Australia's Air Temperature Trend Reviewed

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The hypothesis of an artificially exaggerated temperature trend in the Australian continental surface air temperature record is tested via comparison with four other records of temperature measured in the Australian region. The trends extracted from all five records are consistent, so the hypothesis of bias in the Bureau of Meteorology's Australian surface air temperature record cannot be sustained and is rejected. Using three different methods of trend estimation applied to five temperature anomaly time series, the anthropogenic contribution to warming of the Australian region since 1950 is determined to have occurred at a rate of 0.12 ± 0.02K per decade, which translates to a total anthropogenic warming contribution of 0.78 ± 0.13K over the period 1950 to 2015.

1. Introduction

A century-long warming of Australia has been recorded in the monthly mean surface air temperature data (SAT) from the ~100 surface sites of the national climate observation reference network (ACORN) operated by the Bureau of Meteorology, which also interprets the record (Jovanovic et al. 2012; Trewin 2013). The national science agency CSIRO, other agencies and Australian university groups use ACORN-SAT data in climate science research, as do other institutions internationally (Muller et al. 2013; Rohde et al. 2013). The veracity of Australian temperature records has been questioned (Stockwell and Stewart 2012) along with interpretation of the evident warming trend (Quirk 2009). Claims of bias in the record led to an unsuccessful attempt in 2010 to have the Australian National Audit Office declare the record invalid (Bernadi et al. 2010).

It is important to test these claims scientifically, since Australian data is significant to international evaluation of global climate change given its location in the sparsely sampled southern hemisphere (IPCC 2013). Hence in this work the hypothesis to be tested is that the ACORN-SAT record contains an artificiality elevated temperature trend. It is worth noting here that after the submission of this paper for publication a report was issued by the Technical Advisory Forum set up for a three-year period by the Parliamentary Secretary to the Minister of the Environment to annually review the development and operation of ACORN-SAT and to provide advice and recommendations on further developments. That report (TAF, 2015) has a broad remit focussing on methodological and procedural matters associated with generation of ACORN-SAT data, and does not address in any detail the topic covered by this paper. However it does conclude that "*unsolicited submissions received from the public did not offer a justification for contesting the overall need for (raw data) homogenisation or the scientific integrity of the Bureau's climate records*".

2. Data and Methods

A robust test of the hypothesis of an artificial trend in ACORN-SAT is provided by analysing four additional, independently produced Australian region temperature records to look for evidence of a late 20th century trend that is different from and lower than that evident in ACORN-SAT. The first three of these records are produced by entirely separate measurement systems, providing Australian T records comparable with, but completely independent from the ACORN-SAT surface station record. The fourth record is based on the same surface station raw data used for ACORN-SAT, but is sub-

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ject to quality control and homogenisation methods developed and applied by an overseas group fully independent of the Bureau.

The first additional data set used is the satellite-derived temperature anomaly series for the lower troposphere over Australia published by Spencer and Christy of the University of Alabama, Huntsville (UAH). The second is regionally-averaged radiosonde temperature anomaly records for the globe provided in time-series form on a 10 degree longitude by 5 degree latitude basis by the Hadley Centre in the UK (HadAT2), from which the Australian region 850hPa data (corresponding to an altitude of approximately 1500 metres) were obtained. The third is the Australian region average sea surface temperature (SST) anomalies provided by the Bureau of Meteorology, extracted from the global NOAA Extended Reconstructed Sea Surface Temperature Version 4 (ERSST v4). The fourth is the Australian continental mean temperature series taken from the Country List compiled by Berkeley Earth (Berkeley), which is based on the raw data records that underlie ACORN-SAT but processed independently. All five datasets are available as monthly-average time-series from the sources listed in Table 1.

Date Series	*Source*
ACORN	http://www.bom.gov.au/web01/ncc/www/cli_chg/timeseries/tmean/0112/aus/latest.txt
UAH	http://www.nsstc.uah.edu/data/msu/t2lt/uahncdc_lt_5.6.txt
HadAT2	http://www.metoffice.gov.uk/hadobs/hadat/hadat2.html
SST	http://www.bom.gov.au/web01/ncc/www/cli_chg/timeseries/sst/0112/aus/latest.txt
Berkeley	http://berkeleyearth.lbl.gov/auto/Regional/TAVG/Text/australia-TAVG-Trend.txt

Table 1 Temperature data series used in this analysis and source locations

To extract and then focus on any trend component in each observed temperature series that could be attributed to anthropogenic forcing an empirical multiple regression analysis method applied to global temperature anomaly series by Lean and Rind (2008) and further developed in various forms by others (Lean 2010; Foster and Rahmstorf 2011; Kopp and Lean 2011; Zhou and Tung 2013; Tung and Zhou 2013; Chylek et al. 2014; Santer et al. 2014) was adopted. The technique as originally outlined models empirically the global temperature anomaly, ΔT, as a linear combination of contributions to temperature variability and trend from variations in El Nino-Southern Oscillation (ENSO), episodic cooling due to major volcanic eruptions (VOLC) injecting aerosol into the stratosphere, a quasi 11-year cycle of variability due to the small but regular cycles in total solar irradiance (TSI) and a trend in net anthropogenic forcing (ANTH; greenhouse gas warming offset to some degree by aerosol and cloud-mediated cooling). The regression equation is:

$$\Delta\mathrm{T}(t) = \mathrm{c0} + \mathrm{c1.ENSO}(t - \Delta\mathrm{t}_E) + \mathrm{c2.VOLC}(t - \Delta\mathrm{t}_V) + \mathrm{c3.TSI}(t - \Delta\mathrm{t}_T) + \mathrm{c4.ANTH}(t - \Delta\mathrm{t}_A) \qquad (1)$$

where ΔT is the monthly T anomaly, the c's are the fitted coefficients, and Δt is a time lag in months specific to each explanatory variable, chosen to optimise the fit of the model by varying the lag to find the lag that maximised the multiple regression coefficient.

The independent variables used here follow Lean and Rind (2008) by adoption of a relevant index for each independent variable but with some additional variables as outlined below. For ENSO the multivariate ENSO index (MEI) was used. For VOLC the stratospheric aerosol optical thickness series of Sato was used. For TSI the monthly series produced by Judith Lean (Lean 2010; Kopp and Lean, 2011) was used (J. Lean, personal communication December 2014). For ANTH the IPPC's representative concentration pathways provide a single estimate of historical net anthropogenic forcing up to 2005, and projected forcings under different emissions and control scenarios post-2005, though the projected pathways post-2005 do not diverge significantly until after about 2020. For the purpose here it thus makes no difference which pathway is used to describe historical forcing and the small extrapolation out to 2013. So a middle pathway, RCP4.5 was used. Other indexes used were the Antarctic Oscillation index (AAO), and the Folland Interdecadal Pacific Oscillation index (IPO) which extended only to late 2008, so the last five years were padded out with the PDO index. A final index employed in this work was the Atlantic Meridional Oscillation Index (AMO), obtained from NOAA/ESRL. The list of indexes used here and the source locations are summarised in Table 2.

Date Series	*Source*
ENSO	http://www.esrl.noaa.gov/psd/data/correlation/mei.data
VOLC	http://data.giss.nasa.gov/modelforce/strataer/
TSI	Lean (2010); Kopp and Lean (2011); J. Lean, personal communication
ANTH	http://tntcat.iiasa.ac.at:8787/RcpDb/dsd?Action=htmlpage&page=welcome
AAO	http://ljp.gcess.cn/dct/page/65609
IPO	http://www.iges.org/c20c/IPO_v2.doc; http://jisao.washington.edu/pdo/
AMO	http://www.esrl.noaa.gov/psd/data/correlation/amon.us.long.data

Table 2 Independent variable used and data sources.

The temperature anomaly series were all analysed using the common reference period of 1961-1990. In the case of the UAH series which did not cover that period the series was adjusted to approximate that base period using the ratio between the 1978-2013 and 1961-1990 period averages from ACORN-SAT.

The application of the Lean model is a straightforward multiple regression task, the statistical character of which has been described elsewhere (Foster and Rahmstorf 2011; Zhou and Tung 2013). Here this technique is applied for the first time to a regional temperature series, and with the addition of regionally-focussed indexes as explanatory variables.

The process adopted was to apply the basic model (eq. 1) to the ACORN-SAT data from 1950 to mid-2013, utilising an eleven-month centred running mean of the ACORN-SAT data rather than the raw monthly data. This was done to reduce the much greater high frequency variability evident in the monthly regional data compared with global average data, enabling a clearer graphical comparison of the fitted model and the temperature series. As discussed later the choice of smoothed rather than raw monthly data makes no difference to the conclusions reached.

The choice to base the main analysis on the period post-1950 was dictated by issues of data record comparability: the HadAT2 radiosonde data is available only from1958 and the UAH satellite-derived data only from December 1978. However, as also discussed later, it makes no difference to the conclusions reached regarding ACORN-SAT whether the full record from 1910 or just the record post-1950 is used. One other point is that the original model (Lean and Rind 2008) applied to global temperature series was later extended (Kopp and Lean 2011) by having the ENSO component incorporated three times each with a different lag while VOLC was included twice with two different lags. For the ACORN-SAT data series preliminary tests showed that only two ENSO components at different lags were significant at 90 per cent confidence, and only a single VOLC component so that was the final structure adopted.

In light of recent suggestions (Zhou and Tung 2013; Chylek et al. 2014) that the fit of the regression model applied to global temperature anomaly time-series is improved by adding the AMO as an explanatory variable, it was added to the basic model and reapplied to ACORN-SAT. The resultant AMO coefficient was not significant, being much less than one standard error different from zero (see Table 3). This is not surprising given the low correlation between continental Australian temperature and the AMO index embodied in the results of a recent global spatial correlation analysis (Muller et al.2013).

However a small amount of additional variance was explained in the empirical fitting process if two more regionally focused climate indices were added, one being the Antarctic Oscillation (AAO), the other being the Interdecadal Pacific Oscillation (IPO). These two modes of climate variability are widely recognised as being important to the Australian region (Power et al., 1999; Hendon et al., 2007; WMO 2015). The final model thus contained two variables for ENSO at lags of two and seven months, VOLC at seven months, TSI at a lag of five months, ANTH, IPO and AAO at no lag. Table 3 lists the regression coefficients returned by the model applied to each of the temperature anomaly series, while Figure 1 provides graphically the component contributions made to overall variance explained for the ACORN-SAT regression. These plots are representative of the results from all five regressions.

ACORN	*AAO*	*IPO*	*ANTH*	*TSI*	*VOLC*	*ENSO*	*ENSO*	*intercept*	*AMO*
coefficient	-0.0116	-0.032	0.436	0.041	-3.51	0.125	0.174	0.039	-0.030
std error	0.0050	0.008	0.024	0.026	0.49	0.013	0.020	0.014	0.055
	$r^2 = 0.567$	F = 121	RSS = 56.3						
ACORN	*AAO*	*IPO*	*ANTH*	*TSI*	*VOLC*	*ENSO*	*ENSO*	*intercept*	
coefficient	-0.0117	-0.031	0.434	0.041	-3.41	0.123	0.172	0.038	
std error	0.0050	0.008	0.024	0.026	0.45	0.013	0.019	0.014	
	$r^2 = 0.567$	F = 139	RSS = 56.3						
UAH	*AAO*	*IPO*	*ANTH*	*TSI*	*VOLC*	*ENSO*	*ENSO*	*intercept*	
coefficient	-0.0056	-0.020	0.439	-0.017	-6.55	0.127	0.122	0.122	
std error	0.0053	0.009	0.050	0.028	0.46	0.015	0.033	0.033	
	$r^2 = 0.524$	F = 63.0	RSS = 20.9						
HadAT2	*AAO*	*IPO*	*ANTH*	*TSI*	*VOLC*	*ENSO*	*ENSO*	*intercept*	
coefficient	-0.0196	-0.042	0.510	0.148	-3.76	0.116	0.164	0.072	
std error	0.0048	0.007	0.024	0.025	0.41	0.012	0.018	0.014	
	$r^2 = 0.635$	F = 160	RSS = 37.4						
SST	*AAO*	*IPO*	*ANTH*	*TSI*	*VOLC*	*ENSO*	*ENSO*	*intercept*	
coefficient	0.0074	-0.024	0.420	0.071	-1.17	0.037	0.004	-0.008	
std error	0.0021	0.003	0.010	0.011	0.19	0.006	0.008	0.006	
	$r^2 = 0.779$	F = 374	RSS = 10.1						
Berkeley	*AAO*	*IPO*	*ANTH*	*TSI*	*VOLC*	*ENSO*	*ENSO*	*intercept*	
coefficient	-0.0103	-0.023	0.469	0.053	-3.09	0.121	0.160	0.013	
std error	0.0049	0.008	0.023	0.025	0.44	0.013	0.019	0.013	
	$r^2 = 0.596$	F = 157	RSS = 53.8						
ACORN-raw	*AAO*	*IPO*	*ANTH*	*TSI*	*VOLC*	*ENSO*	*ENSO*	*intercept*	
coefficient	-0.062	-0.065	0.521	0.016	-3.27	0.088	0.299	0.019	
std error	0.013	0.020	0.061	0.066	1.14	0.033	0.049	0.034	
	$r^2 = 0.214$	F = 29.0	RSS = 365						
ACORN-annual	*AAO*	*IPO*	*ANTH*	*TSI*	*VOLC*	*ENSO*	*ENSO*	*intercept*	
coefficient	-0.015	0.038	0.474	0.131	-2.78	0.115		0.049	
std error	0.048	0.025	0.129	0.128	2.03	0.061		0.058	
	$r^2 = 0.468$	F = 8.2	RSS = 5.9						
ACORN-1910	*AAO*	*IPO*	*ANTH*	*TSI*	*VOLC*	*ENSO*	*ENSO*	*intercept*	
coefficient	-0.0039	-0.043	0.525	0.039	-1.86	0.169	0.124	-0.047	
std error	0.0044	0.008	0.023	0.025	0.50	0.013	0.019	0.012	
	$r^2 = 0.497$	F = 173	RSS = 139						

Table 3 Summary statistics for all regression model cases discussed in the text.

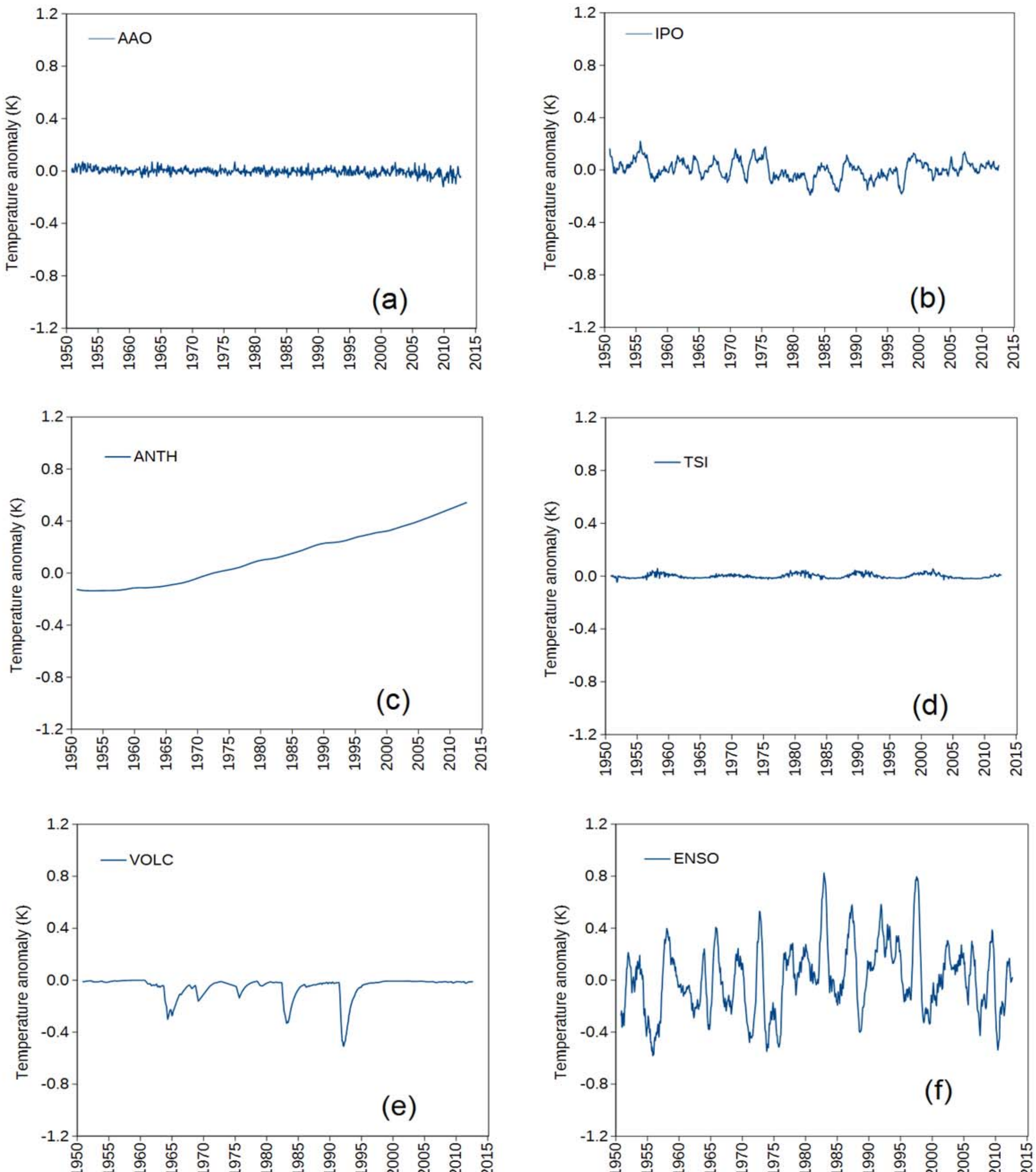

Figure 1 Regression component plots from the standard ACORN regression.

3. Results

Figure 2 demonstrates visually the fit of the regression model to each of the five time-series analysed.

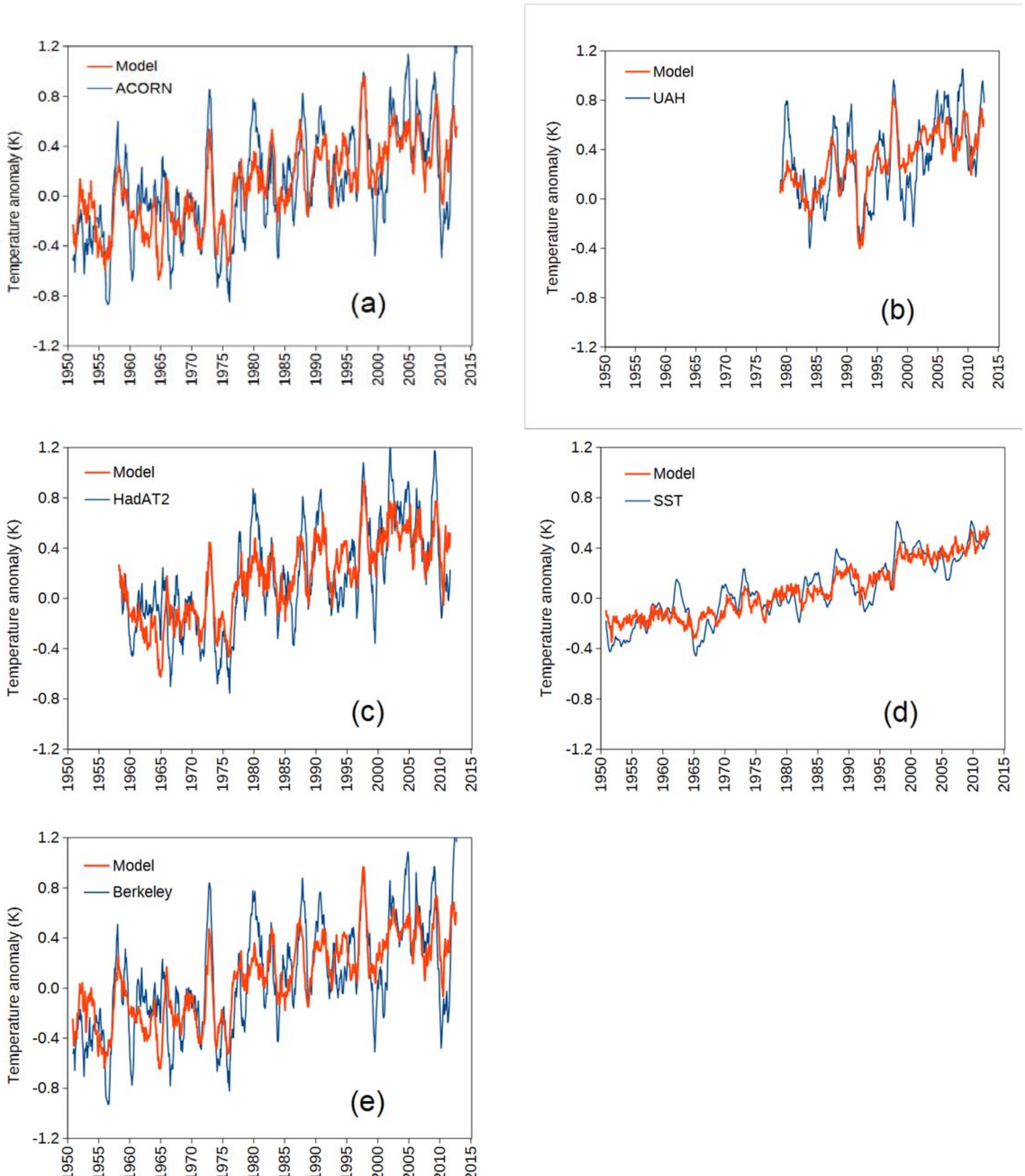

Figure 2 Temperature anomaly time-series for the Australian region (blue lines), overlaid with the fitted regression model (orange lines): (a) ACORN, (b) UAH, (c) HadAT2, (d) SST, (e) Berkeley.

The objective of this work is to determine whether the temperature trend evident in the ACORN-SAT record and attributable to anthropogenic greenhouse forcing is elevated compared with the trends in the comparison data series. Thus the focus here is not on the overall regression model but on the estimated ΔT trend component represented by ANTH, the net anthropogenic forcing, which the regression methodology extracts, allowing for its evaluation independent of variability or trend in ΔT associated with any of the other explanatory variables. The individual ANTH component within each of those full regression models is displayed in the upper left panel of Figure 3, while the upper right panel displays the fitted value of the ANTH coefficients, with their 95 per cent confidence intervals. It is evident from both panels that the hypothesis of a systematically exaggerated trend in the ACORN-SAT record cannot be sustained: each of the five individual data records returns the same ANTH trend from the regression, within the uncertainty of the estimates.

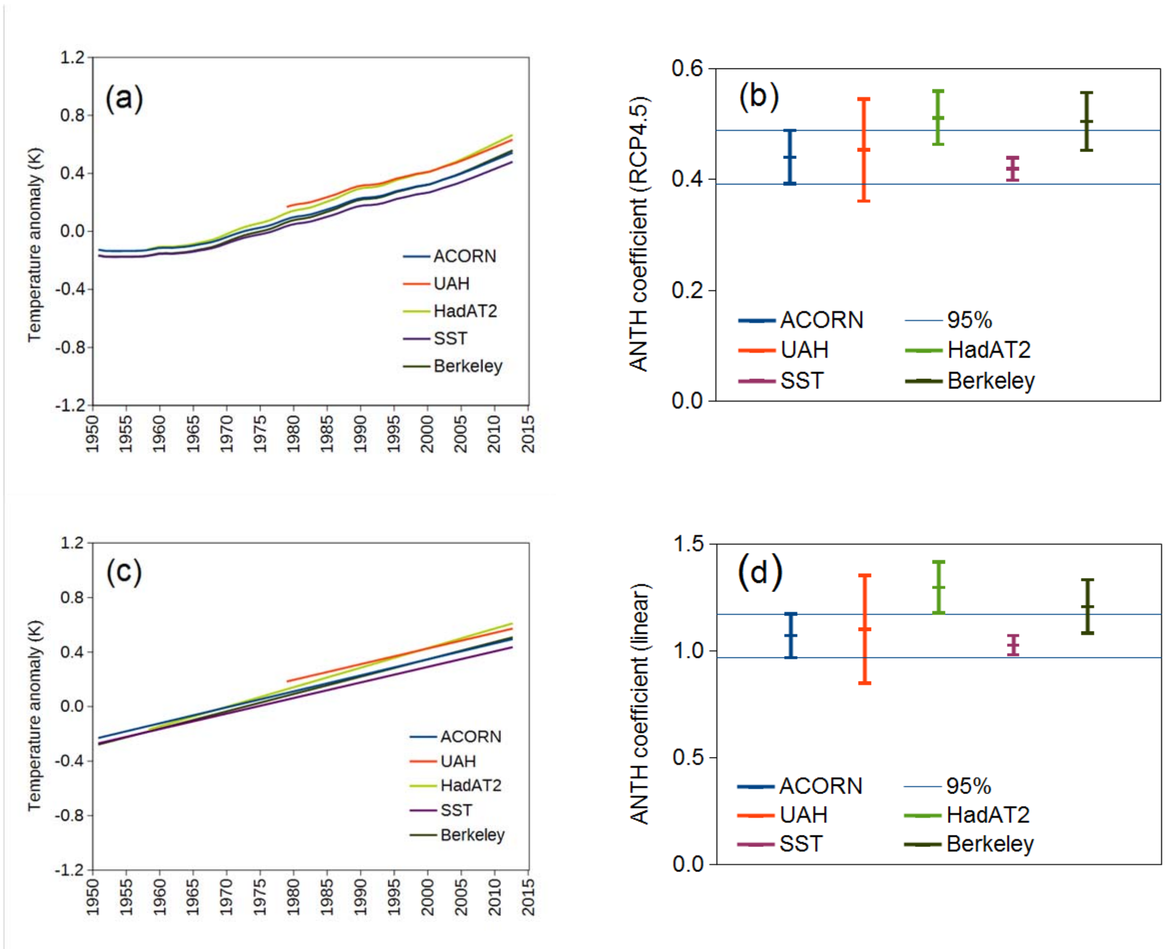

Figure 3 ANTH contributions to Australian T trend based on RCP4.5 from the five regression models (a) and ANTH coefficient values with 95 per cent confidence intervals (b). ANTH contributions to Australian T trend based on an unconstrained linear trend from the five regression models (c) and ANTH coefficient values with 95 per cent confidence intervals (d). In the right-hand panels, (b) and (d), the thin horizontal blue lines depict the 95 per cent confidence interval around the ANTH coefficient from the ACORN-SAT regression.

The only way that the ACORN-SAT series could be biased would be if each of the other series was equally biased. Given the completely separate methods of measurement and quality assurance by unconnected observing systems for UAH, HadAT2 and SST this is not a tenable proposition. In the case of Berkeley, the same raw surface temperature data from the Australian continental sites are used, but the data quality assurance and data homogenisation procedures were developed and validated independently of the Bureau (Rohde et. al. 2013), providing a different but equally robust confirmation that ACORN-SAT is not biased. Rather than revealing any bias, this analysis using multiple data series provides compelling confirmatory evidence that the ACORN-SAT temperature trend attributable to anthropogenic forcing is independently reproducible and reliable.

The only possible caveat would be if this result was an artefact of the analysis method used. To explore that possibility three tests were carried out. The first was to test whether the ΔT trend found for ANTH was general, and not forced in some way by use of RCP4.5 as the explanatory variable. Thus the analysis of each data series was repeated with the RCP4.5 explanatory variable replaced by a simple linear function of arbitrary slope, on the assumption that if the ANTH trend was robust the regression would simply scale the slope to reproduce the trend obtained using RCP4.5. That is exactly what was found, as shown in the lower panels of Figure 3.

The second was carried out to ensure that the smoothing of the ΔT series via an eleven-month running mean did not bias the result. Repeat of the analysis on the post-1950 ACORN-SAT record using the raw monthly data or alternatively each of the data series accumulated into annual averages provided a range of data averaging time-scales from raw monthly to monthly smoothed to annualised. The ANTH coefficients were again not statistically different within their 95 per cent confidence bounds: 0.521 ± 0.121 (raw monthly), 0.434 ± 0.048 (monthly smoothed) and 0.474 ± 0.258 (annualised). These results are depicted graphically in right hand panel (b) of Figure 4.

A final test was to check that the trend found was not an artefact of having restricted the analysis to the subset of the ACORN-SAT record from 1950, chosen to reflect the period during which the UAH and HadAT2 records became available, rather than analysing all of ACORN-SAT from its beginning in 1910. The analysis for the full ACORN-SAT data record available from 1910 yielded the result also shown in Figure 4, where it is evident that the ANTH trend deduced from the record since 1910 and that from the post 1950 record are not greatly different within the uncertainty of the estimates; the ANTH coefficient values returned by the regression were 0.525 ± 0.046 and 0.434 ± 0.048 respectively at 95 per cent confidence. The summary statistics for all regressions referred to in this paper are provided above in Table 3.

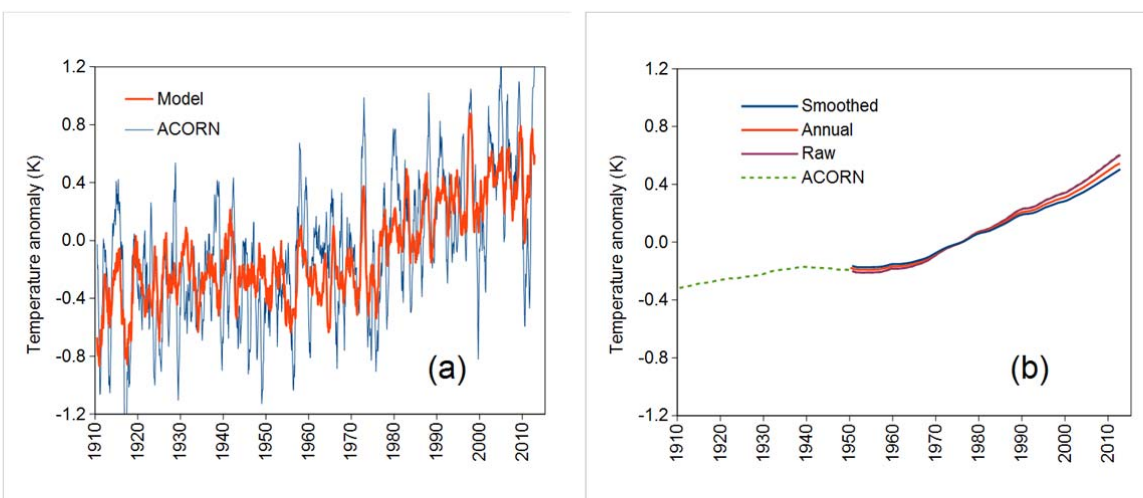

Figure 4 Panel (a) shows the multiple regression fit of the standard model applied to the full ACORN-SAT data series from January 1910. Panel (b) shows the fitted ANTH component from that regression (labelled ACORN) plotted over the ANTH components from the regressions for ACORN-SAT starting in 1950 for data accumulated as 11 month running means (Smoothed), annual averages (Annual), and the raw monthly ACORN data (Raw).

4. Discussion

The ANTH trend for Australia estimated throughout the analyses of all the data series is consistent and robust. In the case of ACORN-SAT the fitted coefficients for ANTH all lie within a range of values that at its extreme covers a maximum spread of only ±0.042 around the mean coefficient value 0.483 from combination of the data averaging (monthly raw data, 11-month running mean, or annual average) and timescale (post-1950 only or full record from 1910) experiments.

What is the magnitude of the warming trend for the Australian region attributable to anthropogenic forcing? The most general result is gained by using all five time-series analysed here and averaging the individual ANTH trend estimates that resulted. Here this is done in three ways, to yield for each series three views on the mean Australian region ANTH trend for the period post-1950, which are presented as K per decade.

The first estimate took the fitted RCP4.5 temperature anomaly trend, subtracted the last monthly value from the first, divided it by the time interval involved, and scaled the result to K per decade. This is identified as Δdates in Table 4.

The second estimate was made by fitting a linear function to the RCP4.5 ANTH curves and estimating the trend as the slope (listed as RCP4.5 in Table 4).

The third method was simply to use directly the slope derived from from the regressions in which RCP4.5 was replaced as dependent variable by a line of arbitrary slope (Linear in Table 4). The mean post-1950 ANTH trends for the Australian region that result from these three ways of estimating the trend are statistically equivalent based on their overlapping confidence intervals, yielding the common value of 0.12 ± 0.02K per decade at 95 per cent confidence. Within that set the individual ACORN-SAT record had a mean warming trend of 0.11K per decade averaged across the three ACORN-SAT estimates given in Table 1. For completeness, the corresponding median values from the data in Table 4 are also 0.12 K per decade (all data) and 0.11 K per decade(ACORN-SAT).

	Δdates	*RCP4.5*	*Linear*
ACORN	0.107	0.113	0.116
UAH	0.136	0.129	0.114
HadAT2	0.142	0.141	0.142
SST	0.103	0.109	0.113
Berkeley	0.115	0.122	0.126
Mean	**0.121**	**0.123**	**0.122**
95% conf	**0.020**	**0.015**	**0.015**

Table 4 Temperature trends obtained from each of the temperature anomaly time-series as detailed in the text. Units: K per decade.

Other environmental records exist that also attest to the occurrence of a significant Australian temperature trend. One example is an analysis of 40 years of snow depth data from Spencers Creek in the Snowy Mountains of SE Australia. A significant downward trend in spring season snow depth was analysed in terms of variability in rainfall and temperature, and found to be associated primarily not with rainfall decline but with the strong warming of the region (Nicholls 2005), which provides yet another, independent confirmation that the upward trend in the ACORN-SAT record for Australia is not artificial, but is a valid part of the global temperature increase signal. The demonstrated validity of the temperature trend found in the Australian surface station record is also important because observed-modelled data comparisons often underpin Australian attribution studies in which climate model outputs provide insight into climate system processes involved in temperature change. Two examples are the works of Karoly and Braganza (2005) and Lewis and Karoly (2013).

For the globe, analysis of available surface air temperature data records over the second half of the 20th Century yields a trend of 0.16 – 0.17 K per decade (Foster and Rahmstorf 2011; Hansen et al. 2011), not all of which can be attributed a priori to anthropogenic forcing (Hunt 2010). In that vein several recent analyses have used a variety of methods aimed at separating the ANTH trend from variability and trend contributed by long-period climate cycles assumed to be natural in origin, such as the AMO. These have concluded that the ANTH component may be only part of the overall signal, with estimates for the late 20th century ANTH trend in the range ~0.08 – 0.1 K per decade (Zhou and Tung 2013; Tung and Zhou 2013; Chylek et al. 2014; Fyfe et al. 2010; Wu et al. 2011) when the long-period variability is removed. However the extent to which the long-period cycles attributed to AMO or AMO-like variability might themselves be responding to anthropogenic forcing remains uncertain (Muller et al. 2013), in which case the global ANTH trend could still lie below 0.17 K per decade but above the alternative estimate of ~0.08 – 0.1 K per decade. In closing, it is also worth noting that the results presented here are entirely consistent with the conclusions reached by the IPCC that the of majority of global warming since 1950 is related to anthropogenic climate change (IPCC, 2013, 2014).

5. Conclusion

The Australian region is warming significantly due to anthropogenic greenhouse gas forcing, exhibiting in five different temperature datasets a warming trend that is reproducible, robust and consistent with, though possibly slightly higher than, some recent estimates of the global average trend in temperature due to anthropogenic forcing. The anthropogenic temperature trend for the Australian region since 1950 was determined to be 0.12 ± 0.02K per decade, which over the period 1950 to 2015 translates to a total warming contribution of 0.78 ± 0.13K.

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