model trends for mean and minimum temperature are significantly smaller than observed. The model trends for DTR are consistently smaller than observed but this difference is not statistically significant.

Over the period 1910-99, there were significant increases in the observed Australian mean, maximum and minimum temperatures and a significant decrease in the observed diurnal temperature range (Fig. 1b). The observed trends in maximum and mean temperature are consistent with the response to anthropogenic forcing in all the models. However, the model trends for minimum temperature and DTR are significantly smaller than observed.

A number of studies have indicated a possible contribution from changes in natural external forcings (solar irradiance and volcanic aerosols) to the observed global warming in the first half of the 20th century (Tett et al. 1999, Stott et al. 2000, Mitchell et al. 2001,). In the following, we use four different climate models to investigate whether natural external forcing can explain the observed trends in Australian mean temperature. Maximum and minimum temperature and DTR data were not available from most of the NAT forced simulations, so this analysis is restricted to

mean temperature. Naturally-forced simulations were not available for the CSIRO and ECHAM4 models. For both 1950-99 and 1900-99, the observed warming trend over Australia is consistent with the ensemble-mean response to anthropogenic forcing from all these models except PCM, which has significantly smaller warming than observed (Fig. 2). Meehl et al. (2003) has noted that PCM has a relatively small climate sensitivity. The observed warming is significantly larger than the ensemble-mean response to natural forcing alone in all the models. There is a very small chance (less than 1%) that the observed warming trend over these periods could be explained as an unusual case of large warming due to natural internal variability combined with an unusual warming due to natural forcing very different from the ensemble-mean response. These results for the Australian region are the same as from the global studies referred to above.

Time series of low-pass filtered Australian-average mean temperatures from the ensemble-means of the anthropogenically-forced model simulations are in good agreement with the observed warming in the second half of the 20th century, with the PCM model showing less warming (Fig. 3), as expected from the analysis of the trends above. The naturally-forced simulations do not show warming in the second half of the century and are clearly separated from the observed temperatures and the anthropogenically-forced simulations in the later part of the century.

Discussion

In summary, we find:

- significant observed increases in Australian mean, maximum and minimum temperatures over the second half of the 20th century and over the whole century, and significant reductions in diurnal temperature range over the whole century,
- general agreement between anthropogenically-forced (GS) model simulations and the observed changes in the second half of the century and over the whole century, although some models simulate smaller changes than observed,
- very small chance that the observed changes can be explained by natural externally forced climate variations, as simulated by these models.

We have greater confidence in the results as they are very similar for all the models, despite differences in the model formulations and differences in the representations of the anthropogenic and natural forcings. However, we have not considered some other possible anthropogenic forcings, such as changes in land cover or the role of carbon-black and other non-sulfate aerosols, which are likely to be more important on regional than on global scales. In particular, Narissa 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.

The models consistently show smaller trends than observed for minimum temperature and for diurnal temperature range. Folland et al. (2001) have noted the relationship between the observed decreases in DTR and increases in cloudiness. In the Australian region, there has been an increase in rainfall over the 20th century (Nicholls, 2003) and it is likely that this has been associated with an increase in cloudiness. It is beyond the scope of this study to identify the causes of the discrepancies between the model and observed trends in DTR but they may be related to model deficiencies in simulating trends in cloudiness.

Based on the results presented above, it is likely that there has been a significant human influence on the observed Australian warming in the second half of the 20th century, associated with increasing atmospheric concentrations of greenhouse gases and sulfate aerosols.

Acknowledgements

We wish to acknowledge the assistance of the many scientists who developed the observational dataset and the climate models used in this study. In particular, we wish to acknowledge the assistance of Julie Arblaster (NCAR), Martin Dix (CSIRO), Tony Hirst (CSIRO), Peter Stott (Hadley Centre) and Ron Stouffer (GFDL) in providing model data for the Australian region. Data from the ECHAM4 simulations were obtained from the IPCC Data Distribution Centre. KB was supported by a Discovery grant from the Australian Research Council.

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Model	Control	Greenhouse forcing (G)	Sulfate Aerosol forcing (S)	Natural forcing	Anthrop ensemble	Natural ensemble
CSIRO Mk2	945 years	Equivalent CO_2	Surface albedo changes	Not available	GS, 7 members	Not available
ECHAM4/ OPYC3	240 years	Individual gases	Interactive sulfur scheme with prescribed sources, direct and first indirect effect	Not available	GS+ozone 2 members	Not available
GFDL R30c	900 years, no DTR	Equivalent CO_2	Surface albedo changes	SOL: Lean (2000) VOL: Andronova et al. (2000)	GS, 3 members	ALL-GS, 3 members
HadCM2	240 years	Equivalent CO_2	Surface albedo changes	SOL: Lean et al. (1995) VOL: Sato et al. (1993)	GS, 4 members	VOL+SOL, 3 members
HadCM3	1250 years, no DTR	Individual gases	Interactive sulfur scheme with prescribed sources, direct and first indirect effect	SOL: Lean et al. (1995) VOL: Sato et al. (1993)	GS+ozone 4 members	NAT, 4 members
NCAR DOE PCM	810 years	Individual gases	Historical sulfate aerosol amounts, direct effect	SOL: Hoyt and Schatten (1993) VOL: Amman et al. (2003)	GS+ozone 4 members	NAT, 3 members

Table 1: Summary of the climate model simulations used in this analysis, including the length of the control runs available, the different anthropogenic and natural external forcings, and the number of members in the anthropogenic and natural forcing ensembles. For the GFDL model, simulations with natural external forcing alone were not available, so the NAT response was estimated from the difference between model simulations with both anthropogenic forcing and natural external forcing combined (ALL) and simulations with anthropogenic forcing alone i.e. NAT response ~ (GS+NAT) response – GS response. For the HadCM2 model, only simulations with separate solar (SOL) and volcanic (VOL) forcing were available, so the NAT response was estimated as the sum of these model responses i.e. NAT response ~ SOL response + VOL response. Descriptions of the forced simulations with the different models include: CSIRO Watterson and Dix (2003); ECHAM4 Roeckner et al. (1999); GFDL Broccoli et al. (2003); HadCM2 Tett et al. (1999); HadCM3 Stott et al. (2000); PCM Meehl et al. (2003).

(a) Interannual variations

Data source	T Mean	T Max	T Min	DTR
Observed	0.34	0.41	0.38	0.38
CSIRO	0.38±0.05	0.61±0.06	0.26±0.03	0.55±0.05
ECHAM	0.41	0.49	0.34	0.24
HadCM2	0.48	0.65	0.41	0.53
PCM	0.34±0.04	0.50±0.06	0.26±0.03	0.40±0.05
GFDL	0.54±0.07			
HadCM3	0.54±0.06			

(b) Decadal variations

Data source	T Mean	T Max	T Min	DTR
Observed	0.17	0.15	0.20	0.12
CSIRO	0.13±0.04	0.23±0.07	0.08±0.02	0.21±0.06
ECHAM	0.19	0.21	0.17	0.10
HadCM2	0.20	0.28	0.14	0.22
PCM	0.14±0.04	0.20±0.07	0.11±0.02	0.15±0.05
GFDL	0.23±0.08			
HadCM3	0.18±0.04			

Table 2. Standard deviations of variations of Australian area-average temperatures (in °C) from observations and model control runs. The observational data had a simple linear trend removed, prior to calculating the standard deviation. The uncertainties on the model values are the 90% confidence intervals for the standard deviation, estimated by resampling the long control runs. Results in (a) are for annual mean data, while those in (b) are for low-pass filtered data with variations on decadal and longer timescales.

Data source	T mean	T max	T min
Observed	0.08	0.53	-0.42
CSIRO	0.72±0.08	0.90±0.03	0.00±0.20
ECHAM	0.65	0.77	0.40
HadCM2	0.51	0.78	-0.06
PCM	0.65±0.10	0.86±0.05	0.09±0.15

Table 3. Correlations of interannual variations of Australian area-average temperatures with diurnal temperature range from observations and control model simulations. The observational data had a simple linear trend removed, prior to calculating the standard deviation. The uncertainties on the model values are the 90% confidence intervals for the standard deviation, estimated by resampling the long control runs.

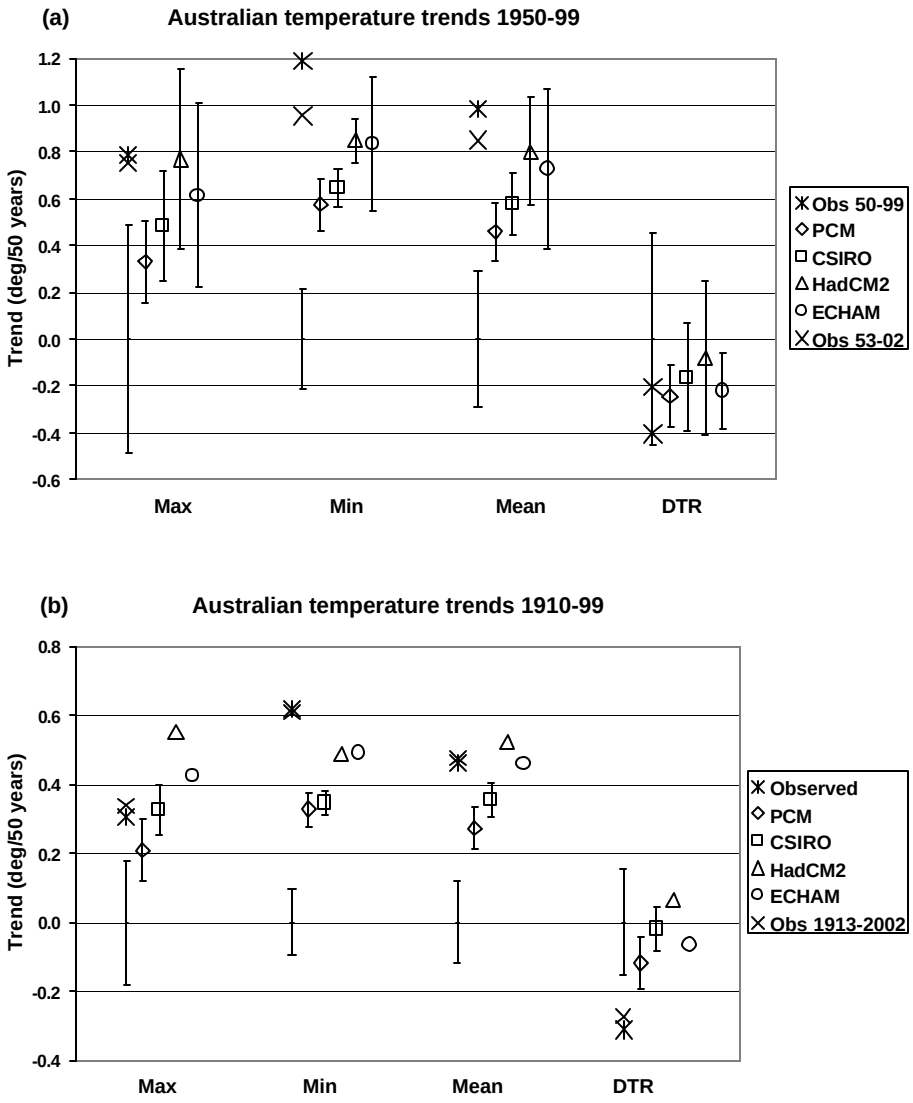

Figure 1. Trends in Australian area-average temperatures from anthropogenically-forced model simulations and observations over (a) 1950-99, and (b) 1910-99. The error bars on the model trends are the 90% confidence intervals for the ensemble-mean trends, estimated by resampling the long control runs from the respective models and allowing for the number of members in each ensemble. No error bars are shown on the HadCM2 and ECHAM 90-year trends because of the short length of control runs available for this analysis. The error bars about zero at the location of the observed trends are the uncertainties in the trend estimates due to natural internal climate variability, as simulated by the models. They are the 90% confidence intervals for a single realisation, estimated using the control runs from the CSIRO and PCM models, which were the only models with long control runs with DTR data available.

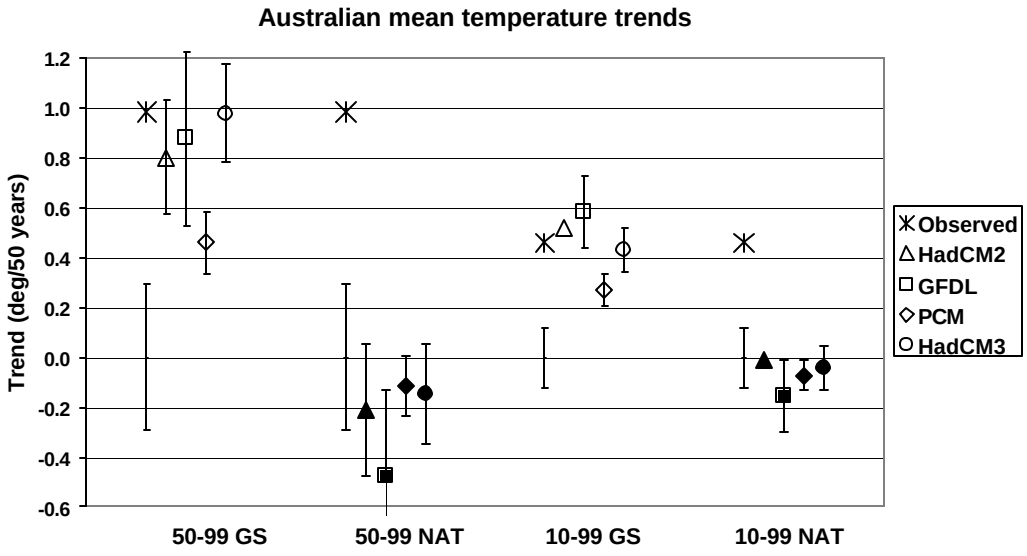

Figure 2. Trends in Australian-average mean temperature from anthropogenically-forced (GS, open symbols) and natural externally-forced (NAT, solid symbols) model simulations and observations during 1950-99 and 1910-99. The error bars on the model trends are the 90% confidence interval for the ensemble-mean trend, estimated by resampling the respective long control runs and allowing for the number of members in each ensemble. The error bars about zero at the location of the observed trends are the uncertainties in the trend estimates due to natural internal climate variability, as simulated by the models. They are the 90% confidence intervals for a single realisation, estimated using the control runs from the CSIRO and PCM models. Results are shown for the HadCM2, GFDL, HadCM3, and PCM models only, as these were the only models with simulations available that included natural external forcing.

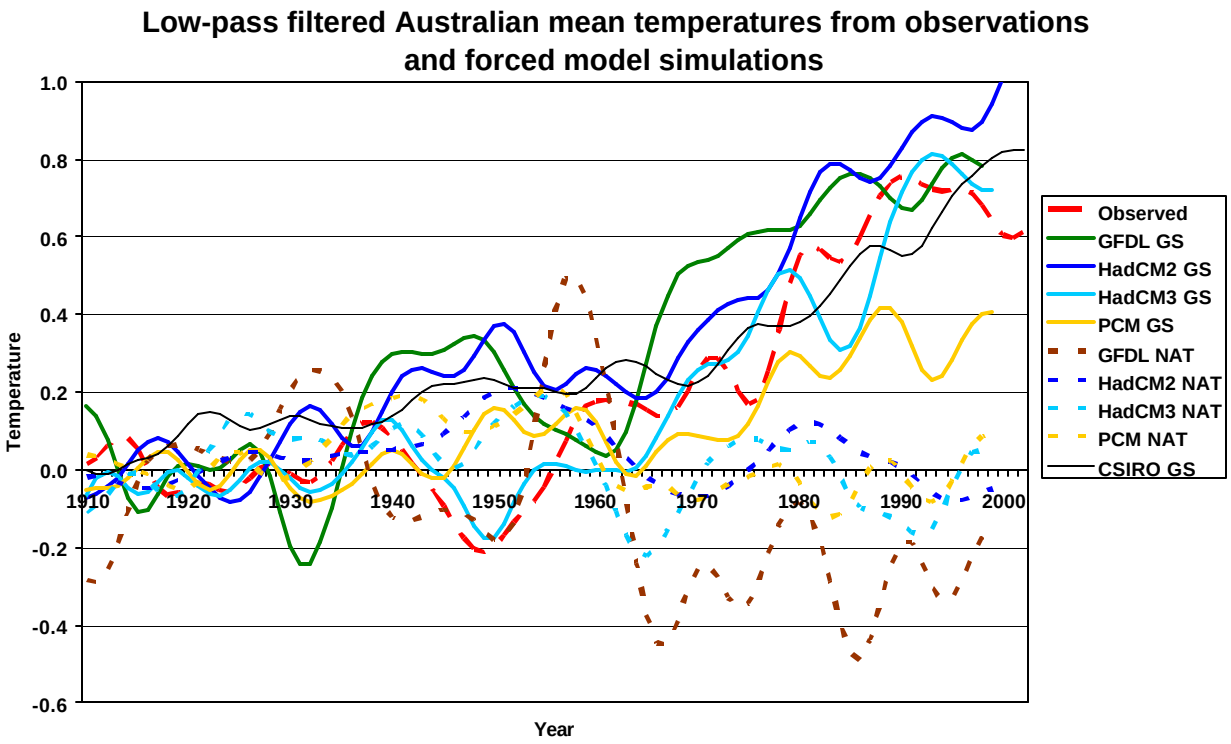

Figure 3. Time series of low-pass filtered Australian mean temperature anomalies from observations (red long-dashed line) and ensemble-mean model simulations with variations in anthropogenic forcing (GS, solid lines) or natural external forcing (NAT, short-dashed lines). Simulations that included natural forcing were available only for the GFDL, HadCM2, HadCM3 and PCM models. All the time series have been adjusted to be anomalies relative to a 1910-1930 average.