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A historical annual temperature dataset for Australia

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A high-quality historical surface air temperature dataset, for mean annual temperatures, has been prepared for Australia by adjusting data for inhomogeneities caused by station relocations, changes in exposure and other discontinuities. An objective procedure was developed for determining the necessary adjustments. Station history documentation was also used for this purpose. Time-series of annual mean maximum and mean minimum temperatures have been produced for 224 stations. Trends in annual mean maximum, minimum, the mean of the maximum and minimum, and the range between maximum and minimum, have been calculated at each site. The dataset provides adequate spatial coverage of Australia back to 1910 for the production of all-Australia average temperatures. Maximum and minimum temperatures have increased since about 1950, with minimum temperatures increasing faster than the maximum temperatures.

Introduction

A high-quality, long-term surface air temperature dataset is essential for the reliable investigation of climate change and variability. Most long-term observing sites will have been disturbed by changes in exposure or shifts in location at some time. Such changes usually introduce large discontinuities into the temperature time series. The presence of such discontinuities and inhomogeneities casts doubt on the representativeness of trends calculated from unadjusted temperature data. Production of a dataset for the credible calculation of long-term temperature trends requires the investigation, identification and adjustment of discontinuities using station history documentation (metadata) coupled with statistical techniques. Such techniques have been used here to produce an improved database of maximum and minimum temperatures for Australia, for the monitoring and detection of twentieth century climate change and variability.

Warming trends in Australian temperature have been identified in the past using unadjusted data (e.g. Tucker 1975; Coughlan 1979). Positive trends were also identified in shorter or smaller datasets that took into account urbanisation (Coughlan et al. 1990) and discontinuities (Balling et al. 1992; Plummer et al. 1995). Regional investigations have also identified warming trends in temperatures adjusted, or checked for discontinuities, in various areas around Australia (Shepherd 1991; Burrows and Staples 1991; Lough 1995).

Adjustment techniques have been developed and temperatures analysed both globally (Jones et al. 1986) and in other countries (e.g. Karl and Williams 1987; Rhoades and Salinger 1993). Of the many techniques used, those of Easterling and Peterson (1995) were seen to be the most successful and were used in this study, although with a new method for constructing a reference series.

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Data and method

Monthly temperature data are available for 1418 stations around the country with almost 100,000 station-years of combined maximum and minimum temperature data. However, the number of stations is much smaller if only stations currently operating and with at least 80 years of data are considered. To increase the number of long-term stations available, previously unused data were digitised and a number of stations were combined to cre-

Table 1. Station number, latitude (degrees and minutes), longitude (degrees and minutes), year of first and last record, and station name for the 224 stations for which adjusted mean annual maximum and minimum temperature series have been prepared.

Rural stations (170 stations)					
1013	1529	12807	1898	1994	WYNDHAM (WYNDHAM PO)
2012	1814	12740	1898	1994	HALLS CREEK (HALLS CREEK AMO)
3003	1757	12214	1894	1994	BROOME (BROOME AMO)
3007	1718	12338	1888	1994	DERBY (DERBY POST OFFICE)
4020	2111	11945	1901	1993	MARBLE BAR (MARBLE BAR)
5016	2138	11507	1887	1994	ONSLOW (ONSLOW PO)
6011	2453	11340	1885	1994	CARNARVON (CARNARVON AMO)
6072	2302	11502	1905	1994	NYANG (NYANG STATION)
7045	2637	11833	1898	1994	MEEKATHARRA (MEEKATHARRA AMO)
7151	2322	11944	1915	1994	NEWMAN (NEWMAN POST OFFICE)
8091	3039	11600	1901	1994	MOORA (MOORA SHIRE)
9038	3201	11530	1880	1994	ROTTNEST (ROTTNEST ISLAND LH)
9510	3357	11608	1901	1994	BRIDGETOWN(BRIDGETOWN POST OFFICE)
9518	3422	11508	1897	1994	AUGUSTA (CAPE LEEUWIN)
9519	3332	11501	1904	1994	BUSSELTON (CAPE NATURALISTE)
9534	3334	11549	1902	1993	DONNYBROOK(DONNYBROOK POST OFFICE)
9581	3438	11739	1905	1994	MT BARKER (MT BARKER COMPOSITE)
9789	3350	12154	1883	1994	ESPERANCE (ESPERANCE MO)
9842	3348	11540	1900	1993	BUSSELTON (JARRAHWOOD)
10073	3138	11743	1910	1993	KELLERBERRIN (KELLERBERRIN COMP.)
10092	3129	11817	1913	1994	MERREDIN (MERREDIN SHIRE COUNCIL)
10111	3139	11640	1902	1994	NORTHAM (NORTHAM COMPOSITE)
10144	3153	11645	1880	1994	YORK (YORK POST OFFICE)
10579	3341	11733	1894	1994	KATANNING (KATANNING POST OFFICE)
10614	3256	11710	1913	1994	NARROGIN (NARROGIN POST OFFICE)
10648	3241	11640	1902	1994	WANDERING (WANDERING SHIRE)
11017	3228	12352	1901	1994	BALLADONIA (BALLADONIA)
11019	3215	12618	1899	1994	MADURA (EYRE)
12022	2858	11934	1906	1994	SANDSTONE (CASHMERE DOWNS)
12038	3047	12127	1897	1994	KALGOORLIE-BOULDER(KALGOORLIE AMO)
12046	2853	12119	1898	1994	LEONORA (LEONORA POST OFFICE)
12052	2942	12102	1897	1994	MENZIES (MENZIES)
12074	3114	11920	1895	1994	SOUTHERN CROSS(SOUTHERN CROSS PO)
12219	2809	12341	1900	1994	LAVERTON (YAMARNA)
13012	2635	12013	1901	1993	WILUNA (WILUNA)
18079	3248	13413	1890	1993	STREAKY BAY POST OFFICE
19062	3302	13843	1892	1994	YONGALA POST OFFICE
21014	3350	13837	1879	1994	CLARE POST OFFICE
21046	3347	13813	1909	1993	SNOWTOWN POST OFFICE
22801	3545	13636	1868	1993	CAPE BORDA (LIGHTHOUSE)
22807	3539	13738	1914	1994	KINGSCOTE POST OFFICE
23020	3432	13841	1909	1993	ROSEWORTHY AGRIC. COLLEGE
25509	3520	14031	1914	1994	LAMEROO POST OFFICE
26005	3804	14040	1889	1993	CAPE NORTHUMBERLAND
26026	3710	13945	1865	1994	ROBE POST OFFICE
26089	3636	14029	1902	1993	PADTHAWAY (LINDEMANS)
27005	1357	14312	1908	1994	COEN POST OFFICE
27022	1035	14213	1908	1993	THURSDAY ISLAND MO
28004	1600	14404	1907	1994	PALMERVILLE
28007	1447	14330	1907	1994	MUSGRAVE
29004	1745	13933	1907	1994	BURKETOWN POST OFFICE
29008	2043	14031	1888	1992	CLONCURRY COMPOSITE
29012	1812	14215	1912	1994	CROYDON POST OFFICE
29041	1740	14104	1908	1994	NORMANTON POST OFFICE
30018	1818	14333	1907	1994	GEORGETOWN POST OFFICE
30024	2051	14412	1888	1994	HUGHENDEN POST OFFICE
30045	2044	14308	1908	1994	RICHMOND POST OFFICE

31017	1527	14512	1907	1994	COOKTOWN (MISSION STRIP)
31029	1723	14523	1907	1991	HERBERTON POST OFFICE
32004	1816	14601	1907	1994	CARDWELL
32025	1731	14602	1908	1994	INNISFAIL
33002	1937	14722	1908	1994	AYR DPI RESEARCH STATION
33257	2001	14813	1907	1994	BOWEN AIRPORT
34084	2003	14616	1907	1994	CHARTERS TOWERS AIRPORT
35019	2250	14738	1910	1994	CLERMONT POST OFFICE
35264	2334	14810	1907	1994	EMERALD AIRPORT
36007	2333	14517	1913	1994	BARCALDINE POST OFFICE
36026	2416	14426	1913	1994	ISISFORD POST OFFICE
36031	2326	14417	1907	1994	LONGREACH AMO
37010	1955	13807	1907	1994	CAMOOWEAL POST OFFICE
38003	2255	13954	1888	1994	BOULIA POST OFFICE
39039	2538	15137	1894	1994	GAYNDAH POST OFFICE
39069	2338	15023	1913	1992	MOUNT MORGAN
39085	2444	15313	1907	1994	SANDY CAPE LIGHTHOUSE
40043	2702	15328	1913	1994	CAPE MORETON LIGHTHOUSE
41011	2743	15152	1913	1992	CAMBOOYA POST OFFICE
41056	2820	15218	1907	1992	KILLARNEY POST OFFICE
41521	2831	15019	1907	1994	GOONDIWINDI AIRPORT
41522	2710	15116	1907	1994	DALBY AIRPORT
42023	2640	15011	1908	1994	MILES POST OFFICE
43020	2629	14759	1907	1994	MITCHELL POST OFFICE
43091	2633	14846	1889	1994	ROMA AIRPORT
44010	2802	14729	1907	1994	BOLLON POST OFFICE
44021	2625	14616	1907	1994	CHARLEVILLE AMO
44026	2804	14541	1907	1994	CUNNAMULLA POST OFFICE
46037	2926	14201	1910	1994	TIBOOBURRA POST OFFICE
46042	3051	14305	1907	1994	WHITE CLIFFS POST OFFICE
46043	3134	14323	1881	1994	WILCANNIA (REID ST)
47019	3224	14225	1907	1993	MENINDEE POST OFFICE
48013	3006	14556	1871	1994	BOURKE POST OFFICE
48015	2958	14652	1911	1993	BREWARRINA HOSPITAL
48027	3129	14550	1890	1994	COBAR MO
48031	2933	14835	1907	1994	COLLARENEBRI (SWIMMING POOL)
49002	3438	14334	1907	1994	BALRANALD (RSL)
50014	3305	14709	1907	1994	CONDOBOLIN POST OFFICE
51010	3058	14823	1907	1994	COONAMBLE POST OFFICE
51049	3159	14757	1913	1994	TRANGIE AGRIC.RESEARCH STATION
52020	2859	14859	1915	1994	MUNGINDI POST OFFICE
52026	3001	14807	1878	1993	WALGETT POST OFFICE
53030	3020	14945	1871	1994	NARRABRI WEST PO
55023	3059	15015	1907	1994	GUNNEDAH COMPOSITE
55049	3131	15041	1907	1994	QUIRINDI POST OFFICE
55054	3105	15051	1907	1992	TAMWORTH (AIRPORT)
56011	2944	15144	1907	1993	GLEN INNES POST OFFICE
56017	2947	15107	1907	1994	INVERELL POST OFFICE
56032	2903	15201	1907	1994	TENTERFIELD (DERBY STREET)
56229	3013	15141	1911	1994	GUYRA HOSPITAL
58012	2926	15322	1877	1994	YAMBA PILOT STATION
58063	2853	15303	1908	1994	CASINO AIRPORT
59017	3103	15250	1907	1994	KEMPSEY (NORTH STREET)
61051	3146	15050	1907	1994	MURRURUNDI POST OFFICE
61086	3230	15055	1907	1994	JERRYS PLAINS POST OFFICE
61089	3204	15056	1907	1994	SCONE SOIL CONSERVATION SERVICE
62021	3236	14935	1907	1994	MUDGEE POST OFFICE
63053	3327	14911	1907	1993	MILLTHORPE POST OFFICE
64008	3117	14917	1879	1994	COONABARABRAN POST OFFICE
65016	3323	14800	1873	1994	FORBES (CAMP STREET)
65026	3309	14809	1907	1994	PARKES (MACARTHER STREET)
65034	3234	14857	1907	1994	WELLINGTON POST OFFICE

65091	3351	14839	1907	1994	COWRA AIRPORT
68034	3506	15048	1907	1994	JERVIS BAY (PT PERPENDICULAR L/H)
68102	3429	15024	1907	1994	BOWRAL (PARRY DRIVE)
69002	3640	14950	1907	1994	BEGA COMPOSITE
69018	3555	15009	1876	1994	MORUYA HEADS PILOT STATION
70005	3655	14914	1912	1994	BOMBALA POST OFFICE (COMPOSITE)
70091	3450	14855	1907	1994	YASS (LINTON HOSTEL)
70263	3443	14944	1858	1994	GOULBURN COMPOSITE (PROGRESS ST.)
70278	3614	14908	1858	1994	COOMA (VISITORS CENTRE)
72000	3519	14804	1907	1994	ADELONG POST OFFICE
72150	3510	14728	1908	1994	WAGGA AMO
73007	3500	14836	1912	1994	BURRINJUCK DAM
73009	3438	14801	1894	1994	COOTAMUNDRA POST OFFICE
73014	3354	14810	1907	1994	GRENFELL POST OFFICE
73056	3419	14818	1907	1991	YOUNG POST OFFICE
74034	3600	14621	1907	1993	COROWA COMPOSITE
74128	3533	14457	1858	1994	DENILIQUIN POST OFFICE
75031	3431	14451	1881	1994	HAY (MILLER STREET)
75032	3329	14532	1907	1994	HILLSTON POST OFFICE
75039	3318	14622	1907	1994	LAKE CARGELLIGO POST OFFICE
77042	3520	14333	1899	1994	SWAN HILL
78031	3620	14138	1897	1994	NHILL COMPOSITE /MO 1941-1943
78072	3622	14259	1899	1994	DONALD (WATER TRUST)
79028	3640	14218	1891	1994	LONGERENONG AGRICULTURE COLLEGE
79080	3704	14247	1903	1994	STAWELL COMPOSITE
80015	3609	14446	1881	1994	ECHUCA (AERODROME)
80023	3544	14355	1903	1994	KERANG POST OFFICE
80101	3604	14527	1908	1992	NUMURKAH IRRIGATION RESEARCH
82002	3633	14559	1903	1994	BENALLA
82039	3606	14631	1903	1994	RUTHERGLEN (RESEARCH)
82137	3619	14641	1908	1994	BEECHWORTH (WOOLSHED)
83025	3706	14736	1879	1994	OMEO
84016	3734	14955	1877	1994	GABO ISLAND
85096	3908	14625	1877	1994	WILSONS PROMONTORY LIGHTHOUSE
86017	3830	14453	1883	1994	CAPE SCHANCK LIGHTHOUSE
87021	3749	14412	1903	1994	DURDIDWARRAH
87031	3752	14445	1903	1994	LAVERTON AERO AMO
87036	3725	14433	1887	1994	MACEDON FORESTRY
88043	3703	14344	1899	1994	MARYBOROUGH
88110	3705	14414	1907	1994	CASTLEMAINE PRISON
89085	3716	14259	1899	1994	ARARAT PRISON
90015	3852	14331	1865	1994	CAPE OTWAY LIGHTHOUSE
90173	3739	14204	1886	1994	HAMILTON (WILKEN)
91057	4103	14647	1895	1994	LOW HEAD LIGHTHOUSE
97014	4127	14532	1892	1994	WARATAH
97067	4209	14520	1900	1991	STRAHAN (VIVIAN STREET)
98001	3956	14351	1913	1994	KING I. (CURRIE POST OFFICE)
Urban stations (54 stations)					
4032	2022	11837	1912	1994	PORT HEDLAND (PORT HEDLAND AMO)
4035	2047	11709	1881	1994	ROEBOURNE (ROEBOURNE POST OFFICE)
8051	2848	11442	1880	1994	GERALDTON (GERALDTON AMO)
9034	3157	11552	1897	1992	PERTH (PERTH REGIONAL OFFICE)
9058	3159	11604	1908	1993	KALAMUNDA (KALAMUNDA)
9741	3457	11748	1880	1994	ALBANY (ALBANY AMO)
14015	1226	13053	1882	1994	DARWIN AIRPORT
15590	2349	13353	1879	1994	ALICE SPRINGS AMO
18070	3443	13551	1892	1994	PORT LINCOLN POST OFFICE
23090	3455	13837	1887	1994	ADELAIDE REGIONAL OFFICE(KENTTOWN)
23703	3500	13837	1900	1994	BELAIR (KALYRA)
23733	3504	13852	1862	1994	MOUNT BARKER POST OFFICE
23747	3516	13853	1861	1993	STRATHALBYN POST OFFICE

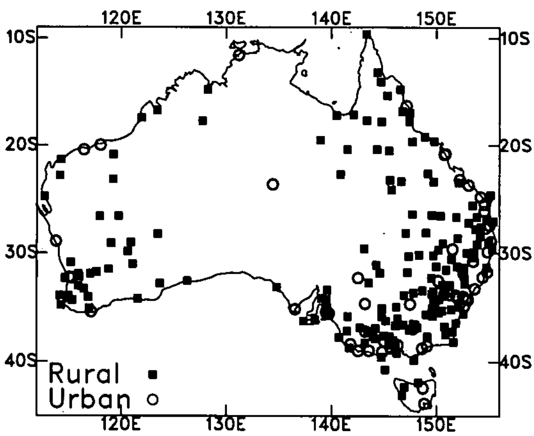
26021	3745	14047	1861	1994	MOUNT GAMBIER AERO AMO
31011	1653	14545	1907	1994	CAIRNS AMO
33047	2110	14907	1908	1994	MACKAY (TE KOWAI EXP. STN)
33119	2107	14913	1889	1994	MACKAY MO
39083	2323	15029	1888	1994	ROCKHAMPTON AMO
39123	2351	15116	1909	1993	GLADSTONE MO
39128	2454	15219	1907	1994	BUNDABERG AERO
40062	2649	15251	1913	1994	BEERWAH (CROHAMHURST)
40082	2733	15220	1913	1994	GATTON-LAWES
40093	2610	15239	1908	1994	GYMPIE (FORESTRY)
40101	2737	15246	1913	1993	IPSWICH COMPOSITE
40126	2533	15241	1908	1994	MARYBOROUGH COMPOSITE
40158	2640	15200	1913	1992	NANANGO
40223	2723	15307	1887	1994	BRISBANE AMO
47007	3159	14128	1891	1994	BROKEN HILL (PATTON STREET)
53048	2928	14951	1879	1994	MOREE MO
56002	3031	15140	1857	1994	ARMIDALE RADIO STATION 2AD
58037	2849	15316	1907	1994	LISMORE (CENTRE STREET)
58130	2941	15256	1907	1994	GRAFTON OLYMPIC POOL
60026	3127	15255	1907	1994	PORT MACQUARIE (HILL STREET)
60030	3154	15229	1907	1994	TAREE RADIO STATION 2RE
61055	3255	15148	1862	1994	NEWCASTLE (NOBBYS SIGNAL STATION)
63005	3326	14934	1858	1994	BATHURST (AGRICULTURAL RES. STN.)
63039	3343	15018	1907	1994	KATOOMBA COMPOSITE
63224	3330	15009	1912	1994	LITHGOW COMPOSITE
63231	3323	14907	1907	1994	ORANGE AIRPORT
65012	3213	14834	1871	1994	DUBBO (COOREENA RD)
66062	3352	15112	1859	1994	SYDNEY REGIONAL OFFICE
66124	3348	15101	1907	1994	PARRAMATTA NORTH
67033	3336	15047	1863	1994	RICHMOND AMO/MO CLOSED 1946-1953
68188	3424	15053	1871	1994	WOLLONGONG UNIVERSITY
75041	3416	14604	1915	1994	GRIFFITH AERO
76031	3414	14205	1889	1994	MILDURA AIRPORT AMO
79023	3639	14206	1898	1994	HORSHAM COMPOSITE
82138	3625	14618	1901	1994	WANGARATTA (AIRWORLD)
85072	3807	14708	1892	1994	EAST SALE AMO
85279	3753	14734	1896	1994	BAIRNSDALE (AIRPORT)
86071	3749	14458	1855	1994	MELBOURNE REGIONAL OFFICE
87117	3805	14420	1903	1994	GEELONG (NORLANE)
89002	3731	14347	1908	1994	BALLARAT COMPOSITE
90171	3819	14128	1863	1994	PORTLAND (CASHMORE AIRPORT)
90172	3818	14226	1897	1994	WARRNAMBOOL AIRPORT
90174	3824	14336	1899	1994	COLAC (ELLIMINYT)
91104	4132	14712	1885	1994	LAUNCESTON AIRPORT WSO
94029	4253	14720	1881	1994	HOBART REGIONAL OFFICE

ate composite records (the date of combination was treated as a discontinuity and subsequently adjusted along with other problems identified in the comparison process). This resulted in a dataset of 224 stations ('candidate stations') being established for further investigation. The stations are listed in Table 1, and their locations are shown in Fig. 1.

Many changes were identified over the period of record covered by the long-term dataset (the longest station commenced continuous temperature measurements in 1855, with all stations in the dataset open by 1915). Changes identified in the station documentation included changes in instrumentation (such as the introduction of the Stevenson screen, usually around the turn of the century), in location (especially away from built up areas to airports, often around the middle of the century), in observer habits and in the environment (such as vegetation growth and urbanisation).

Rigorous statistical techniques were used in conjunction with station documentation to detect, and adjust for, discontinuities. Maximum and minimum temperatures were considered separately, as they behave differently under different synoptic conditions, are influenced by different non-climatic factors and sometimes have different lengths of record. Ideally, for each station requiring adjustment, a reference temperature series from a

Fig. 1 Location of the 224 stations for which adjusted mean annual maximum and minimum temperature series have been prepared. Stations classified as urban are indicated by open circles; rural stations are indicated by full squares.



neighbouring station that has experienced no discontinuities, has had a diligent observer, has little missing data and experiences similar climatological conditions to the candidate station is required. The time series of temperature from the candidate station can then be compared with the 'reference' series. Any disagreements between the two series would, because of the absence of problems in the reference series, be attributable to discontinuities in the temperature record at the candidate station. Unfortunately, no such perfect reference station exists in the entire Australian network, let alone near every long-term temperature station.

Therefore an 'ideal' reference temperature record was created for each candidate station using the median interannual temperature differences from surrounding stations. A station with a long-term temperature record was selected from the dataset of all climatological stations as the candidate station to be tested for inhomogeneities. Although this procedure was repeated for maximum and minimum temperatures, for all 224 candidate stations, only the case of minimum temperatures at Mildura will be described here, as an example of the procedure. In the first step, neighbour stations, within six degrees latitude and longitude of the candidate station, were identified. The use of only nearby stations ensured that stations with climates dissimilar to that of the candidate station were not used. Stations within six degrees latitude and longitude but in a location likely to be climatologically dissimilar to the candidate station, e.g., over a mountain range, were excluded. Stations likely to be at risk of urbanisation were not included in the reference series. The difference in temperature, from one year to the next (ΔT) was calculated for each year. All neighbouring ΔT series were correlated with the candidate ΔT series. Only stations which were strongly, significantly correlated with the candidate station were used in the development of the 'neighbouring' record (it was necessary for the correlation to be at least 0.7, significance level to be below 0.05, and the number of years of record to be greater than ten for a nearby station to be selected as a part of the neighbour dataset). The values of ΔT at the remaining neighbouring stations were sorted and the median value of ΔT for each year was used to compile the reference series. The median value was used to ensure that discontinuities at a neighbouring station had minimal influence on the reference series. The value therefore represents how the temperature should have changed from one year to the next in the area surrounding the candidate station. The median ΔT series was then converted to a median reference temperature series by the addition of ΔT values to the temperature in the first year of record at the candidate station. The candidate and reference series are shown in Fig. 2, for Mildura. The number of neighbours used to compile the reference series is also shown. The drop in the number of neighbours in 1957 reflects the introduction of a priority system of archiving data in the Bureau. The number of neighbour stations used for a candidate station was typically about 65. However, only about half of these would be available in each year, because of missing data and because of the short periods of record at some neighbour stations.

It is next assumed that the median reference series is free from discontinuities, and therefore any change in the relationship between the candidate and median reference series is likely to be due to a change at the candidate station. This will appear as an abrupt change or spurious trend in the difference series (candidate minus median reference temperatures). This series is shown for Mildura minimum temperature in Fig. 3. Change points in the difference series were objectively identified using automated techniques developed by Easterling and Peterson (1995). The method is based on a regression of the difference series against time. A two-phase regression is fitted, for each year of the series, to all

Fig. 2 The minimum temperature series for Mildura, and the reference series constructed from the ΔT median series. The number of stations used to construct the reference series is also shown.

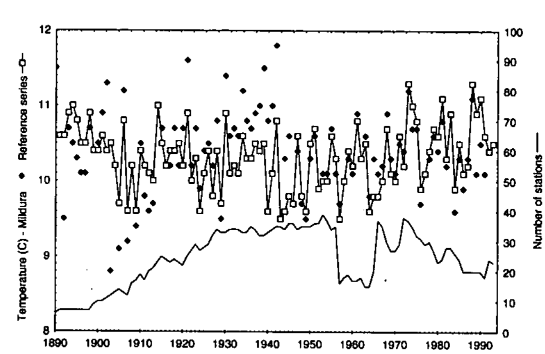


Fig. 3 Difference between the two series in Fig. 2.

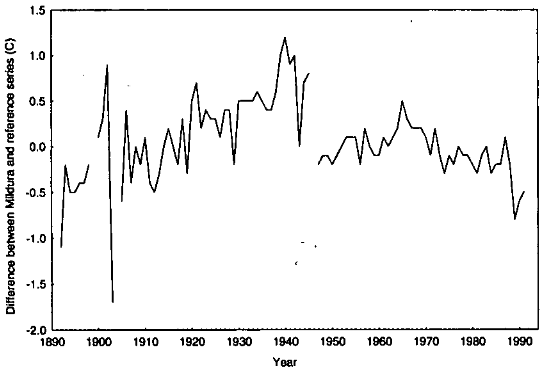
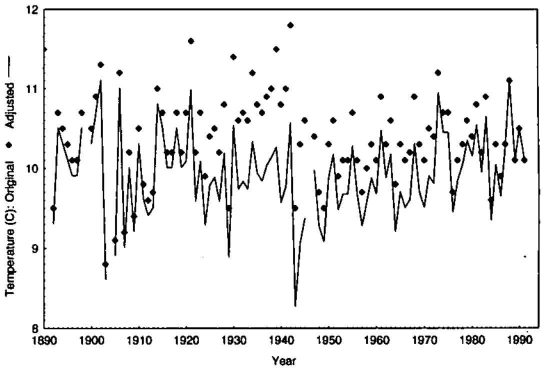


Fig. 4. The adjusted and original minimum temperature series for Mildura.



years before and all years after the year being tested, and the residual sum of squares is calculated for each of the two regressions. The year with the minimum residual sum of squares is noted as a potential discontinuity, and the significance of the two-phase fit is tested. The difference in means of the two portions of the difference series is also tested using Student's t-test, and the potential discontinuity is noted. The series is then divided at the point of the identified potential discontinuity and the test repeated until no further discontinuities are identified. All potential discontinuities are tested for statistical significance using a non-parametric test. Required adjustments are calculated from the longest possible discontinuity-free periods either side of the change. These are applied and the test is repeated until no further discontinuities are identified.

The median reference and candidate series (Fig. 2), and the series of differences between the two (Fig. 3), were printed for visual analysis for each station. Any years with a change in the difference, with the corresponding recommended adjustment from the objective statistical test, were recorded. The objective recommendation, the visual analysis of the median series, individual graphical comparisons with other stations independent of the reference series (using 'Detect' software – see below), visual analysis of the diurnal temperature range series (as discontinuities often affect minimum and maximum temperatures differently) and station history documentation were considered together. A subjective decision was then made on which adjustments were to be made and the magnitude of each adjustment. The year, magnitude and reasons for the adjustments applied to Mildura minimum temperatures are given in Table 2. The adjusted temperature series for Mildura is shown in Fig. 4. This process was repeated for maximum temperatures. The mean temperature (mean of maximum and minimum) and the diurnal temperature range (maximum minus minimum) were then calculated, from the annual mean maximum and minimum temperatures.

The total number of adjustments made to the maximum and minimum temperature series over the 224 candidate stations was 2812. All but one minimum series (Normanton Post Office) and five maximum series (Balladonia, Wiluna, Palmerville, Musgrave and Griffith) required at least one adjustment. The mean number of adjustments to maximum temperature was 6.1 per station, with a mean of 6.6 for minimum temperatures. The size of the adjustments made to the Mildura series (Table 2) are typical of the adjustments made to all the series.

The 'Detect' suite of programs developed by Neil Plummer was also used to identify discontinuities. 'Detect' plots difference series between stations. For

Table 2. Adjustments to Mildura minimum temperature series. The 'Year' column indicates the year in which the adjustment was applied. The symbol '<' indicates that the adjustment was made to all years prior to the indicated year. Otherwise the adjustment was applied only to the indicated year. The column 'Cumulative' takes into account all problems back to that year. The reason for adjustment is from station documentation, where a problem has been identified. All the adjustments were also detected using the objective methods described in the text. The adjustment made in 1890 was identified using the 'Detect' program, but there was no indication in the station documentation of a possible cause for this problem.

Year	*Adjustment*	*Cumulative*	*Reason for adjustment*
<1989	-0.6	-0.6	Move to higher, clearer ground
<1946	-0.9	-1.5	Move from Post Office to Airport
<1939	+0.4	-1.1	New screen
<1930	+0.3	-0.8	Move from park to Post Office
1943	+1.0	+0.2	Pile of dirt near screen during construction of air-raid shelter
1903	+1.5	+0.7	Temporary site one mile east
1902	-1.0	-1.8	Problems with shelter
1901	-0.5	-1.3	Problems with shelter
1900	-0.5	-1.3	Problems with shelter
1892	+1.0	+0.2	Temporary site
1890	-1.0	-1.8	Detect

each station, time series of the differences between annual temperature anomalies were calculated between the candidate station and two neighbours. Any spurious trends or discontinuities at the candidate station should be apparent in the two series involving data from the candidate station, but not in the series of differences between the two neighbours.

Results

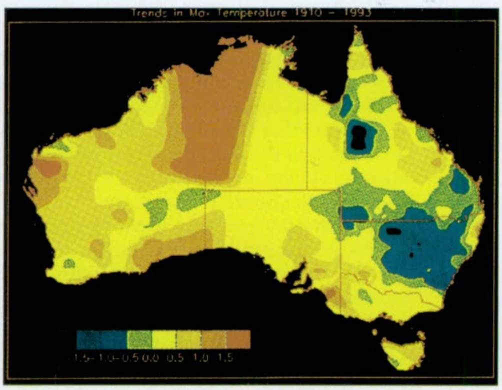
Least squares regression was used to fit trend lines over the 1910-1993 period to each station's adjusted mean annual maximum, minimum, mean and diurnal range of temperature. The trends were interpolated to a regular grid and the contours of trends calculated and plotted for each parameter at all 224 stations (Fig. 5), using the Barnes (1964) objective analysis scheme. The spatial detail in Fig. 5 in data-sparse regions (see Fig. 1) may not be realistic, because of the requirement on the analysis system to extrapolate large distances in these regions. As well, the smaller number of neighbouring stations in data-sparse areas may reduce the reliability of the adjustment of some stations.

Minimum temperatures have shown a warming trend at nearly all stations. Trends are particularly large in the north, especially in the northeast. Maximum temperatures have increased in the west of the country. The eastern Australian maximum temperatures dropped rather abruptly around the middle of the century, coinciding with a rather abrupt increase in rainfall in this area (Nicholls and Lavery 1992). The difference in sign of the trend in the east has resulted in mean temperatures showing small trends in the southeast of Australia. Trends in mean temperature over almost all the rest of Australia are positive. The diurnal temperature range has been decreasing over most of the continent, although small areas in the west have shown slight positive trends.

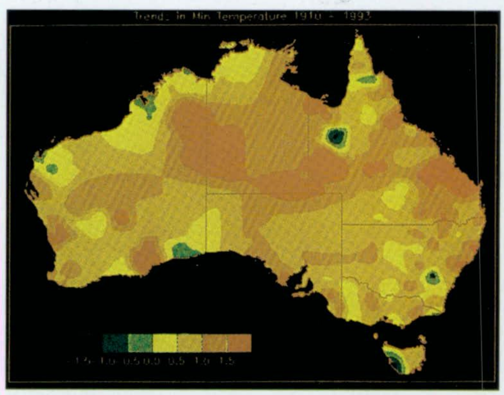
Areal average trends were calculated from the 149 stations in the dataset which had commenced observations by 1910 and which were not located in urban centres (defined as a town with a population of more than 10,000 at any time during the 1910-93 period, unless the station was outside the population centre). The trends were calculated for areal averages across the entire country. The spatial averages (Fig. 6) were calculated

Fig. 5 **Analysis of 1910-93 trends in mean annual maximum (a), minimum (b), mean (c), and diurnal range of (d) temperature, in °C per 100 years. Increases are shown as yellow or orange; decreases indicated by green or blue.**

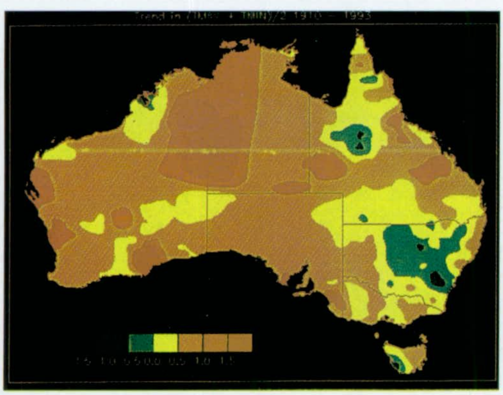
(a)



(b)



(c)



(d)

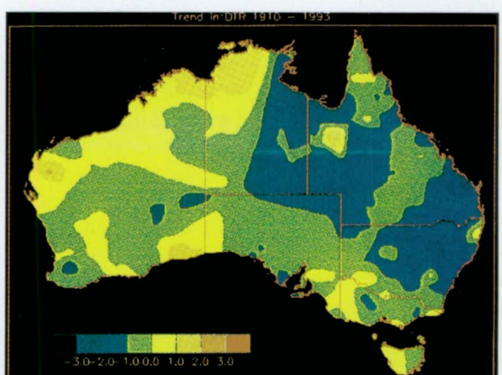


Fig. 6 Time series of maximum and minimum temperature averaged across Australia. The thick lines are the results of applying a distance-weighted least squares smoother to the annual values (thin lines).

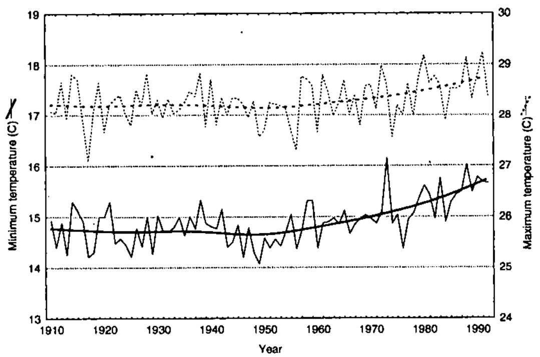
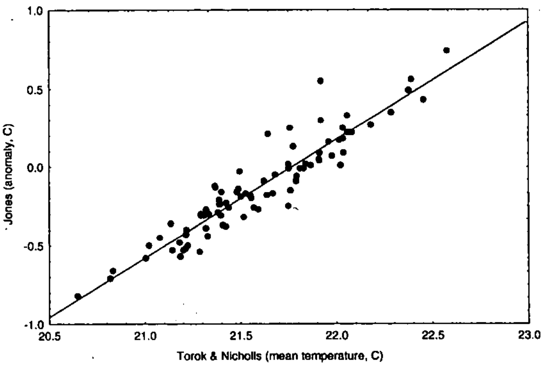


Fig. 7 Scatter diagram of Australian average annual mean temperatures versus Jones (1994) temperatures for the Australian region.



using a technique based on the theory of Thiessen polygons (Louie 1977). Lavery et al. (1996) provide a description of the technique. The station data were not standardised in any way prior to the formation of spatial averages. The linear trends in Australian-average maximum and minimum temperatures from 1910 were 0.54°C per 100 years and 0.98°C per 100 years respectively. Both trends were statistically significant, at the one per cent level. The trend has been strongest since the middle of the century.

Discussion

The adjustments made to the original data are large, relative to the trends observed in the series. The reliability of the adjusted data therefore needs to be examined. This has been done in two ways. Firstly, the all-Australia mean annual temperature series (the mean of the all-Australia annual mean minimum and maximum time series) was compared with an average temperature series for the Australian region (10-50°S, 110-160°E) prepared by Jones (1994). Jones used fewer stations than this study, did not exclude urban stations, and used different methods to correct for discontinuities and different spatial averaging techniques. Despite these differences, the two series have a correlation of 0.94 (Fig. 7) for the period 1910-1992. Very few years exhibit major differences between the two series.

The second method used to assess the accuracy of the dataset was to correlate the all-Australia mean maximum and minimum temperatures to an all-Australia annual rainfall average (Lavery et al. 1996), for the period 1910-1992. The multiple correlation with rainfall, with maximum and minimum temperature as the two independent variables, was 0.78 (statistically significant at the 0.05% level). This strong correlation confirms that the rainfall and temperature series have much of their variations in common, as would be expected from synoptic considerations. The high correlation provides some confidence in the accuracy of the data.

These two simple tests, plus the objective technique and careful examination of the station documentation involved in the adjustment procedure, means that the adjusted temperature series should provide the best available record of 20th century temperatures across Australia. There remain doubts about the quality of the 19th century record (Nicholls et al. 1996a) because of known changes in exposure of thermometers (Nicholls et al. 1996b). The small number of stations available in the 19th century means that confidence in the adjustments made for such changes is relatively low.

Some doubts remain regarding possible discontinuities in the early 1970s, when Australian temperature recordings changed from the Fahrenheit scale to the Celsius scale. New thermometers were issued at that time. Thermometers before and after the change to metric units underwent calibration tests and a search through the documentation regarding the change does not suggest possible instrumental discontinuities. As well, measurements with thermometers manufactured before and after the changeover date have been compared. This check revealed no instrumental reason for expecting discontinuities at the time of the changeover to metric units.

One possible source of a non-climatic discontinuity is observer practice in recording temperatures. Some observers, prior to the change to metric units, recorded temperatures in whole degrees Fahrenheit, instead of recording to the nearest tenth of a degree, as specified in directions to observers. If many observers 'truncated' their measurements to the nearest whole degree below the actual measurement, prior to metrication, and after metrication recorded to tenths of a degree, this would result in an artificial warming in the early 1970s.

Discontinuities caused by such a practice, if it was common, would not be detected by the statistical programs used here. Examination of field books does not suggest that this practice was sufficiently common to produce a major discontinuity.

Changes occurred in the time of temperature measurements after the introduction of daylight saving time. These changes seem unlikely to have led to a major artificial discontinuity in the temperature series.

The original and adjusted mean annual maximum and minimum temperature data over the entire period of record are available for the 224 long-term stations in digital form on request.

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Wasyl Drosdowsky produced Fig. 1. Scott Power produced the analyses in Fig. 5. Beth Lavery produced the spatial averages for Fig. 6. Phil Jones provided his Australian average temperatures for the comparison in Fig. 7. Neil Plummer provided the 'Detect' suite of programs. Alex Kariko tested Fahrenheit and Celsius thermometers. This research was a PhD project funded by the National Greenhouse Advisory Committee.

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