Australian warming: observed change and global temperature targets

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Key Points:

- Australia has warmed by around 1.5 °C since the early industrial era of 1850–1900, more than the global average.
- The ratio of historical regional to global warming in many global climate models is less than observed in Australia and many other areas.
- Observations and model outputs can be combined to visualize regional warming to date and progress towards global warming targets.

Abstract

Quantifying warming of the Earth's climate system since the late 19th century and the ratio of regional to global warming are required when examining implications of Paris Agreement global warming targets. To estimate these terms reliably, the limitations in quality and length of observed records, differences between climate models and observations, and different results dependent on temporal and forcing contexts must be taken into account. Here we use observational datasets currently available back to 1860 and the latest set of global climate model simulations from CMIP5/6 to examine the warming of Australia in the past and projected future. We find that Australia has warmed by 1.5 °C (1.3–1.8 °C) during 1850–2019, at a ratio of ~1.4 times the global warming of ~1.1 °C. Models generally produce a lower ratio of Australian to global warming than in observations, which may be related to model biases or internal climate variability.

Plain Language Summary

The Paris Agreement of 2015 aims to keep global average warming below 2 °C above pre-industrial times. There is interest in understanding the temperature change in individual countries since pre-industrial times, how this compares to the global average, and what the local temperature will be when the global temperarture is at 2 °C above preindustrial. For Australia, there are barriers to this understanding including practical issues of definitions, but also incomplete and incorrect temperature observations prior to 1910, and complications with using climate models. In this study we examine various datastes and models to estimate that Australia has warmed by around 1.5 °C since 1850–1900 , which is around 1.4 times the global average. We present the change in context on a time series plot, including progress towards global warming levels. The methods used here are applicable in other countries, and we identify regions where climate models produce a different ratio of regional to global warming compared to observations.

1 Introduction

Since the Paris Agreement in 2015, there has been strong interest in assessing regional climate change at defined global warming levels of 1.5 and 2 °C since the pre-industrial era (or at least since 1850–1900 as an 'early industrial' baseline; Hawkins et al., 2017; Schurer et al., 2017). These assessments require an estimate of both global and regional change since this baseline period. Both the global and especially the regional change since 1850–1900 are uncertain since data are sparse prior to the 20th century in many places (e.g. Morice et al., 2012). Limited standardisation of instruments and observational procedures in the 19th Century adds additional uncertainty to global and regional averages. Calculating the regional warming associated with future global warming targets is a topic of great interest as countries seek to mitigate the impacts of climate change (e.g. Harrington et al., 2018). It is therefore useful to provide information on a set of possible regional climate changes as the global climate stabilises or passes through the Paris Agreement warming levels. However, this requires estimating the ratio of regional to global temperature increases through different rates of change of global warming, ranging from near-equilibrium states to continued rapid warming, and under different combinations of greenhouse gas and aerosol forcings.

There are various methods to estimate warming, using both observational datasets and climate models. Here we examine several methods for estimating warming since 1850–1900 to the present and in future projections in Australia and in the global average. This enables the calculation of the ratios of regional to global warming to the present and under future warming level targets and under different forcing scenarios, and illustrate the range of issues involved. Australia, like most places in the world, has no high-quality long-term observational temperature series for the full post-1850 period, so we use quality-controlled temperature series back to 1910 and a more limited range of observations available from 1860.

2 Data and Methods

2.1 Datasets

The Australian mean annual temperature anomaly (using a 1961–1990 baseline) for the 1910–2019 period is derived from the homogenised, Australia-wide temperature records in the Australian Climate Observations Reference Network - Surface Air Temperature version 2 (ACORN-SATv2; Trewin et al., 2020). ACORN-SATv2 comprises daily temperature observations from 112 locations across Australia that have been thoroughly examined for non-climatic influences and inhomogeneities.

The global mean annual temperature (median estimate) is taken from HadCRUT4 (1850–2019; Morice et al., 2012), Berkeley Earth (1850–2019; (Rohde & Hausfather, 2020), NOAA GlobalTemp (1880–2019; Huang et al., 2019; Zhang et al. 2020), Cowtan and Way (1850–2019; Cowtan & Way, 2014) henceforce referred to as CW; and GISTEMP (1880–2019; Lenssen et al., 2019). Australian mean annual temperature is also derived from these global gridded datasets for comparison with ACORN-SATv2.

Mean annual temperature for Australia and the globe in Run 1 from up to 35 models contributing to Coupled Model Inter-comparison Project phase 5 (CMIP5; Taylor et al., 2012) and 20 models from phase 6 (CMIP6; Eyring et al., 2016) to 2100 are also examined and compared to observed estimates (Table S1).

Future projections were examined under two Representative Concentration Pathways (RCPs) of van Vuuren et al. (2011) for CMIP5: RCP2.6 (24 models) and very high RCP8.5 (35 models), and the roughly equivalent Shared Socio-economic Pathways (SSPs) of Meinshausen et al. (2019) for CMIP6: SSP1-26 and SSP5-85 (20 models, 30 models for historical spatial analyses). At the global scale, two aspects to be considered are (a) that model fields are globally complete whereas observed data sets have gaps in spatial coverage which are treated differently; and (b) observed global mean annual temperature anomalies are surface air temperature over land and sea surface temperature over ocean, whereas models use surface air temperature for the whole globe (see Cowtan et al., 2015; Richardson et al., 2018; Simmons et al., 2017). Neither issue would be expected to have a major impact on model-observation comparisons over the Australian continent.

2.2 Extending the Australian temperature record before 1910

Before the 1900s, very limited data are available from Western Australia or the Northern Territory, and there are almost no available data outside mainland southeast Australia before the mid-1870s. There are also substantial inhomogeneities in the dataset as a result of the wide range of instrument exposures in use prior to the introduction of the Stevenson screen as a standard. The change to Stevenson screens was largely complete by the mid-1890s in Queensland, South Australia and the Northern Territory, but did not occur in New South Wales and Victoria until 1906–1908 (Nicholls et al., 1996). The observed dataset for southeast Australia in Ashcroft et al. (2012) addresses these homogeneity issues (e.g. adjusting for the introduction of the Stevenson screen), and uses monthly observations from 38 long-term stations to calculate a regional average over 138–154 °E, 24–40 °S (land-masked).

While global gridded datasets extend prior to 1910, the data quality and availability in the early record is often poor and there is not adequate handling of Australian data taken in a non-standard way. Different datasets disagree by more than 1 °C for some years, and there are cases of extreme hot anomalies (e.g. 1851 in HadCRUT4) that appear unrealistic (Figure S1b). Also, the Australian mean annual temperature in global datasets will differ from the official record of ACORN-SATv2 for 1910–2019 because of different methods of spatial interpolation and, in some cases, different homogenisation methods and/or station selection. To derive an estimate of Australian warming since 1850 that uses the benefits of ACORN-SATv2 and overcomes some of the problems with the global datasets, we have explored three options:

1. Stitching the estimate from global gridded datasets for 1850–1910 to ACORN-SATv2 for 1910–2019. Here we used CW as this series shows the fewest unrealistic hot anomalies in the 1850–1910 period, likely due to the improved kriging technique used compared to HadCRUT4. We used the period 1910–1930 to calibrate the two datasets to the same baseline. Titled *CW-ACORN*

2. Stitching Ashcroft et al. (2012) for 1860–1910 to ACORN-SATv2 for 1910–2019, again using the common 1910–1930 period baseline. Stitching a dataset for the southeast to an Australia-wide value assumes that the variability and trends in southeast Australia are broadly representative of the nation. Correlations between the datasets suggest this assumption is valid, as the annual SEA and Australia series correlation R = 0.90, 11-year running average R = 0.98. Additionally, 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 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. Titled *Ashcroft-ACORN*.

3. Stitching a set of synthetic linear series for 1850–1910 to ACORN-SATv2 for 1910–2019. The series use the range of plausible linear trends from global datasets, with changes ranging from -0.2 °C to +0.3 °C over the 60 years. Titled *Linear-ACORN*

Time series for all observed and 'stitched' datasets are shown in Figure S1. These three approaches give us a range of possible 'truths' for warming over Australia during the data sparse 1850–1910 period.

2.3 Historical and projected change

Here we examine historical temperature change in the observed period for Australia and the globe, and the ratio between them, in all relevant datasets and model outputs. Historical change is estimated using two methods (Figure 1a): the difference between the historical baseline (1850–1900 or as much data are available within this period) and the recent ten-year period (following current IPCC standard practice); and total change from the historical baseline and the year 2019. The 2019 value in this context was defined using a 41-year Lowess smoother, which was applied to distinguish the secular trend distinct from inter-annual or decadal variability (after Hawkins et al., 2020). Temperature change estimated using a linear trend for 1910–2019 has historically been the standard Bureau of Meteorology practice but now does not describe the change adequately (Fawcett et al., 2012).

Projected temperature changes and the Australia to global ratio in CMIP5 and CMIP6 are examined using the difference between 2081–2100 and 1850–1900 and also at 1.5 °C and 2 °C global warming levels using the time sampling method (see James et al., 2017). Here we examine the first crossing of the warming level relative to 1850–1900 by the smoothed series to estimate the Austrlaian equivalent, which is commonly used but is not a full analsyis of the Paris Agreemnt long-term temperature goal that includes long-term implications to the carbon budget (Rogelj et al. 2017).

3 Results

3.1 Historical change

Global average temperature change are similar across the five global datasets measured as a difference (0.9 to 1.1 °C) and smoother (1.0 to 1.2 °C; Figure 1b, Table 1). Berkeley gives the highest estimate and HadCRUT4 gives the lowest. Global land warming is greater than ocean warming (IPCC 2019), and changes for the global land area using the difference method are 1.4 °C for HadCRUT4 and 1.6 °C for Berkeley (1.6 and 1.8 °C respectively using the smoother method).

For Australia, estimates are lower for the difference method (CW-ACORN 1.4 °C, Ashcroft-ACORN 1.6 °C) than for smoother (1.6 °C and 1.8 °C), expected given the positive trend in 2010–2019 and record temperature in 2019. These values are typically higher than the change of 1.4 °C in 1910–2019 using a linear fit used previously, but as mentioned in the methods this is no longer a good fit for the data. Temperature change in 1910–2019 is 1.5 °C using a second-order polynomial fit and by taking the difference between the start and end date, which is a possible alternative to the linear fit. Global datasets give lower estimates (Table 1), suggesting trends are generally suppressed compared to ACORN-SATv2 and closer to those that existed in ACORN-SATv1 (Trewin et al., 2020). This is the case both for the HadCRUT4 dataset (which explicitly uses ACORN-SATv1 as source data) and the other datasets (which carry out their own homogenisation). This may reflect the emergence of new findings on the homogeneity of post-1990s Australian temperature data, as the most recently reassessed of the global data sets, NOAAGlobalTemp, shows the strongest warming trend. Menne et al. (2018) found that version 4 of the Global Historical Climatology Network data set (which forms the land data source for the NOAA and NASA datasets) showed stronger warming over Australia than the earlier version.

Changes before 1910 in Australian mean annual temperature in CW-ACORN and Ashcroft-ACORN are between -0.2 and 0.1 °C when measured as a linear trend over the period before 1910. Using the synthetic linear data between 1850 and 1910 with changes of between -0.2 to +0.2 °C stitched to ACORN-SATv2 (Figure S1), changes to 2019 roughly bracket the range of possible warming values in the various observed datasets: 1.4 to 1.8 °C.

These historical changes are in line with other reconstructions using early hisrtorical datasets, including the small trends found in Australasian September–February temperature in 1860–1910 by Gergis et al. (2020). The changes are also consistent with treering paleocliamte records, such as the small 60-year trends in the 1731–1910 period for cool season temperature in southeast Australia (Allen et al. 2019).

The ratio between Australian to global warming is noisy until a stronger signal emerges in the late 20th Century. In line with Austrlaian warming, the ratio is lower in global datasets than comparing between Ashcroft-ACORN and global (Table 1). The ratio of Australian temperature change to global land is 0.7 to 0.9 in global datasets and 0.8 to 1.2 when using ACORN-SATv2-based estimates for Australia.

The historical change in CMIP5 and CMIP6 spans a greater range than observations, and the Australian-global ratio varies widely between models for all cases of different warming levels and time periods (Table 1). Many models produced a ratio lower than any observational datasets, including values lower than one, and a high end consistent to that within global datasets (up to around 1.5) rather than the ratio of ACORN to global. Ratio values of Australian to global warming are generally lower in CMIP6 than CMIP5.

3.2 Future change, including global warming targets

The range of global and Australian temperature change to 2100 depends strongly on the forcing scenario, with Australian temperature change between 1850–1900 and 2081–2100 in the range 1.4 to 2.9 °C for SSP-126 and 3.7 to 7.4 °C for SSP-585 (5th-95th percentile range of 20 models). There is no significant and systematic difference in the range of Australian-global temperature change ratios between RCP/SSP or between warming levels, where the model range for a specific RCP/SSP or warming level is larger than any difference between RCP or SSP (Figure 2a).

Using the results from the smoother method, the ratio of Australian to global temperature change in 2019 is loosely correlated with the value in 2100 ($R = 0.73$), with a slope near the 1:1 line (Figure 2b). This suggests that an evaluation of the warming ratio to date is some guide to the ratio throughout the rest of the century. Given that the observed value is generally in the range 1.2 to 1.6 (Table 1), this suggests the projected changes from models with lower ratios are less plausible than the models with higher ratios for temperature to date and for the projected future.

Some insights into the different ratios in different models can be found looking at example simulations (Figure S2). Some simulations show a higher ratio partly due to a regional drying signal (GFDL-ESM2M RCP8.5), while others show a ratio less than one, due in part to periods of regional cooling and a projection of increased mean annual rainfall over most of Australia (MIROC-ESM, RCP8.5). Other simulations show low warming and a temperature decerase late in the century, creaitng a low signal-to-noise ratio, affecting the warming ratio (GFDL-ESM26 RCP2.6). These examples show that projected changes in circulation and rainfall, as well as climate the relative magnitude of variability and change all affect the simulation of the regional-to-global warming ratio in models.

3.3 Presenting Australian temperature change to date in relation to Paris targets

Plotting the Ashcroft-ACORN series relative to the 1860–1900 baseline, we can estimate warming to various historical baselines (Figure 3a), and this can be used to calibrate projected changes allowing for change since early industrial, such as done in Schurer et al. (2017) and other studies. This includes:

- 1961–1990 from World Meteorological Organization (WMO): +0.7 °C;
- 1986–2005 from IPCC Fifthe Assessment Report: +1.1 °C, higher than global value of +0.85 °C reported in IPCC (2013);
- 1995–2014 from IPCC Sixth Assessment Report: +1.3 °C.
- 2019: +1.8 °C (using smoother).

Modelled Australian temperature can be plotted relative to the the 1850–1900 baseline and annotated with lines of Australian temperature change equivalent to different global warming levels (Figure 3b). Here the ratio from observations and the top end of models of 1.4 appears plausible, given the timing of crossing these warming levels at the global average. Given this ratio, 2019 was equivalent to slightly warmer than an average year under a 1.5 °C global warming level. The 1.2x ratio (or lower) indicated by some models appears implausible, since according to this ratio, the 2 °C global warming level would have had to be almost crossed currently.

If we assume that the global warming estimate from each model is reliable, but the ratio of Australian to global warming is underestimated, then we can derive an Australian temperature projection from the global warming according to the observed ratio. In this case we show the global warming scaled by 1.4, producing a notably higher projected range than the raw model output (Figure 3b, right panel). If there is further evidence that the global projection is reliable but the ratio in models is too low, then these high projected changes should be considered possible.

3.4 Spatial context

The above analysis relates only to the Australian land average temperature to the global average, however there are notable spatial differences across Australia, and across the world. The spatial distribution of the ratio (using 1850–1900 to 2005–2014 to coincide with the end of CMIP6 hostorical simulations) directly follows the mean temperature change, featuring a maxima in the Arctic and large continents and minima in the Southern Ocean and north Atlantic Ocean in both CW and CMIP6 mean (Figure 4). The difference between the two (Figure 4c) shows differences of over 0.3 in much of Eurasia, the Arctic, Greenland, Africa, parts of the Americas, the Southern Ocean and Antarctic sea ice. However, the CW ratio is only outside the 5–95 percentile of the range of CMIP6 models in some of these areas (stippling in Figure 4c), in particular the maritime continent, north Atlantic, the Arctic and China.

The ratio in CW is lower than the CMIP6 mean in northern Australia, and in fact outside the 5–95% range of models in part of northwest Australia (Figure 4). This difference is related to the regional cooling experienced in this area, which is not reproduced in all models (Grose et al., 2016). In contrast, the ratio in CW is higher than CMIP6 in the southern part of Australia.

4 Conclusions

In this analysis we estimate pre-1910 warming in Australia and estimate the regional-to-global warming ratios to the present and projected future. We use multi-method approaches with local datasets, global gridded products and model projections to address issues of data scarcity and quality. Our results indicate an Australia-wide warming of ~1.5 °C since 1850–1900 (1.3 to 1.8 °C) , giving a ratio of ~1.4 times the global warming of around 1.1 °C over the same period. Model results offer a generally lower warming ratio than observation-based assessments for both historical and future periods, suggesting possible model biases or the influence of internal climate variability. These findings can be used to contextualize historical and future temperature change within Austrlaia to the global average during considerations of the Paris Agreement temperature change targets. The methods used in this study can also be applied to other regions around the world.

Acknowledgments, Samples, and Data

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Data used in the study are freely available from the relevant observed data portals (see references), the Earth Systems Grid Federation (ESGF) portal of climate model outpus (https://esgf-node.llnl.gov/projects/cmip6/ and https://esgf-node.llnl.gov/projects/cmip5/) and the Bureau of Meteorology website (http://www.bom.gov.au/climate/change), summary of data used available at http://doi.org/10.5281/zenodo.3956909.

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Table 1. Temperature change for the globe and for Australia and the ratio between them using Ashcroft, ACORN-SATv2, global gridded datasets and CMIP5/6 models. Change is measured as the difference between 1850–1900 and 2010–2019 (ACORN-Ashcroft is 1860–1900, NOAA and GISTEM are 1880–1900), and also as the difference between 1850–1900 and 2019 after a 41-year Lowess smoother is applied. Ratios of Australian to global change are calculated from within global datasets and models (Ratio) and to the ACORNSATv2 stitched to Ashcroft (Ratio ACORN).

Dataset	Difference 1850–1900 to 2010–2019				Smoother 1850–2019			
	Global (°C)	Australia (°C)	Ratio	Ratio ACORN	Global (°C)	Australia (°C)	Ratio	Ratio ACORN
ACORN-Ashcroft		1.6				1.8		
ACORN-C&W		1.4				1.7		
HadCRUT4	0.9	1.0	1.1	1.7	1.0	1.3	1.3	1.8
C&W	1.0	1.1	1.1	1.5	1.1	1.4	1.2	1.6
NOAA global	1.0	1.3	1.3	1.6	1.1	1.5	1.4	1.7
GISTEM	1.0	1.2	1.1	1.5	1.1	1.3	1.2	1.6
Berkeley	1.1	1.2	1.1	1.4	1.2	1.5	1.2	1.5
Mean	**1.0**	**1.2**	**1.2**	**1.6**	**1.1**	**1.4**	**1.2**	**1.6**
CMIP5 0 percentile	0.9	0.7	0.7		0.8	1.0	0.7	
10 percentile	0.9	0.9	0.9		1.0	1.0	0.9	
50 percentile	1.0	1.2	1.1		1.2	1.4	1.1	
90 percentile	1.1	1.5	1.4		1.6	1.8	1.2	
100 percentile	1.2	1.6	1.5		1.8	2.0	1.3	
CMIP6 0 percentile	0.9	0.6	0.7		1.2	1.0	0.7	
10 percentile	0.9	0.8	0.7		1.2	1.2	0.8	
50 percentile	1.1	1.0	0.9		1.5	1.4	1.0	
90 percentile	1.2	1.3	1.2		1.8	1.7	1.1	
100 percentile	1.3	1.3	1.3		1.9	2.0	1.2	

Figure 1. Measurement of temperature change in observed series: a) Ashcroft-ACORN data series relative to 1961–1990 (dark line shows ACORN-SATv2, faint line shows the Ashcroft series stitched to ACORN) with coloured lines illustrating: difference between data within 1850–1900 and 2010–2019 (blue) and 41-year Lowess smoother (red); b) global average temperature in the five global datasets relative to 1961–1990 with 41-year smoother indicated; c) Australian mean annual temperature anomaly in gridded datasets (black), 41-year smoother on global datasets (red) and in Ashcroft-ACORN with smoother (blue).

Figure 2. Ratios of Australian to global warming from different models for different ensembles and conditions, a). global warming targets and end of century; b). Ratio of Australian warming to global warming in model simulations from CMIP5 and CMIP6 under different RCP/SSPs in 2019 compared to 2099. Both panels show Run 1 from each model.

Figure 3. Mean annual Australian temperature relative to 1850–1900 in observations and projections, a). Ashcroft-ACORN with averages for various baselines marked; b). the 10th–90th percentile range of CMIP6 models under SSP-585 (red plume), SSP-126 (blue plume) and Ashcroft-ACORN (black line). Horizontal lines indicate the Australian equivalent for 1.5 °C (blue) and 2 °C (black) of global warming assuming a 1.4x ratio (faint dotted lines indicate a 1.2x and 1.6x ratio for 2 °C warming), and the dotted box indicates the 2081–2100 period used in the bars in the panel to the right, which shows the 10th–90th percentile range of CMIP6 models in 2081–2100, thinner dashed lines show the equivalent range using the global warming projection multiplied by 1.4 ratio.

Figure 4. The ratio of temperature change in each grid cell to the global average in observations and models, calculated as the difference between 1850–1900 and 2020–2019; a) in the Cowtan and Way gridded historical dataset; b) in the mean of 30 CMIP6 historical model simualtions, and; c) the difference between a and b, stippling denotes where the Cowtan and Way ratio is outside the 5–95 percentile of the CMIP6 model range.

Figure 1.

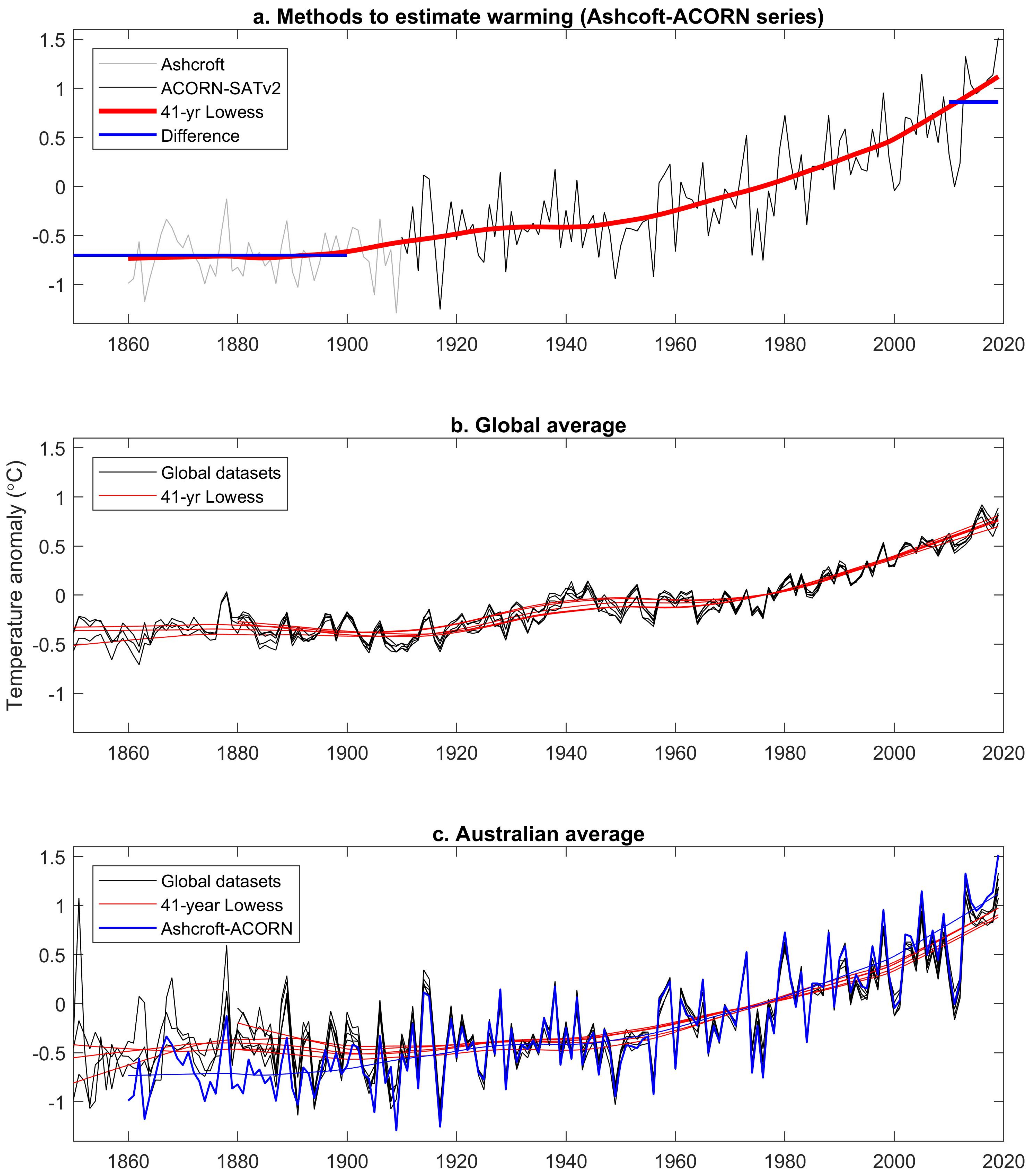

a. Methods to estimate warming (Ashcoft-ACORN series)
Ashcroft
ACORN-SATv2
41-yr Lowess
Difference
b. Global average
Global datasets
41-yr Lowess
Temperature anomaly (°C)
c. Australian average
Global datasets
41-year Lowess
Ashcroft-ACORN
1.5
1
0.5
0
-0.5
-1
1860
1880
1900
1920
1940
1960
1980
2000
2020

Figure 2.

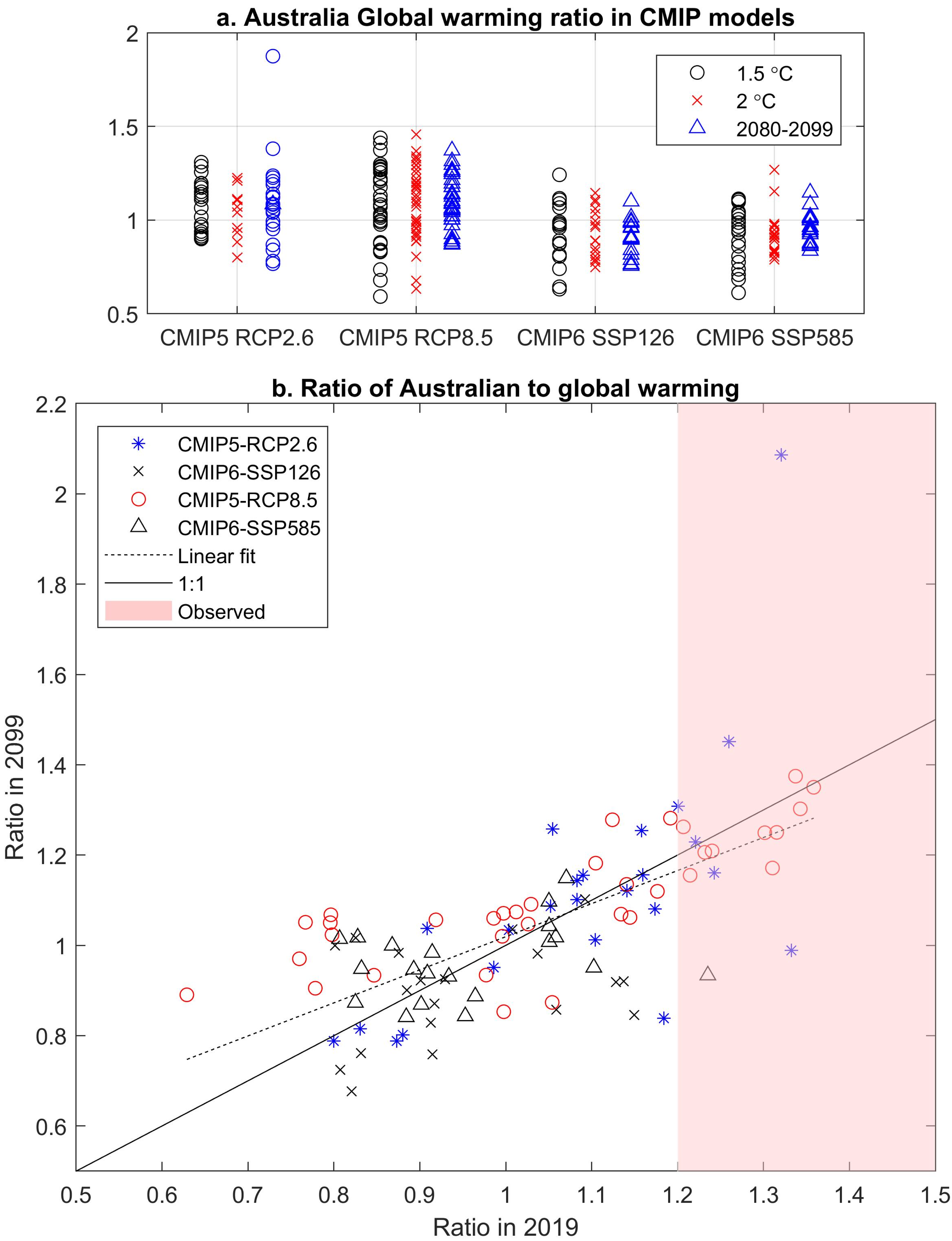
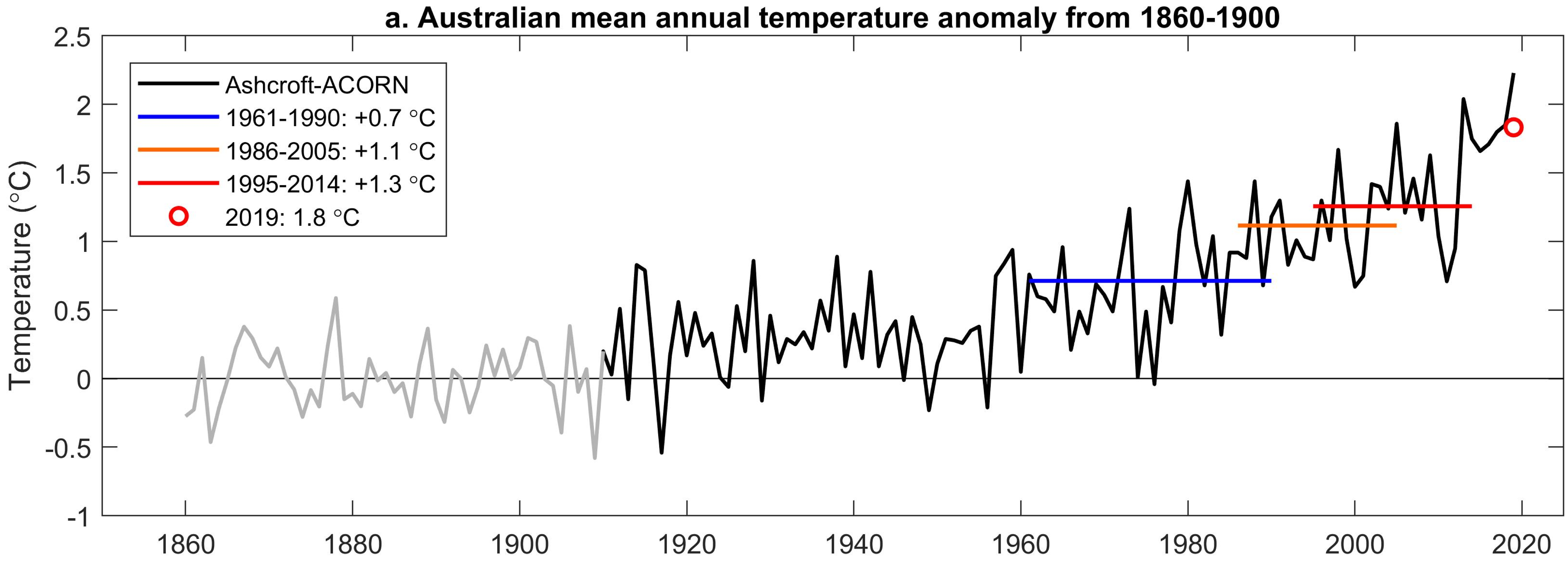

a. Australia Global warming ratio in CMIP models
1.5 °C
2 °C
2080-2099
CMIP5 RCP2.6
CMIP5 RCP8.5
CMIP6 SSP126
CMIP6 SSP585
b. Ratio of Australian to global warming
CMIP5-RCP2.6
CMIP6-SSP126
CMIP5-RCP8.5
CMIP6-SSP585
Linear fit
1:1
Observed
Ratio in 2099
Ratio in 2019

Figure 3.


a. Australian mean annual temperature anomaly from 1860-1900
Ashcroft-ACORN
1961-1990: +0.7 °C
1986-2005: +1.1 °C
1995-2014: +1.3 °C
2019: 1.8 °C
Temperature (°C)
2.5
2
1.5
1
0.5
0
-0.5
-1
1860
1880
1900
1920
1940
1960
1980
2000
2020

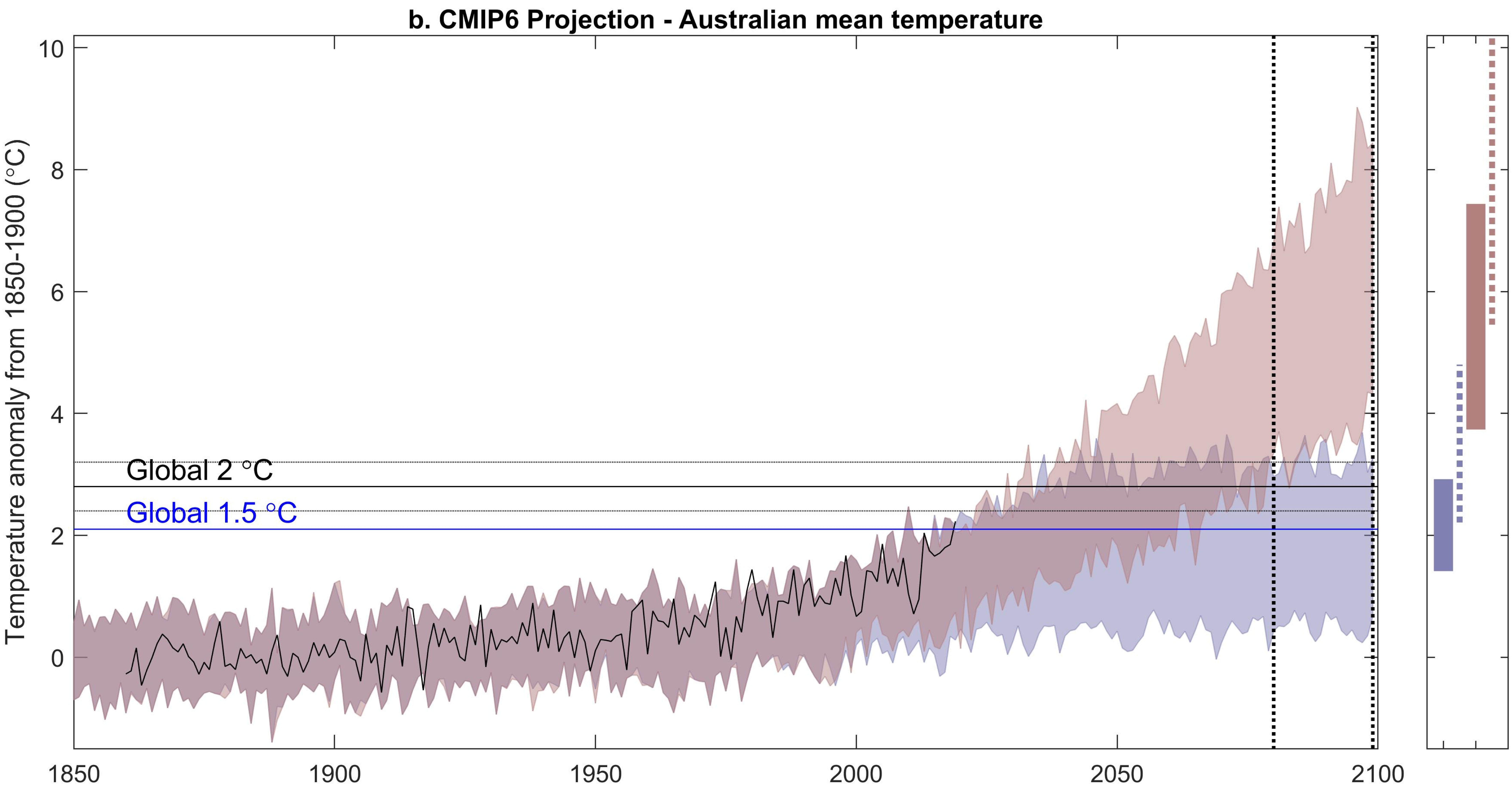

b. CMIP6 Projection - Australian mean temperature
Temperature anomaly from 1850-1900 (°C)
Global 2 °C
Global 1.5 °C
10
8
6
4
2
0
1850
1900
1950
2000
2050
2100

Figure 4.

a. Ratio to global warming 1850-1900 to 2010-2019, Cowtan and Way
b. CMIP6 mean
c. Difference