Warming levels projections – average temperature and rainfall Technical Note 1 – estimating warming since 1850–1900

Linked to at: Future Climate Scenarios > Global Warming Levels > Australian warming

Introduction and context

The 1.5, 2, 3 and 4 °C global warming levels are defined relative to the 'early industrial' baseline of 1850-1900. In order to understand what the warming levels mean for our region, we need to be able to estimate how much the globe, Australia and regions within Australia (e.g. states and territories) have warmed since this baseline.

However, there are very limited observational records of temperature during this early industrial period across many regions of globe, including Australia (e.g. Morice et al, 2012). The Australian Climate Observations Reference Network - Surface Air Temperature version 2.1 dataset (ACORN-SATv2.1) is the current national standard product, combining daily temperature observations from 112 stations across the country (Trewin et al, 2020), but it is only available since 1910 due to poor coverage or low quality of station observations before this date (see **Figure 1a**).

Prior to 1910, our estimation of warming in Australia relies on information provided by early historical temperature records (e.g. Ashcroft et al, 2012; **Figure 1b**), global observational gridded datasets (**Table 1 and Figure 1c**), historical simulations from global climate models (**Figure 1d**), or from paleo-climate reconstructions such as those based on tree rings (Figure 2). based on statistical analyses that can be performed on observed datasets or climate model datasets.

Early historical records are only available and quality-controlled for the southeast of Australia (Ashcroft et al. 2012) but may also be applicable as a proxy for a wider region including the Australian average. Global observational datasets use observations of air and water temperature and fill in gaps in place and time to produce broad spatial and temporal coverage and therefore have the advantage of providing data prior to 1910. However, each of the five major datasets considered here (see **Table 1**) uses its own choices on how to quality-control input data, statistically fill gaps, and the spatial coverage and resolution to report. Importantly, all the datasets can only use the limited historical records prior to 1910, and some don't use those – much of the data for Australian states and territories is interpolated using data from outside the region.

Climate models, such as those from the Coupled Model Inter-comparison Project phase 5 (CMIP5) ensemble of Taylor et al. (2012) use the historical conditions of greenhouse gas concentrations and major volcanic eruptions as the 'forcing' to simulate the historical climate. They are not in lockstep with observed climate variability from internal sources (e.g. El Niño Southern Oscillation) but are designed to produce a realistic global and regional response to the forcing conditions. In this way they are expected to provide a reasonable estimate of historical trends due to forcing, allowing for the effect of natural variability, and so may be useful for estimating the plausible range of historical trends. As well as the effect of natural variability, models are imperfect and do not simulate some aspects of the climate in a realistic way, so may not be fit for some purposes. For this reason, the range of different models needs to be examined, and results should be critically evaluated.

Statistical techniques for using observations and models can include methods such as bias correction of model simulations or examining a statistical regression between observed global temperature (more reliable) with local observed temperature in the 1910-2019 period, then extrapolating this back to 1850.

Data and Methods

In this technical note we use the ACORN-SATv2.1 dataset wherever it is available (since 1910) to document temperature changes in Australia and each of its states and territories, namely New South Wales (NSW, which contains Australian Capital Territory ACT), Western Australia (WA), Queensland (QLD), South Australia (SA), Tasmania (TAS), Northern Territory (NT) and Victoria (VIC). We then estimate warming between 1850–1900 and 1910–1930 using various four main methods to supplement ACORN-SATv2.1:

1) Using early historical records from the southeast of Australia
2) From 5 standard global gridded observational datasets (see **Table 1**)
3) From 40 CMIP5 model simulations
4) Applying a statistical bias correction method to CMIP5 outputs during 1850–1900

We also do an additional analysis as a check:

5) Using a regression from Australian to global warming to generate a timeseries for Australia prior to 1910

Results are summarized in **Table 2**.

Table 1. Global gridded temperature datasets

	Name	Reference and weblink
1	Hadley Centre, Climate Research Unit version 5 (HadCRUT5)	Morice et al. 2020, https://www.metoffice.gov.uk/hadobs/hadcrut5/
2	Berkeley Earth Surface Temperature (Berkeley or BEST)	Rohde and Hausfather 2020, http://berkeleyearth.org/
3	GISS Surface Temperature Analysis v4 (GISTEMP)	Lenssen et al. 2019, https://data.giss.nasa.gov/gistemp/
4	NOAA Global Temperature Analysis v5 (NOAA)	Zhang et al. 2020 https://www.ncdc.noaa.gov/data-access/marineocean-data/noaa-global-surface-temperature-noaaglobaltemp
5	Cowtan and Way (C&W)	Cowtan and Way (2014), https://www-users.york.ac.uk/~kdc3/papers/coverage2013/series.html

Results

Raw data

Australian average annual temperature relative to the 1910–1930 baseline in ACORN-SATv2.1 (**Figure 1a**) shows a notable warming: the difference between 1910–1930 and 2010–2019 is +1.3 °C, the anomaly for 2019 was +1.96 °C. Overlaying the Ashcroft early historical record for southeast Australia as a proxy for Australian temperature onto the ACORN-SATv2.1 series (**Figure 1b**) suggests there was a small increase in mean temperature between 1850-1900 and 1910-1930. The trends and anomalies since 1910 are similar in all five of the global gridded datasets (**Figure 1c**) but there is greater disagreement prior to around 1885. The equivalent time series from global datasets for Australian states and territories are found in **Figure S1** and show greater uncertainty and probable error for some regions in the early period – especially in areas away from the southeast.

Changes in CMIP5 models (**Figure 1d**) are similar to the gridded observed datasets but without obvious artefacts caused by poor station coverage prior to 1910. However, there is a large spread between models and a more notable temperature reduction in the mid-1880s in response to the Krakatoa volcanic eruption than in global gridded datasets. Changes by state and territory (**Figure S2**) have similar features.

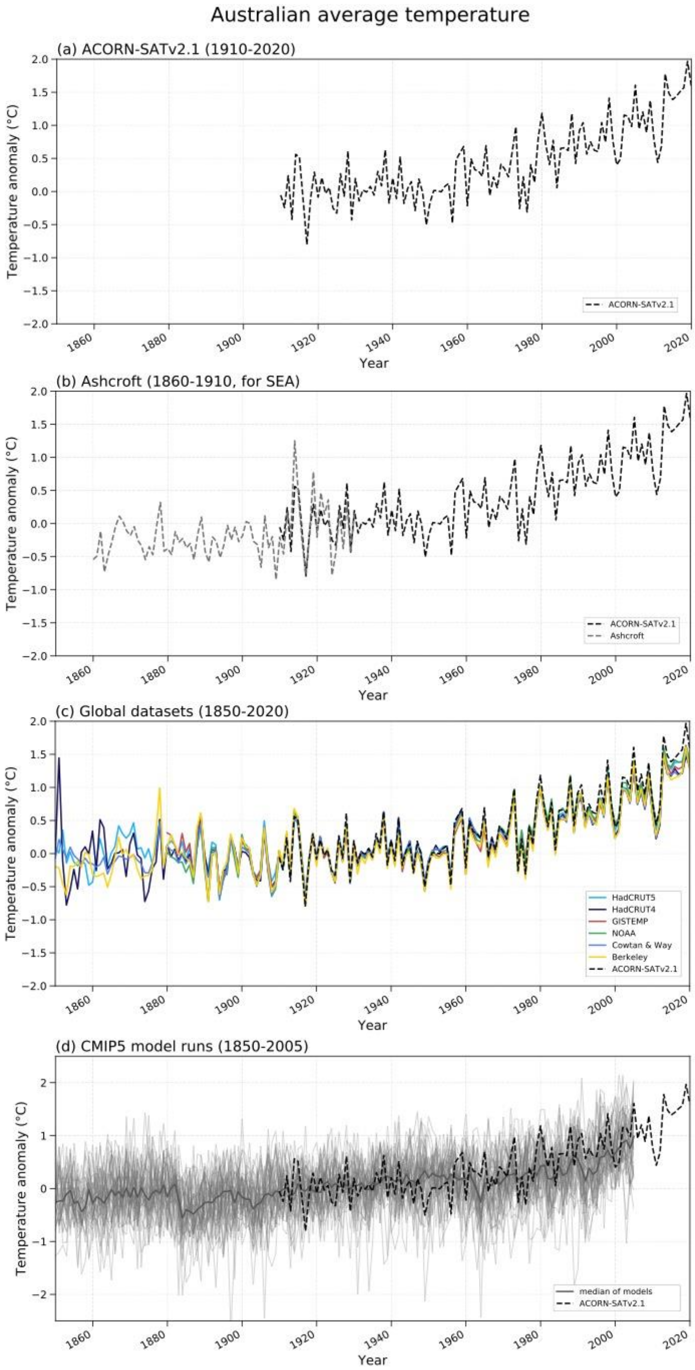

Figure 1: Australian average annual mean temperature anomalies from ACORN-SATv2.1 during 1910-2019 and other datasets overlaid: (a) just ACRON-SATv2.1, (b) with early temperature records for Southeast Australia during 1860-1930 (c) from global gridded observational datasets (listed in **Table 1**) available from 1850 or 1880 onwards and (d) from historical simulations from 40 CMIP5 climate models during 1850-2005. Anomalies are calculated relative to 1910-1930.

Estimated change since 1850-1900

Method 1: Using early historical records

Before the 1900s, Australian station coverage was not as dense as the current temperature network. Data was particularly limited across WA and NT, and significant inhomogeneities existed in datasets across most of southeast Australia (SEA) until the introduction of the Stevenson thermometer screens as standard observational practice in the late 19th century. Through a sophisticated homogenization process (based on 38 stations in VIC, SA, NSW and south QLD), Ashcroft et al (2012) were able to reconstruct monthly surface air temperatures across SEA for 1860–1909 (a regional average over 138–154 °E, 24–40 °S). Although this early historical record is only available and quality-controlled for the southeast of Australia, it may be applicable as a proxy to the Australian average, based on the assumption that temperature variability and trends in SEA are broadly representative of the nation.

Figure 1b shows this early historical record for SEA (Ashcroft et al. 2012) and ACORN-SATv2.1 for all of Australia, both as anomalies from 1910-1930. Correlations between the datasets from 1910 to 2010 (not shown) are R = 0.90 for annual data, R = 0.97 for 11-year running averages, and the difference in the 30-year changes calculated as rolling linear trends in 1910-2016 are all less than 0.1 °C. As we are interested here in the *magnitude* of the warming trend and not the variability, differences in interannual variability between the SEA and Australia series do not impact on our analysis. The results show:

- Higher interannual variability in the southeast than in Australia during 1910-1930, as expected since it is a smaller region
- Warming between 1860-1900 and 1910-1930 of +0.26 °C
- Results are applicable to VIC, and possibly to NSW, and appear acceptable as a proxy for all of Australia, but not to most other states and territories as there is no overlap in the spatial domain.

Also, **Figure 2** shows a temperature reconstruction available for the combined land–ocean region of Australasia (0°–50°S, 110°E–180°, see Figure 1 in Gergis et al., 2016) and spanning the period 1000 to 2000. This 1000-member reconstruction of regional temperature is based on the composite plus scale (CPS) technique which is robust and widely accepted and provides the longest temperature record possible for the region. However, like with most paleoclimate reconstructions, there are important inconsistencies to consider: for e.g. they cover only the warm season (September-February) rather than the whole year, they cover both land *and* ocean points (therefore probably underestimating temperature trends over land only) and are spatially sparse. The results show a mean warming between 1850-1900 and 1910-1930 of 0.04°C for Australasia, well within the uncertainty bounds estimated from our independent lines of evidence.

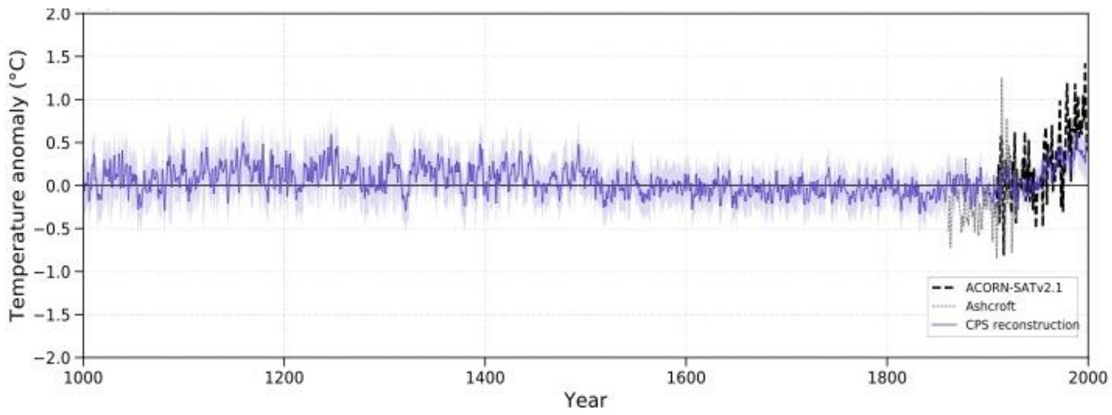

Figure 2. Mean annual temperature relative to 1910-1930 for: Australian average from ACORN-SATv2.1, southeast Australian average from Ashcroft early historical records in Ashcroft et al. (2012), and Australasian average from paleo-climate reconstructions from Gergis et al. (2016).

<u>Method 2:</u> Using global gridded observational datasets

The temperature change from 1850-1900 to 1910-1930 is calculated directly from each of the five global datasets (see **Table 1**) and shown in **Figure 3**. Australia is expected to have warmed by 0.07°C (median value) over these two periods, with estimations ranging from 0.18°C warming in WA to a cooling of 0.10°C in NT, and quite a significant spread across datasets for most of the regions, most likely affected by data error (e.g. in NSW and SA). The global gridded datasets each use their own set of station records, most do not include those from Ashcroft et al. (2012) – see links in Table 1 for more detail. Each dataset also uses its own statistical techniques.

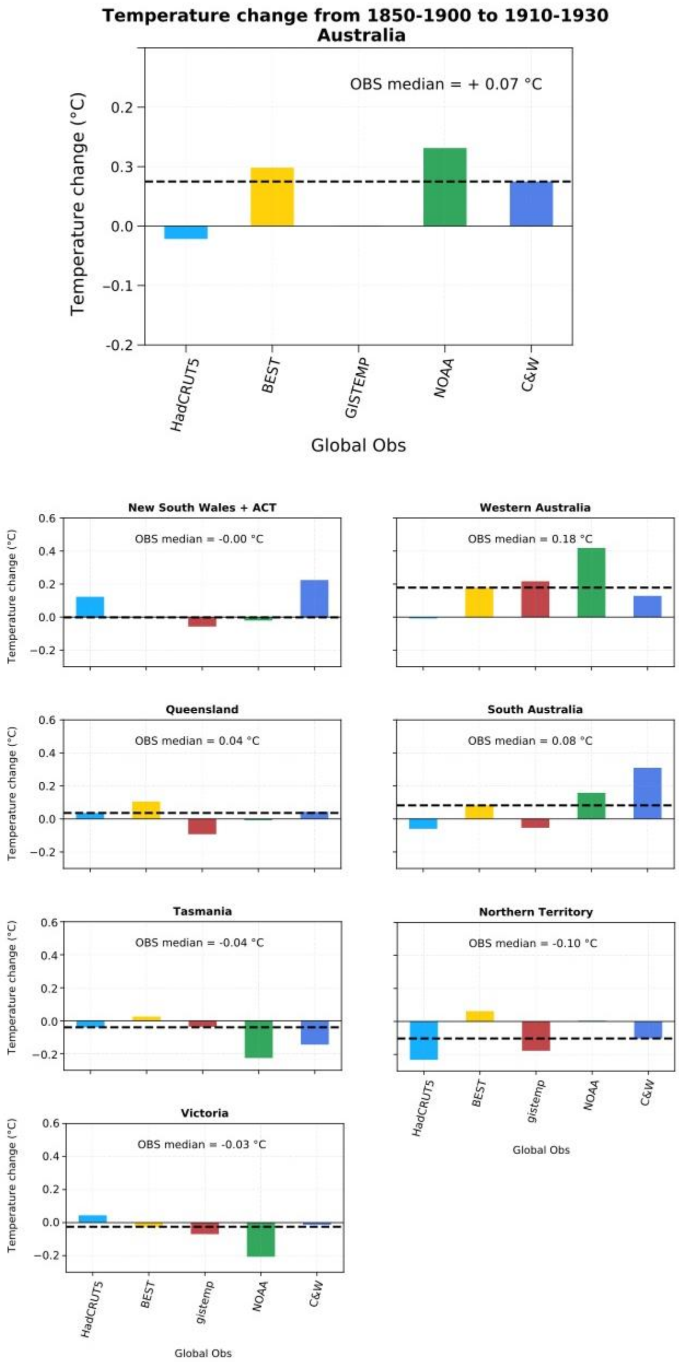

Figure 3: Average temperature change over Australia (top) and each state and territory (bottom) from 1850-1900 to 1910-1930 estimated from five global gridded observational datasets (**Table 1**). The median value across these five datasets is included as text within each plot.

Method 3: Using global climate models

We examine historical simulations from 40 CMIP5 climate models and calculate mean annual temperatures for Australia and its states and territories in each model from 1850 to 2005. These timeseries are shown in **Figure 1d** (for Australia) and **Figure S2** (for states and territories). The temperature difference between 1910–1930 and 1850–1900 mean values is then derived (see **Figure 4**).

The results show:

- A large range of estimated change between models, reflecting the different natural variability in each model, a different response to the Krakatoa eruption, as well as possible model biases.
- Apart from outliers, a reasonable model agreement on a *small* warming for each region (i.e. the total range is large but the 25-75% range is notably narrower)
- Results are comparable between each state and territory (models have complete spatial coverage), with a quite uniform warming of 0.21 °C in Australia, 0.17 to 0.18 °C in most states and territories and a slightly lower 0.13 °C warming estimated for TAS
- Changes between 1850–1900 and 1910–1930 as spatial maps (see **Figure S3**) show the likely effect of differences in rainfall and land surface variables on the modeled change, from a strong drying and warming over the inland region (GFDL-ESM2G) to strong rainfall increase and cooling over the northeast (MRI-ESM1).

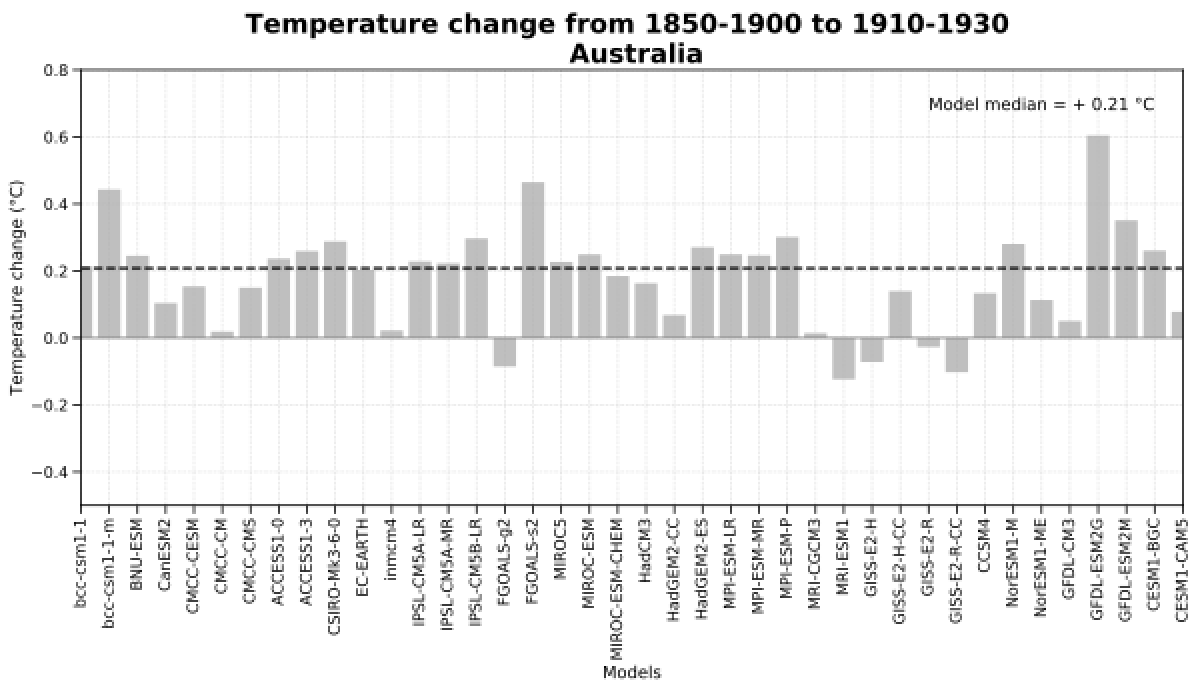

Figure 4a: Average temperature change over Australia from 1850–1900 to 1910–1930 as simulated in historical simulations of individual climate models. The median value across all models is indicated (+0.21 °C).

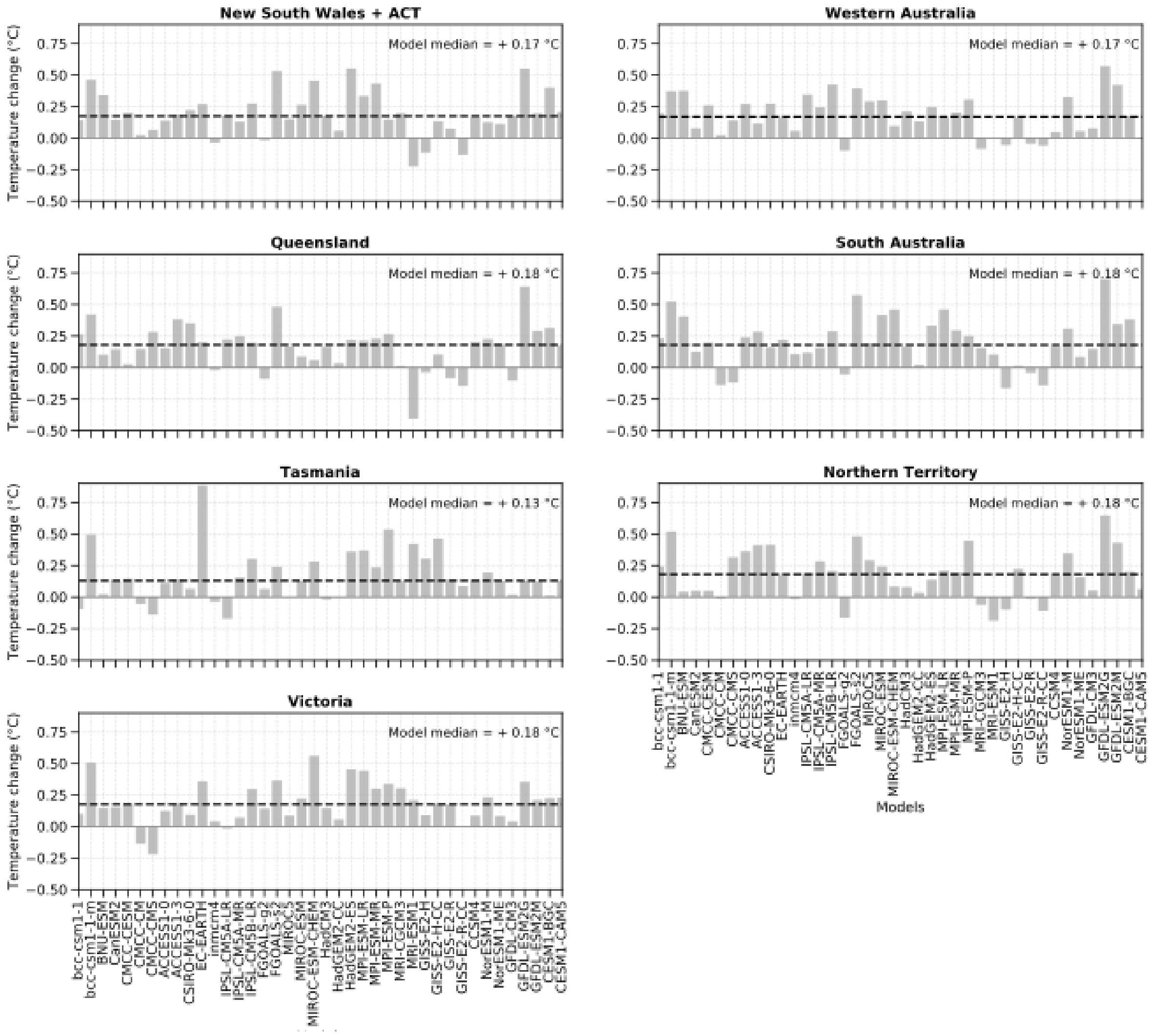

Figure 4b: Average temperature change over each state and territory from 1850–1900 to 1910–1930 as simulated in historical simulations of individual climate models. The median value across all models is shown at the top of each bar plot.

Method 4: Applying a bias correction to climate models

A bias correction technique is performed here to adjust the simulated output from each model (from 1850 to 1909) based on differences between the observations (ACORN-SATv2.1) and the model output over a training period (here 1910-1960). The method we use is the Empirical Quantile Mapping method which consists in calibrating the simulated Cumulative Distribution Function (CDF) based on a nonparametric function that amends mean, variability, and shape errors in the CDF (for more detail see Amengual et al, 2012).

The results of the calibrated model temperature anomalies (**Figure 5**) show:

- A slightly reduced spread between models and reduction on outliers for any given year and for temperature trends
- A similar median and 25–75% range of models as raw outputs, and a similar cooling response to the Krakatoa eruption in the mid-1880s.

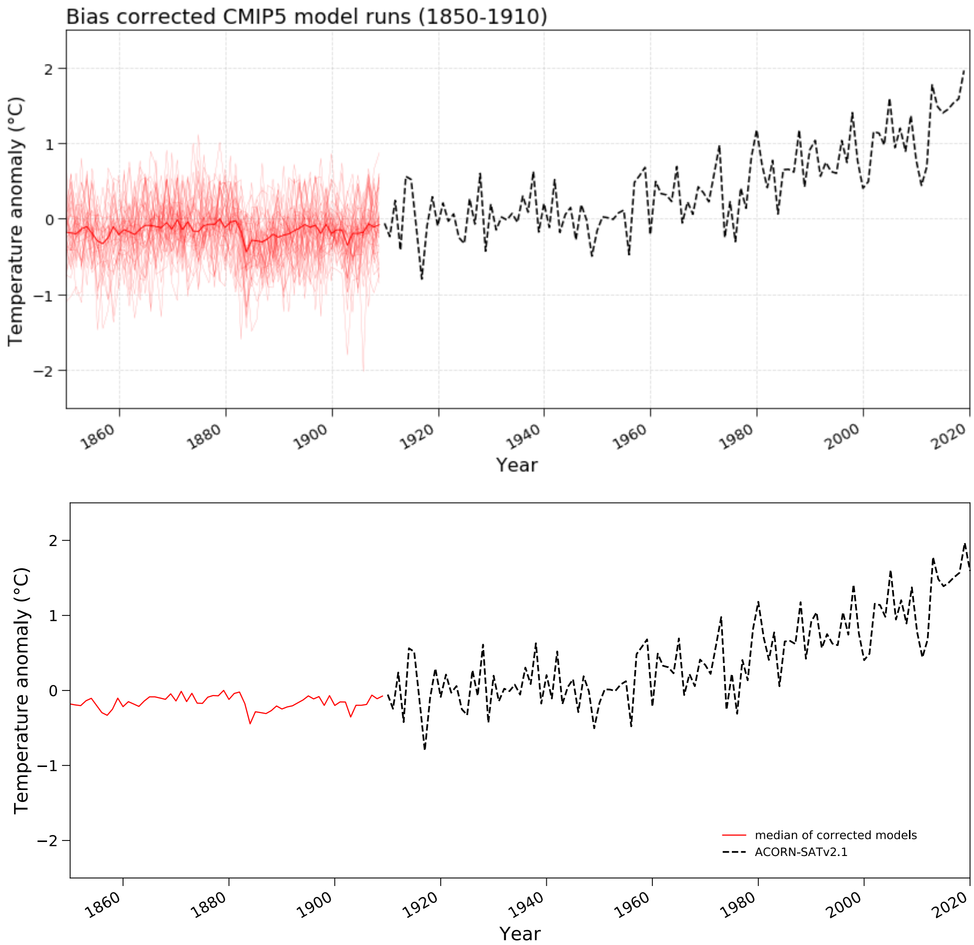

Figure 5: Australian averaged annual temperature in observations from 1910 to 2019 (black dotted line) and estimated from bias corrected CMIP5 model outputs from 1850 to 1909 (individual models as thin red lines; median of corrected models as thick red line). Lower panel just shows model median for added clarity.

Method 5: Statistical method based on observed Australian to global warming ratio

Global mean temperature is likely to be more reliably estimated in 1850–1910 than regional temperature. Given this, a regression model can be used to derive the local temperature from the global temperature and estimate trends. However, there is considerable noise inherent in this regression – this relationship is in fact used to estimate the 'noise' when estimating climate emergence (see Webpage 5).

Here the linear regression model is calculated from 1910 to 2019, then used to generate a predicted regional time series with confidence bounds for the entire 1850–2019 period (**Figure 6**). The difference between 1850–1900 and 1910–1930 is then calculated, allowing for the confidence bounds.

The results show:

- The predicted series has the variability and short-term trends of the global temperature series, which are sometimes counter to the local temperature trends (e.g. see 1940 to 1980 in **Figure 6**), however 20 to 40 year trends are likely small in 1850 to 1920, so the error introduced is likely reduced compared to the mid-20th century
- The confidence intervals are at around 0.2 °C through the series (0.1 to 0.3 °C)
- The difference between the two periods is between 0.0 and 0.2°C for Australia, and between -0.1 and 0.2 °C for every state and territory (medians are all 0.1°C except for Tasmania which is 0.05 °C, see **Figure S5**)
- This technique is not suitable for deriving an estimate of change but is presented as an independent check, and it does confirm that the range of 0.0 to 0.2 °C for Australia does align with other results.

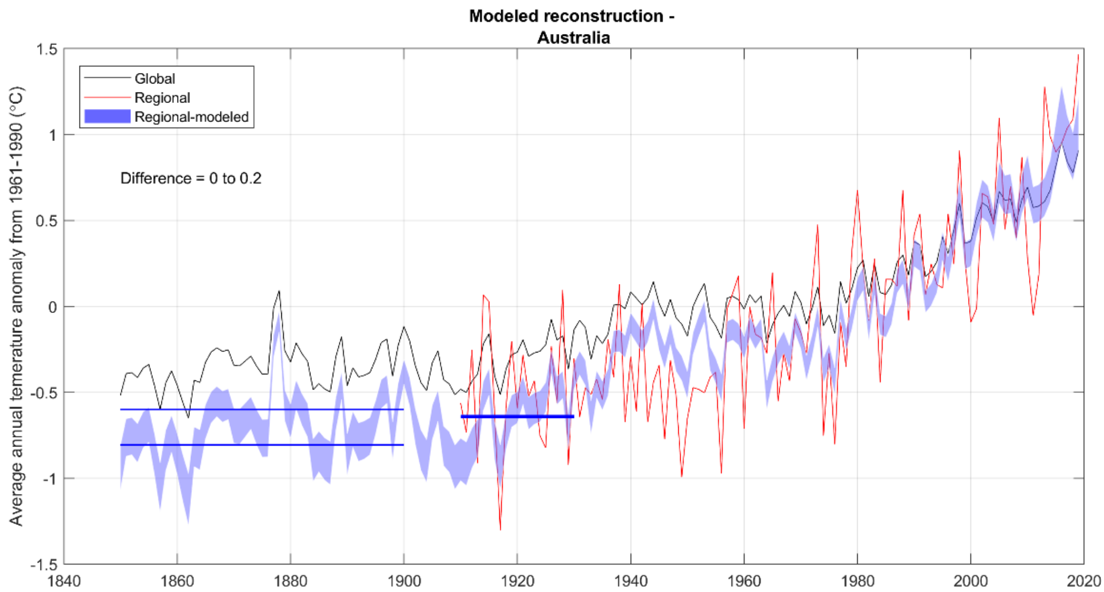

Figure 6: GMST and Australian average annual mean temperature anomalies from 1961-1990 (black and red lines respectively), and a predicted timeseries for regional temperature based on linear regression with global temperature in the overlap period with confidence bounds (blue band). Differences between the modeled mean in 1910–1930 and the high and low end of the confidence bound in 1850–1900 are marked as blue lines.

Discussion and summary: estimation of change since 1850-1900 and associated uncertainty

Figure 7 and **Table 3** summarize our estimation of temperature change from 1850–1900 to 1910–1930 for Australia and individual states and territories, provided by each of the four methods described in this note (after using the fifth method of statistical regression against global temperature as a check but then not using it further). Uncertainty ranges are also shown, based on low/high percentiles or standard deviation/spread across datasets and models (**Table 2**). These methods provide quite different estimates, ranging from a slight cooling (e.g. in NT, TAS or VIC) based mostly on global observational datasets, to higher and more uniform warming based mostly on climate models (e.g. in VIC and QLD). With larger sample size, the models estimate a more consistent warming of about 0.20 °C which is uniform across states.

On Website 4, we use this median model estimation of change between 1850–1900 to 1910–1930 to add to the ACORN-SATv2.1 observed temperature record which is shown relative to 1910–1930 (e.g. **Figure 1a**). However, given these large disparities, we have decided to provide the most conservative estimate of change by accounting for the minimum and maximum of uncertainty bounds detected across all methods for each state and territory (shown in blue and red respectively in **Table 2**). This estimate of the uncertainty bound is added onto the whole observed time series and shown as a grey band on webpages 5 and 6, an example is shown here in **Figure 8**.

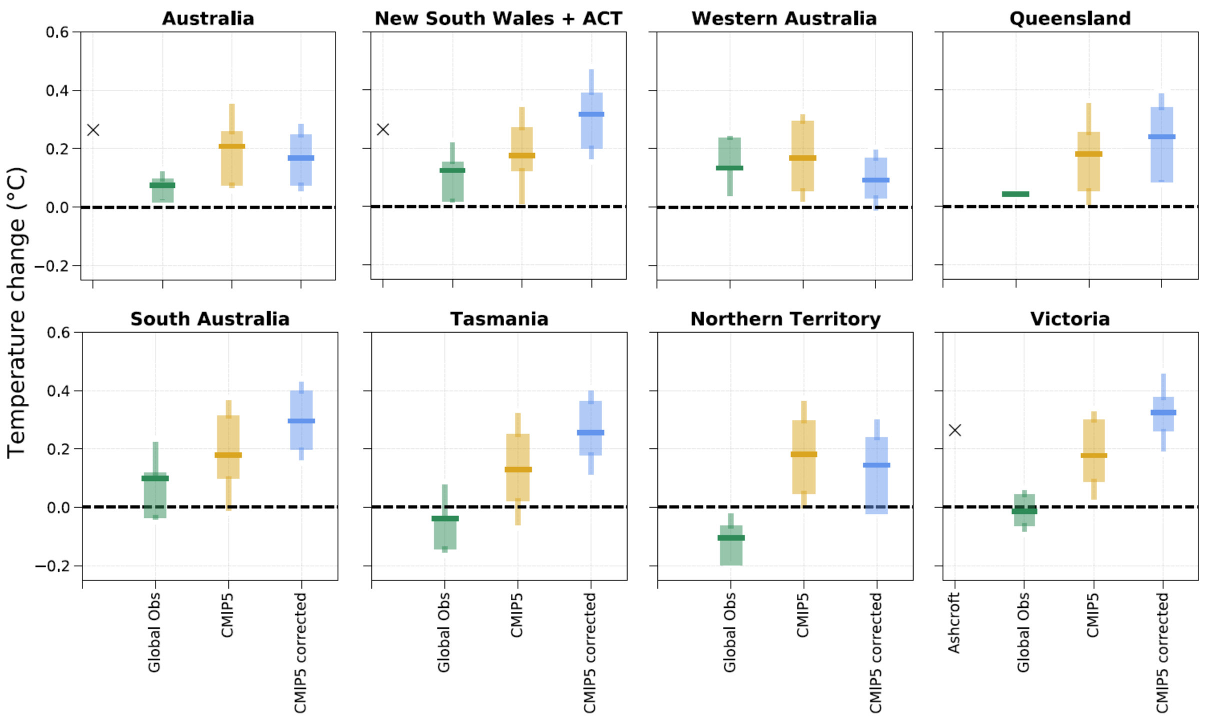

Figure 7: Estimation of temperature change from 1850-1900 to 1910-1930 for Australia and each state and territory, based on the four methods detailed in this note. Note the Ashcroft reconstruction method only provides an estimate for VIC, NSW and possibly Australia. The median value is shown with a horizonal line and whiskers provide an estimation of uncertainty associated with each method (see **Table 2**).

Table 2. Estimated average temperature change from 1850-1900 to 1910-1930 for Australia and each state and territory, based on the 4 estimation methods detailed in this note. The median value is listed, along with uncertainty estimates from associated percentile and standard deviation values. For each state and territory, the minimum (maximum) estimated warming is shown in blue (red).

		Australia	NSW + ACT	WA	QLD	SA	TAS	NT	VIC
1. Early Historical Record	Median	0.26	0.26						0.26
	Uncertainty	N/A	N/A						N/A
2. Global gridded datasets	Median	0.07	0.00	0.18	0.04	0.08	-0.04	-0.10	-0.03
	25th percentile	0.00	-0.02	0.13	-0.01	-0.05	-0.14	-0.18	-0.07
	75th percentile	0.10	0.12	0.22	0.04	0.16	-0.04	0.00	-0.01
	-1 standard dev	0.02	-0.11	0.04	-0.03	-0.06	-0.13	-0.21	-0.11
	+1 standard dev	0.13	0.10	0.32	0.10	0.22	0.05	0.01	0.06
3. CMIP5	Median	**0.21**	**0.17**	**0.17**	**0.18**	**0.18**	**0.13**	**0.18**	**0.18**
	25th percentile	0.08	0.12	0.06	0.05	0.10	0.02	0.05	0.09
	75th percentile	0.26	0.27	0.29	0.25	0.31	0.25	0.30	0.30
	-1 standard dev	0.05	0.00	0.01	-0.01	-0.02	-0.07	-0.01	0.02
	+1 standard dev	0.36	0.35	0.33	0.36	0.38	0.33	0.37	0.34
4. CMIP5 bias corrected	Median	0.17	0.32	0.09	0.24	0.30	0.26	0.14	0.32
	25th percentile	0.08	0.20	0.03	0.08	0.20	0.18	-0.02	0.26
	75th percentile	0.25	0.39	0.17	0.34	0.40	0.36	0.24	0.38
	-1 standard dev	0.04	0.15	-0.02	0.08	0.15	0.10	-0.02	0.18
	+1 standard dev	0.29	0.48	0.21	0.40	0.44	0.41	0.31	0.47

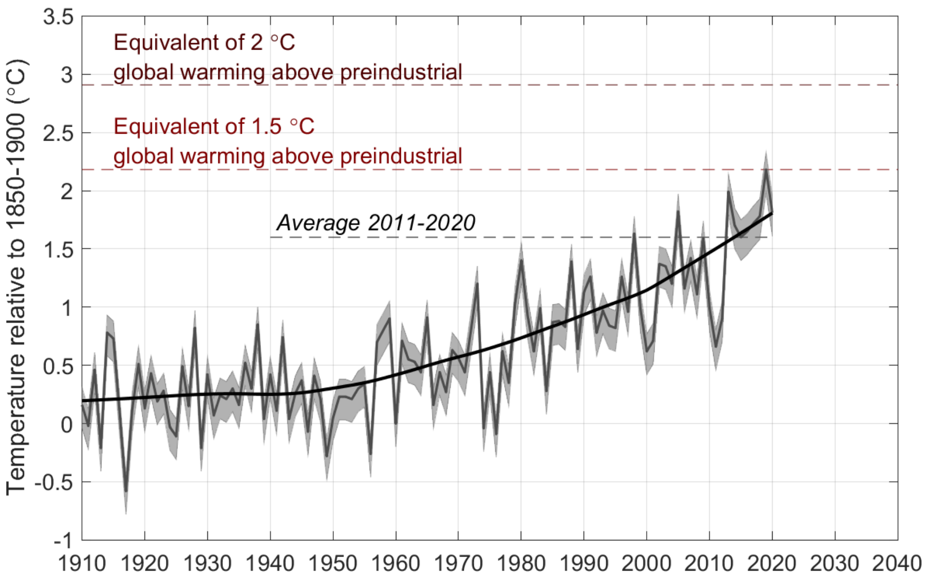

Figure 8. An example plot from the web pages showing the temperature series for Australia relative to 1850–1900, using the median CMIP5 warming for 1850–1900 to 1910–1930 (+0.21 °C), and the maximum and minimum value shown as an error band (+0.04 to +0.36 °C)

Supplementary figures:

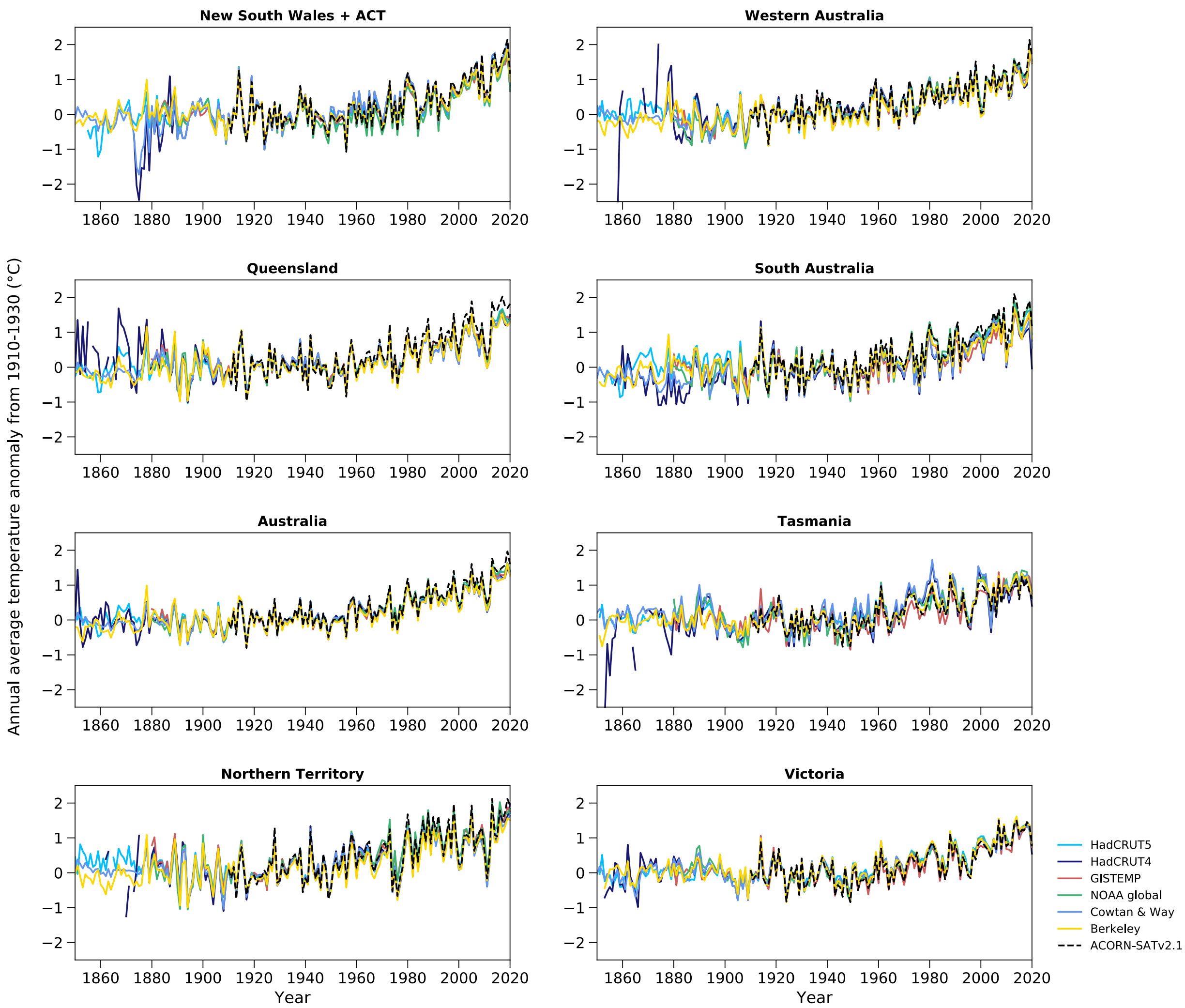

Figure S1: Same as **Figure 1b** for Australian states and territories. Note that HadCRUT4 temperature is only calculated at a given timestep when data is available at a minimum of 3 grid point location for each state and territory.

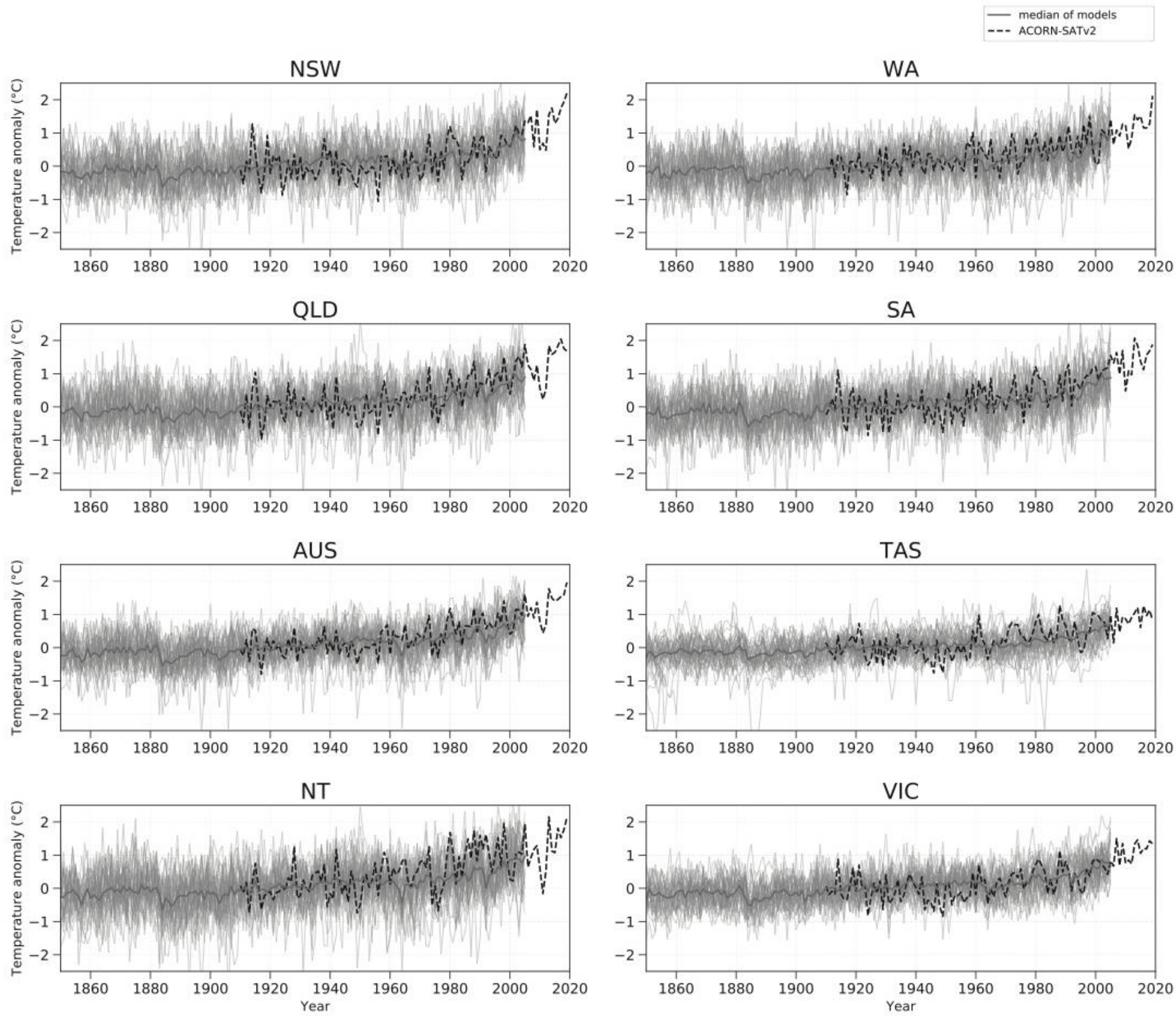

Figure S2a: Same as **Figure 1c** for Australian states and territories. Each grey line corresponds to one model simulation and the thick grey line represents the median of model estimations.

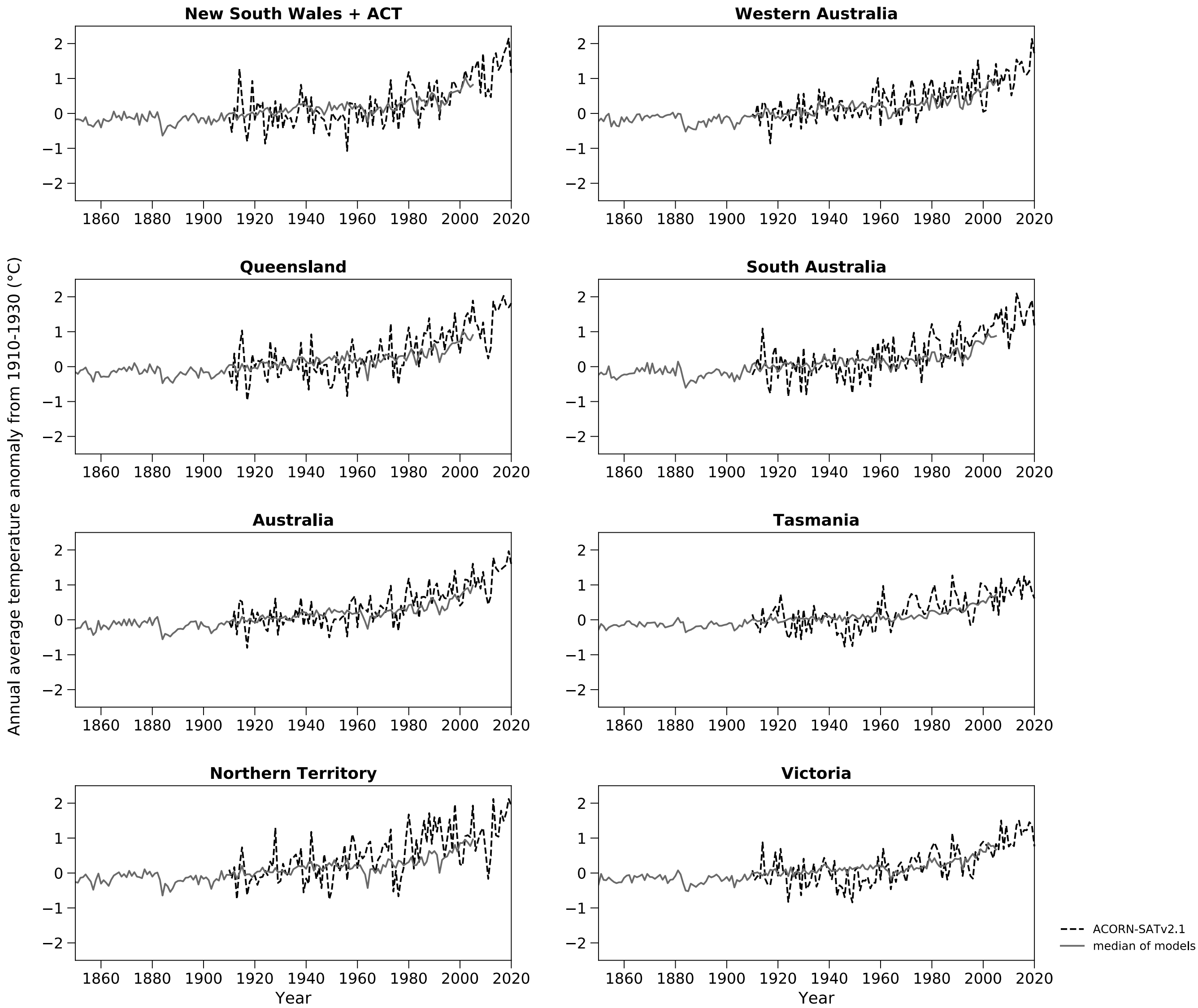

Figure S2b: Same as **Figure 1c** for Australian states and territories. Only the median of model estimations is shown for added clarity.

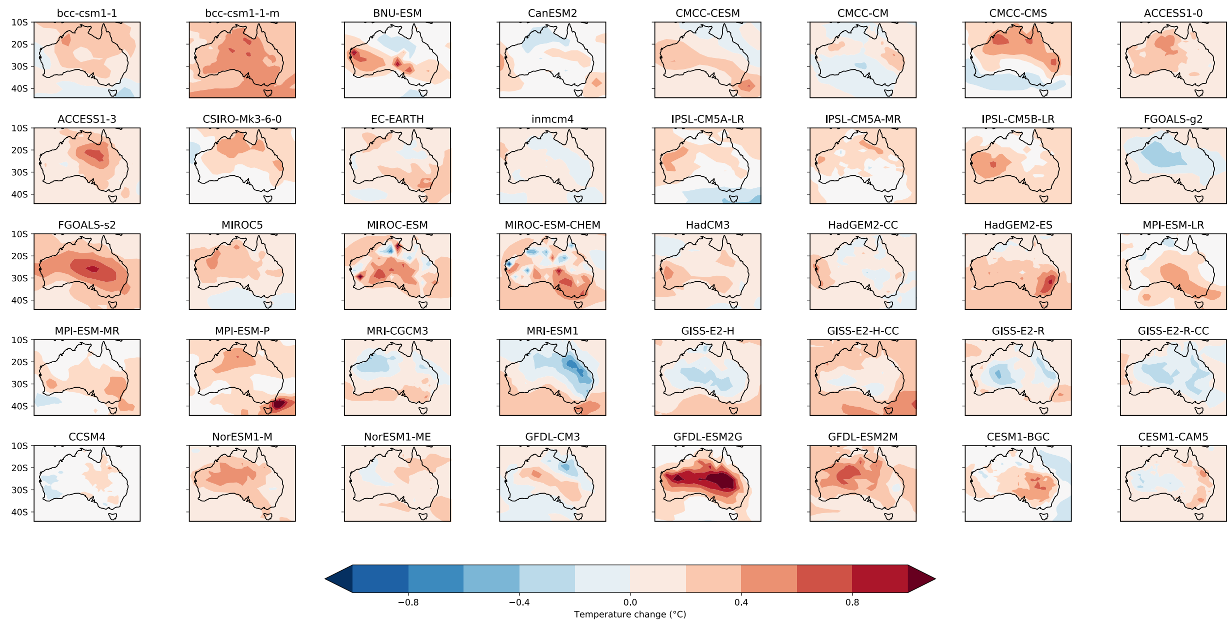

Figure S3: Temperature change from 1850-1900 to 1910-1930 over Australia as simulated by historical runs from global CMIP5 models.

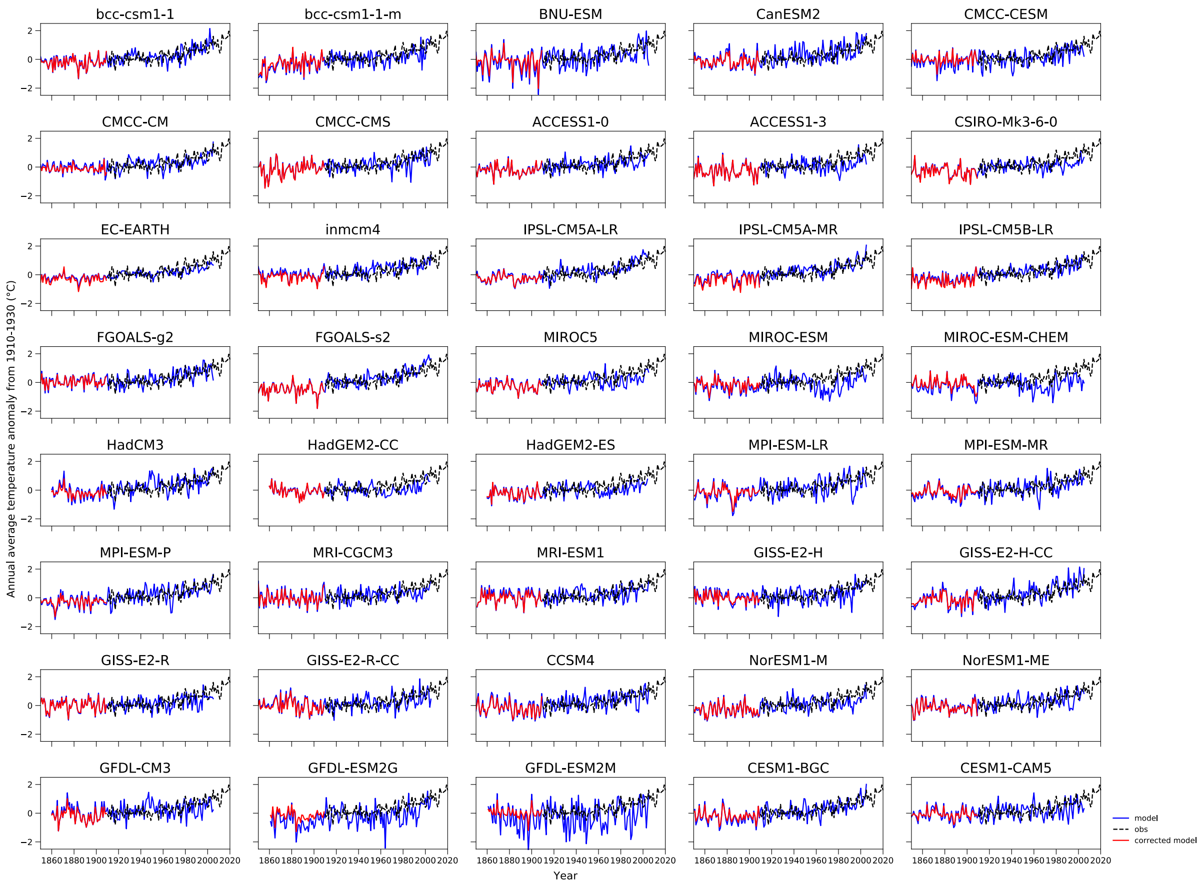

Figure S4: Australian averaged annual temperature anomalies in observations from 1910 to 2019 (black dotted line) and estimated from bias corrected CMIP5 model outputs from 1850 to 1909 (in red). Bias correction is applied to each model simulation and results are shown for individual models in the bottom panels.

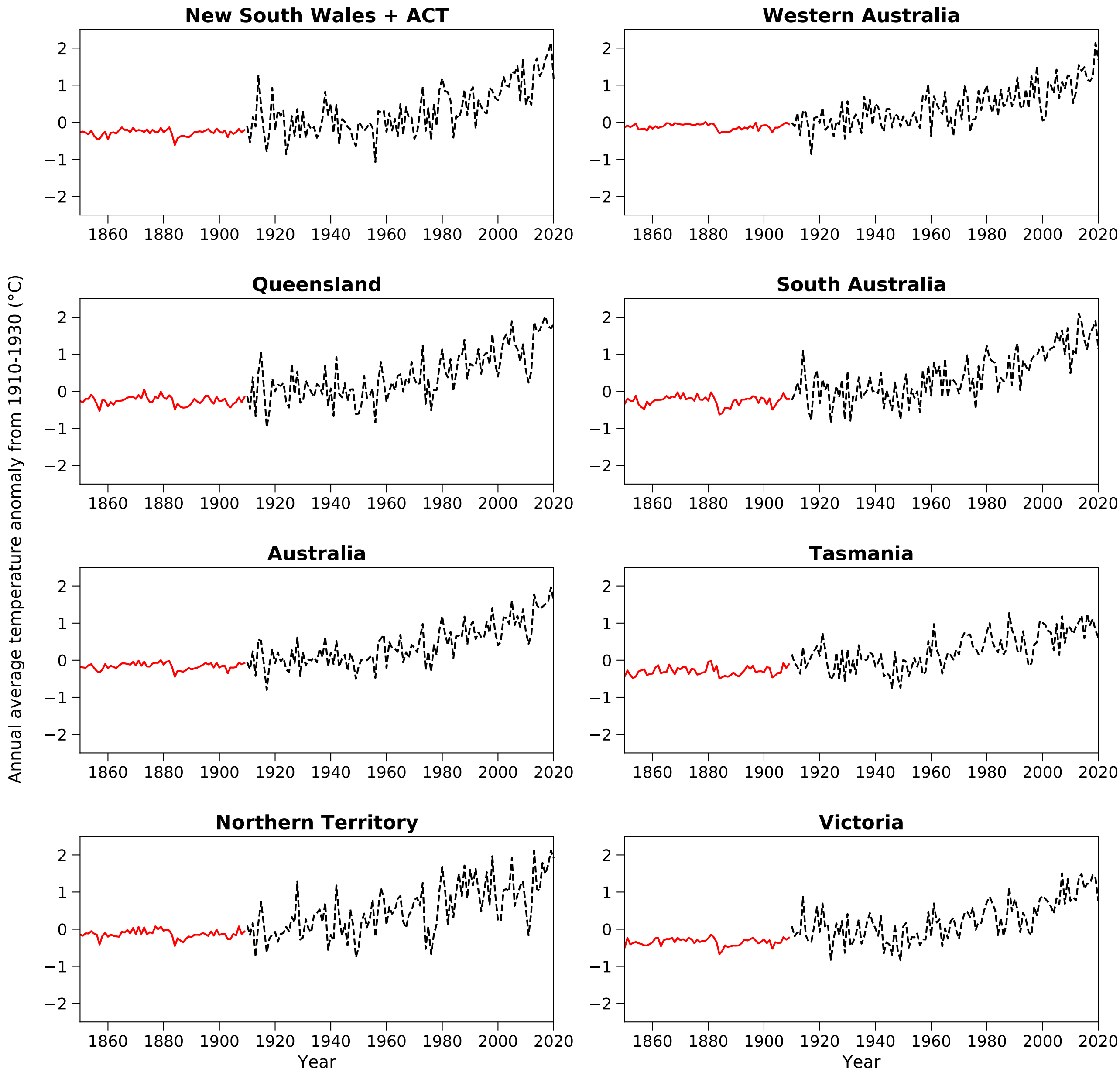

Figure S5: Same as **Figure 5 (lower panel)** but for Australian states and territories.

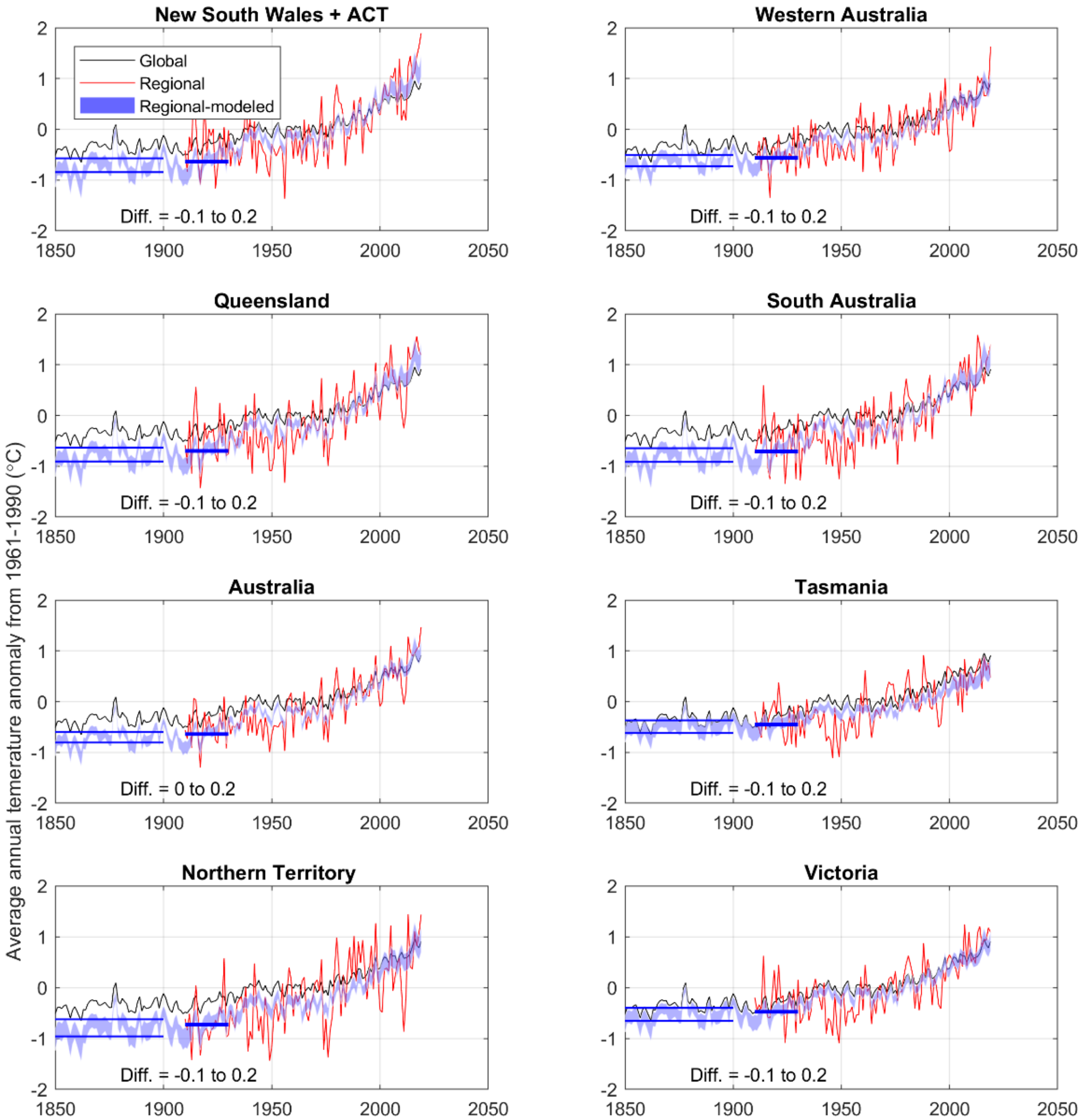

Figure S6. As for **Figure 6**, but for Australian states and territories

References:

Amengual, A., Homar, V., Romero, R., Alonso, S., & Ramis, C. (2012). A statistical adjustment of regional climate model outputs to local scales: application to Platja de Palma, Spain. Journal of Climate, 25(3), 939-957. http://journals.ametsoc.org/doi/pdf/10.1175/JCLI-D-10-05024.1

Ashcroft, L., Karoly, D., & Gergis, J. (2012). Temperature variations of southeastern Australia, 1860–2011. *Australian Meteorological and Oceanographic Journal*, *62*, 1860–2011. http://www.bom.gov.au/amoj/docs/2012/ashcroft.pdf

Cowtan, K., & Way, R.G. (2014). Coverage bias in the HadCRUT4 temperature series and its impact on recent temperature trends. *Quarterly Journal of the Royal Meteorological Society*, *140*(683), 1935–1944. https://doi.org/10.1002/qj.2297

Gergis, J., Neukom, R., et al. (2016) Australasian Temperature Reconstructions Spanning the Last Millennium. Journal of Climate, vol.29,no.15, pp. 5365-5392. doi:10.1175/JCLI-D-13-00781.1

Hawkins, E., Ortega, P., Suckling, E., Schurer, A., Hegerl, G., Jones, P., et al. (2017). Estimating changes in global temperature since the pre-industrial period. *Bulletin of the American Meteorological Society*, BAMS-D-16-0007.1. https://doi.org/10.1175/BAMS-D-16-0007.1

Huang, B., Menne, M.J., Boyer, T., Freeman, E., Gleason, B.E., Lawrimore, J.H., et al. (2020). Uncertainty Estimates for Sea Surface Temperature and Land Surface Air Temperature in NOAAGlobalTemp Version 5. *Journal of Climate* 33: 1351-1379.

Lenssen, N., G. Schmidt, J. Hansen, M. Menne, A. Persin, R. Ruedy, and D. Zyss, 2019: Improvements in the GISTEMP uncertainty model. *J. Geophys. Res. Atmos.*, **124**, no. 12, 6307-6326, doi:10.1029/2018JD029522.

Morice, C.P., J.J. Kennedy, N.A. Rayner, J.P. Winn, E. Hogan, R.E. Killick, R.J.H. Dunn, T.J. Osborn, P.D. Jones and I.R. Simpson (in press) An updated assessment of near-surface temperature change from 1850: the HadCRUT5 dataset. Journal of Geophysical Research (Atmospheres) doi:10.1029/2019JD032361

Rohde, R.A., & Hausfather, Z. (2020). The Berkeley Earth Land/Ocean Temperature Record. *Earth System Science Data Discussions*. Retrieved from https://essd.copernicus.org/preprints/essd-2019-259/

Taylor, K.E., Stouffer, R.J., & Meehl, G.A. (2012). An Overview of CMIP5 and the Experiment Design. *Bulletin of the American Meteorological Society*, *93*(4), 485–498. https://doi.org/10.1175/BAMS-D-11-00094.1

Trewin, B., Braganza, K., Fawcett, R., Grainger, S., Jovanovic, B., Jones, D., Martin, D., Smalley, R., & Webb, V. (2020). An updated long-term homogenized daily temperature data set for Australia. Geoscience Data Journal, gdj3.95. https://doi.org/10.1002/gdj3.95

Zhang, H.-M., Huang, B., Lawrimore, J., Menne, M., Smith, T.M. (2020). NOAA Global Surface Temperature Dataset (NOAAGlobalTemp), Version 5. NOAA National Centers for Environmental Information. doi:10.25921/9qth-2p70. Accessed May 2020.

Contact for more information: Michael Grose (CSIRO): Michael.Grose@csiro.au