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Climate variations and change evident in high-quality climate data for Australia's Antarctic and remote island weather stations

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High-quality homogeneous rainfall and temperature time series have been developed from observations taken by the Australian Bureau of Meteorology for remote island sites: the subantarctic Macquarie Island, Lord Howe Island in the Tasman Sea, Norfolk Island in the southwest Pacific Ocean, Willis Island in the Coral Sea and Cocos Island in the eastern Indian Ocean. In addition, high-quality monthly temperature time series have been developed for three east Antarctic stations operated by Australia (Davis, Mawson and Casey).

The quality control process for developing the high-quality data involved two steps. Firstly, a thorough examination of historical station metadata was conducted, with the aim of reconstructing the history of measurements at all stations. An objective statistical test was then applied to detect possible break points in the data series. Where an inhomegeneity was detected by the statistical test and subsequently confirmed based on metadata (historical information about stations and recordings), adjustment was applied at the monthly timescale (as the size of adjustments generally vary from month to month and from season to season).

While annual mean surface temperature at Australian Antarctic stations is characterised by high year-to-year variability, results for the homogenised series indicate an increase in mean annual temperatures at Mawson and Davis by 0.35 °C and 0.40 °C respectively in the period 1958–2009. At Casey the mean annual temperature has decreased by –0.2 °C since the beginning of 1970s. This decreasing trend is not statistically significant and is, most likely, related to the existence of the ozone hole.

Annual mean surface temperature at the remote island stations is characterised by a relatively small year-to-year variability with all stations showing a warming trend. The annual mean total temperature increase ranges from 0.3 to 0.6 °C over the period 1950–2009 for Macquarie, Norfolk, Lord Howe and Willis Islands, while at Cocos Island temperature increased by 0.3 °C since 1960.

Rainfall declined at most subtropical and tropical sites analysed in this study: 20 mm/decade at Norfolk Island (since 1915), 23 mm/decade at Lord Howe Island (since 1950), 17 mm/decade at Cocos Island (since 1916), while little change was found for Willis Island (an increase of 3 mm/decade since 1924). In percent of the annual mean for the indicated period of measurements, rainfall declined about 15 per cent at Norfolk Island, 9 per cent at Lord Howe Island and 8 per cent at Cocos Island, while it slightly increased (about 2.5 per cent) at Willis Island. In contrast, Macquarie island has experienced a sharp increase in rainfall of 30 mm/decade since 1949 (or about 20 per cent of the annual mean for the whole period of record), suggesting that areas south of Australia may have become wetter over recent decades. The patterns of change are broadly consistent with climate change simulations (Trenberth et al. 2007) under the enhanced greenhouse effect which show general warming and a tendency for rainfall declines in subtropical parts and rainfall increases in the subantarctic.

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Introduction

The world has warmed by about 0.74 °C over the last hundred years (Jones and Moberg 2003, Brohan et al. 2006, Jones at al. 2012). Almost all parts of the globe have warmed, with the southern hemisphere warming at a somewhat slower rate than the northern hemisphere owing to the larger expanse of oceans (Trenberth et al. 2007). Rising global temperatures have also been accompanied by changes in precipitation (Chen et al. 2002, Adler et al. 2003). Observations show that there have been changes not only in the amount, but also in intensity, frequency and type of precipitation. Reducing rainfall trends over land are present in the deep tropics from 10°N to 10°S, especially after 1977 (Trenberth et al. 2007) but, in general, substantial uncertainties remain in precipitation trends because of the spatial and temporal incompleteness of the data and large regional differences (Huntington 2006).

Over the inhabited land masses, the station networks available to monitor climate variability and change are dense enough to provide a reasonably detailed description of climate (e.g., Hansen et al. 2010). Mainland Australia is currently monitored by a network of nearly 1000 surface temperature and around 6000 rainfall stations reporting to the Bureau of Meteorology (Jones and Trewin 2002; Jones et al. 2009). The associated data have allowed temperature analyses to be developed back to the mid 1800s for global scale temperatures (e.g., Trenberth et al. 2007; Hansen et al. 2010).

Temperature data for continental Australia suitable for climate change analyses have been prepared back to 1910 by a number of researchers (Torok and Nicholls 1996; Della Marta et al. 2004; Trewin 2012) and compared by Jones et al. (2009). These show a warming of about 0.9 °C since 1910 with trends in rainfall emerging in recent decades, including drying in parts of the south and east and wetting in the north (Smith 2004; CSIRO 2007).

A good understanding of climate trends that exists for the Australian mainland stands in contrast to the situation for Australia's remote islands and Antarctic sites. While the data is extant, these sites are not routinely monitored by the Bureau of Meteorology (e.g., Bureau of Meteorology 2011) for climate variations and change, and are not included in the current Australian high-quality datasets.

Australia's Antarctic and remote island sites are particularly important for monitoring climate as they tend to be representative of large geographical areas and are located in unique climate zones. While small changes in physical environment around any instrumental equipment can lead to spurious artefacts in the observational data, relatively pristine sites are still valuable when it comes to climate data. The sites analysed are largely unaffected by high intensity, local, anthropogenic activities, such as proximity to large urban centres or influences from infrastructure development or agriculture. In this respect they provide unique opportunities to monitoring the changes of global climate away from common local human influences.

This paper describes the variations and trends in annual mean maximum and minimum temperatures at the Australian Antarctic sites Davis, Mawson and Casey, and the remote Macquarie, Lord Howe, Norfolk, Willis and Cocos islands, over the last 50 to 100 years. Precipitation trends are also described for the island sites only, noting major problems with observing precipitation in Antarctic due to the large fraction that falls as snow and ice, and the prevalence of strong winds and blowing snow. The stations we analysed occupy unique and diverse geographical locations. This makes them extremely valuable in monitoring long-term trends in climate variables.

Data and Method

Climate data inhomogeneities are discontinuities in a historical record caused by non-climate influences (e.g., Jovanovic et al. 2008). Common sources of inhomogeneities in climate data series include site moves and changes in instrument type and exposure (Easterling and Peterson 1995). The impact of these inhomogeneities on the climate record can be as large as genuine climate shifts, and consequently they need to be removed, or at least minimised, before trends can be accepted with confidence at the station level (e.g., Rayner 2007; Trewin 2012). A corollary is that if series are found to be homogeneous, this adds confidence that the variations and trends identified are real and reliable.

There is some confusion in scientific literature and more so in the public discourse about methods of data homogenisation for the development of high-quality time series. In many cases homogenisation is used to enable two or more different stations to be 'merged' to provide a longer composite record. Limitations with station numbering (primarily the reuse of station numbers) or with common names applied to more than one station may give the impression that the data came from one location when in reality they do not. This process of merging data from different stations and accounting for different locations and climates, as well as implementation of new instruments, is often referred to as homogenisation (Trewin 2012).

Even for small islands a station shift can be important; for example, the observation site at Christmas Island was moved in 1973 leading to more than a 2 °C drop in the recorded mean annual temperature. In this instance the decision was made to preclude the station from further analysis rather than attempt a homogenisation as the change was very large in comparison to known variability and change.

Meteorological observations from Australian Antarctic and remote island stations are reported to the Bureau of Meteorology, where they are quality checked for gross errors and archived in the electronic database known as

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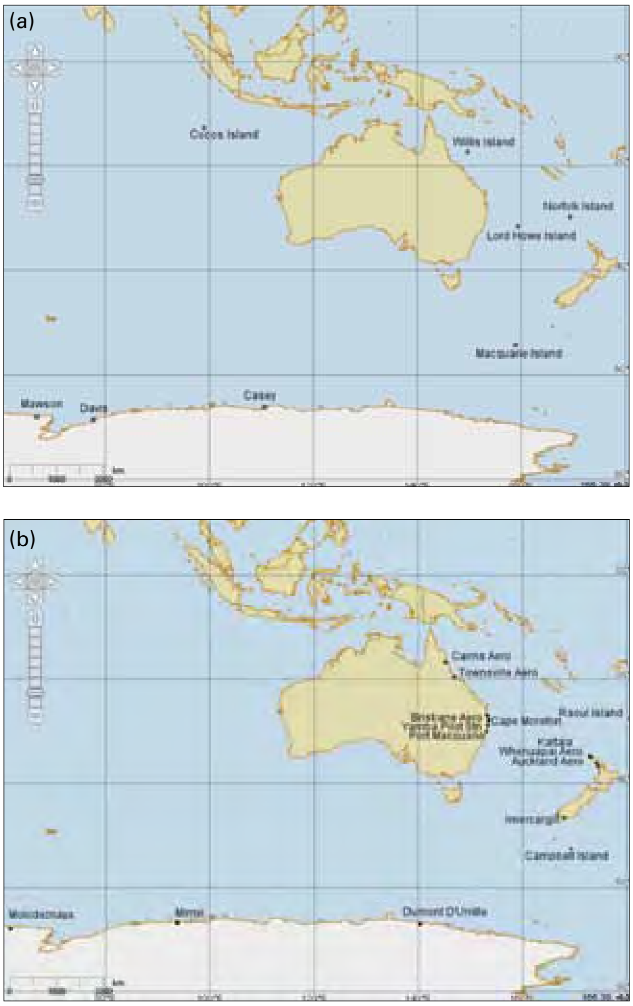
Fig. 1. (a) Locations of the Australian Antarctic and remote islands stations and (b) locations of the reference stations.



the Australian Data Archive for Meteorology (ADAM). Observations at all of these sites are performed by professional observers or more recently using automatic weather stations (AWS). This adds confidence to both the data and the metadata recorded. Locations of the stations used in this study are shown in Fig. 1.

In Australia, maximum and minimum temperatures and precipitation are currently measured for 24 hours ending at 9.00 am local standard time, although there have been variations in observing times in earlier years. The main purpose of this study is to analyse changes in mean climate, so we focus on monthly data. This also reduces the impact of outliers and occasional data errors in individual daily observations.

Monthly mean temperature and the monthly total for precipitation were generated for each station based on the daily values available in ADAM. If more than five daily values were missing during a month, then the monthly mean value was classified as missing following guidelines from the World Meteorological Organization (WMO 1989). An annual value was generated from the monthly values only if all 12 monthly means were available. Annual and monthly mean temperature values were generated as a simple average of the maximum and minimum values when both were available.

Potential inhomogeneities in monthly maximum and minimum temperature and (log-transformed) precipitation data series were detected using a combination of station history information (metadata) and a statistical homogeneity test. The examination of all available metadata included archived station history files (containing inspection reports and correspondence with observers), records from the Australian Bureau of Meteorology's electronic metadata database (SitesDB) and Australian National Antarctic Research Expeditions (ANARE) reports. Personal knowledge from experienced observers, who performed observations at some of these stations, was also sought (in order to clarify details regarding work technologies at these remote sites).

The statistical homogeneity test is generally based on the comparison between a candidate data series (the series to be homogenised) and a reference series (a series highly correlated with the candidate series) during available overlap periods in observations. A change in the difference between the two series over time (see Fig. 5 for an example) was used to flag a potential discontinuity (change point) in the candidate series. These change points were identified using the statistical RHTestV2 software package (Wang and Feng 2007), which is designed to detect single or multiple change points (mean-shifts) in a climate time series (when using reference series) based on the t statistic (Wang et al. 2007; Wang 2008). All statistical tests were assessed at the 95 per cent confidence level. Note that detection of inhomogeneities is also possible without a reference series using the F statistics, detecting a change in slope. Our experience with Australian data has been that use of a reference series generally improves the ability to detect inhomogeneities (as creating difference series using carefully chosen reference series significantly reduces 'background noise' such as inter-annual variability).

In addition to the ADAM data, we have made use of international temperature and precipitation data series as reference series for homogenisation. These additional data were obtained from the NASA/GISS station data portal (http://data.giss.nasa.gov/gistemp/station_data/), the New Zealand National Climate Database (http://cliflo.niwa.co.nz/) and the Bureau of Meteorology's high-quality climate network data portal (http://www.bom.gov.au/climate/change/hqsites/). We have also made use of sea surface temperature (SST) observations in the region of the island sites to construct reference series for the remote island sites based on the NOAA Extended Reconstructed Sea Surface Temperature (NOAA ERSST; Smith et al. 2007, available at http://data.giss.nasa.gov/gistemp/station_data/). It is known that SST variations tend to be reflected in changes of temperature on small islands on longer timescales (e.g., Adamson et al. 1988) and there is a strong correlation between SST and both maximum and minimum temperatures in the stations we have explored. The SST data are particularly powerful in identifying inhomogeneities as they are not affected by the same issues as land surface temperatures and therefore provide quite independent information for tests.

Total cloud amount (TCA) data were also used as reference series for precipitation and diurnal temperature range (DTR). Previous work (Jovanovic et al. 2011) had shown that, at stations with professional observers (as is the case at all eight candidate sites), TCA is generally homogeneous and of good quality despite the human element to the observations.

An attempt was made to use at least two independent reference series for each site to gain confidence in the statistical homogeneity tests. It is not a *priori* known whether a reference series itself is homogeneous and there is a possibility that a detected change point is actually in the reference series and not in the candidate series. Therefore only change points that were identified using at least two independent reference series were considered for comparison against metadata.

Every homogenisation process contains a degree of subjectivity owing to the need to make choices about reference series, incompleteness of metadata, and the weight applied to objective versus subjective information. To minimise the number of subjective decisions, it was decided to only adjust data at change points identified by the objective statistical tests and confirmed by the metadata, as the metadata were found to be of a relatively good quality, particularly since the 1950s. The only exception was maximum temperature for Willis Island which is discussed below in more detail.

Monthly anomalies were calculated as the difference between the monthly mean for a given month and the long-term monthly mean for that month. These anomalies were plotted and visually assessed to check and confirm change points detected by the objective statistical test. Occurrence of a discontinuity in the time series of anomalies would be expected to coincide with inhomogeneities detected by the statistical test in the candidate data series.

Discontinuities verified by the metadata were adjusted in each monthly series using the difference in the mean of the variable (maximum or minimum temperature) from the discontinuity-free periods on either side of the change point. For each identified change point, adjustments were added from the beginning of the data series to that change point meaning that series were adjusted to the most recent homogeneous period of the record. Identified change points and reasons for adjustments are given in Table 1. The process of homogenisation for each of the eight sites is described below together with a summary of findings. In Table 2 we provide trend values for maximum, minimum and mean temperature and rainfall across the eight sites.

A significant limitation when homogenising data from geographically isolated sites is the lack of proximate records. In practice this means working with the records that are extant in the most appropriate way. While this is a caveat for the results presented here, it should also be noted that climate anomalies have a much larger length scale than climatological temperature, and hence more remote locations combined with gridded data (and here we use proximate grids from gridded sea surface temperature) should allow for the objective detection of significant inhomogeneities in monthly and annual data.

Norfolk Island

Norfolk Island (29.0°S, 167.6°E) is a small island of volcanic origin, located approximately 1,600 km northeast of Sydney (Fig. 1(a)). It is about 8 km long and 5 km wide, with the highest point (Mt Bates) 319 m above the mean sea level (MSL). Norfolk Island is one of Australia's oldest Territories, first settled in the late 18th century. Records of rainfall commenced in 1890 in Kingston, the capital. Measurements were performed by government staff.

Norfolk Island has a marine subtropical climate, which is affected by the belt of high pressure systems which moves north and south over the island through the year. The climate is characterised by small diurnal and annual temperature ranges, with mean annual maximum and minimum temperatures of 21.5 °C and 16.4 °C respectively. Relative humidity is high, averaging between 71 and 79 per cent, while winds are predominantly from east to southeast during summer and autumn, south to southwest in winter and southerly in spring. The annual mean rainfall is around 1300 mm, with June being the wettest month (Bureau of Meteorology 2002).

In 1939 the observation site was transferred from Kingston towards the centre of the island and observations were performed by the Bureau of Meteorology observer. Observations included rainfall, temperature, wind and clouds. The Royal New Zealand Air Force moved the observation site to the airport in January 1943 and performed observations until April 1948, when control of the station was transferred back to the Bureau. Metadata suggest another possible move to a new site in mid-1950s. Over subsequent years, more instruments were installed at the station, resulting in additional measurements: a Campbell-Stokes Sunshine Recorder (1946), pluviograph (1948), barometer and cloud base searchlight (1951) and radar (1969). In February 1997 the observation site moved approximately 100 m to the northeast and an automatic weather station (AWS) was installed.

For Norfolk Island we used the remote sites Auckland Aero, New Zealand (37.0°S, 174.8°E), Whenuapai Aero, New Zealand (36.8°S, 174.6°E), Brisbane Aero (27.4°S, 153.1°E) and Raoul Island (29.2°S, 177.9°W) maximum (minimum) temperature data series as reference series for detecting inhomogeneities in the Norfolk Island maximum (minimum) temperature data (see Fig. 1(b) for the location of the reference sites). The assumption for this was that monthly temperatures fluctuate in a similar way over a wider, but reasonably climatologically uniform geographical areas. A similar assumption was made for monthly precipitation. We also used as reference series the averages of Auckland

Table 1. Summary of the dates and reasons (SM: site move, IC: instrument change, UK: unknown) for adjustments in the Tmax, Tmin and precipitation data series. In station names, AP indicates airport.

Station Name	*Station No.*	*Long. (°E)*	*Lat. (°S)*	*HQ temp from*	*HQ prcp. from*	*Dates of adjustments*			*Reason for adjustments*		
						Tmax	*Tmin*	*Prcp*	*Tmax*	*Tmin*	*Prcp*
Norfolk Is. AP	200288	167.6	29.0	1944	1915	None	Dec-53	None	N/A	SM	N/A
Lord Howe Is. AP	200839	159.1	31.3	1940	1950	Jan-55	None	None	SM	N/A	N/A
Willis Is.	200283	150.0	16.3	1939	1924	Jan-66, Jan-87	None	None	UK, UK	N/A	N/A
Cocos Is. AP	200284	96.8	12.2	1960	1916	Jan-79, Oct-97	Jan-79	None	SM, IC	SM	N/A
Macquarie Is.	300004	158.9	54.5	1948	1948	None	None	None	N/A	N/A	N/A
Davis	300000	78.0	68.6	1958	N/A	Feb-70	None	N/A	IC	N/A	N/A
Mawson	300001	62.9	67.6	1958	N/A	None	Feb-73, Jan-92	N/A	N/A	IC, IC	N/A
Casey	300017	110.5	66.3	1970	N/A	None	None	N/A	N/A	N/A	N/A

Table 2. Trends in maximum, minimum, mean and sea surface temperature and precipitation across the eight stations. Trends significant at the 95 per cent level are indicated in bold. Trends are calculated for the period of observations described in the text and indicated in the table.

Station Name	*Station No.*	*Long. (°E)*	*Lat. (°S)*	*Tmax (°C/dec.)*	*p-value*	*Tmin °C/dec.*	*p-value*	*Tmean °C/dec.*	*SST °C/dec.*	*HQ rainfall from*	*Rainfall mm/dec.*
Norfolk Is. AP	200288	167.6	29.0	0.05	0.008	0.06	0.027	0.05	0.06	1915	20
Lord Howe Is. AP	200839	159.1	31.3	0.08	0.00002	0.12	0.0	0.10	0.10	1950	23
Willis Is.	200283	150.0	16.3	0.01	0.69	0.10	0.00002	0.05	0.10	1924	4
Cocos Is. AP	200284	96.8	12.2	0.03	0.24	0.10	0.00009	0.07	0.11	1916	17
Macquarie Is.	300004	158.9	54.5	0.08	0.004	0.07	0.01	0.08	0.02	1948	30
Davis	300000	78.0	68.6	0.10	0.31	0.05	0.76	0.08	N/A	N/A	N/A
Mawson	300001	62.9	67.6	0.09	0.19	0.05	0.51	0.07	N/A	N/A	N/A
Casey	300017	110.5	66.3	–0.06	0.59	–0.03	0.82	–0.05	N/A	N/A	N/A

Aero, Whenuapai Aero, and Brisbane Aero maximum (minimum) temperature series, assuming that this way the statistical test would only detect inhomogeneities in the candidate data series. Another independent reference series for testing homogeneity of Norfolk Island maximum (minimum) temperatures was based on SSTs near Norfolk Island, because we had found strong correlations between local SSTs and temperatures (0.75 for maximum and 0.74 for minimum temperatures).

The statistical tests found no consistent inhomogeneities in maximum temperature data series, and it was concluded that the maximum temperature data series for Norfolk Island was likely homogeneous for the period 1944–2009. The minimum temperature data series had one inhomogeneity (December 1953) which was supported by the metadata (possible but somewhat uncertain move) and it was adjusted. Minimum temperature data were adjusted for each month separately, with an annual adjustment of +0.4 °C. Expressed as a rate of change, minimum temperature increased slightly faster (0.06 ± 0.06 °C/decade, total 0.4 °C) than maximum temperature (0.05 ± 0.04 °C/decade, total 0.3 °C) over the period of record (confidence intervals are at the 95 per cent level). An increase in maximum temperature occurred in all seasons, with the fastest warming in winter and spring. Similarly, an increase in minimum temperature has occurred in all months (except February) and in all seasons, with the largest rise in minimum temperature occurring in spring and the smallest in summer.

The homogeneity of rainfall data series for Norfolk Island was objectively tested using the Auckland, New Zealand (37.0°S, 174.8°E) and Kaitaia, New Zealand (35.1°S, 173.3°E) log-transformed rainfall data series (Fig. 1(b)), as well as total cloud amount for Norfolk Island (from 1939) as a reference series. Results showed that rainfall data were likely homogeneous at least since 1915, with no inhomogeneities detected.

Norfolk Island rainfall exhibits strong year-to-year variability with fluctuations in total annual rainfall of more than 500 mm. Even more noticeable are the large fluctuations between exceptionally wet and dry years, especially in recent decades: 1989 was very wet, with a total annual rainfall of about 2000 mm, and was followed by several dry years (800–1100 mm), then was again wet in 1998 with a subsequent dry period (see Fig. 2). The rainfall has shown a substantial (though not statistically significant at the 95 per cent confidence level) drying trend since 1915 at the rate of 20 ± 25 mm/decade which translates into a total decline of about 200 mm (or about 15 per cent of the annual mean for the indicated period of measurements). The decrease has occurred in all seasons except summer, with the largest decrease in rainfall in autumn and winter. From 1970 to 2009, the decrease in rainfall is more pronounced, on average being 40 mm/decade. The decline is consistent with that which has been observed in some regions of Australia (CSIRO 2007) where rainfall variability is influenced by the subtropical high pressure ridge (Timbal et al. 2010).

Correlations between the annual precipitation and the Southern Oscillation Index (SOI) over the period 1915–2009 were calculated for different parts of the year. The strongest association (0.57) was found for the four-month period starting in June of the concurrent year. Similarly, correlations between the annual mean temperature and the SOI over the period 1944–2009 showed that the strongest association (0.60) was for the three months period starting in September of the concurrent year. Such strong correlation over a relatively long period of time reflects the influence of the El Niño – Southern Oscillation on the Norfolk Island climate, and in part explains the marked local rainfall variability.

Lord Howe Island

Lord Howe Island (31.3°S, 159.1°E) is a small island in the Tasman Sea, 600 km east of the Australian mainland (Fig. 1(a)) and was first settled in the early 19th century. It is roughly crescent-shaped, about 10 km long and up to 2 km wide, and is an eroded remnant of a volcanic crater rim. The highest point (Mt Gower) is 875 m above the mean sea level.

Lord Howe Island has a subtropical climate, with mild to warm summers with fairly regular rain, and wetter, cool to mild winters. Climate is characterised by small diurnal as well as small annual (about 5 °C) temperature ranges, relative humidity of between 60 and 70 per cent, and predominantly easterly winds during summer months and southwesterlies during the winter months as the island experiences the trade winds and the winter westerly wind regime respectively. The annual mean rainfall is around 1500 mm, with the wettest months between May and August (Bureau of Meteorology, 2002).

Rainfall reading at Lord Howe Island commenced in 1886, and recording of temperature began a year later. Observations were performed by local residents and Post Office staff. In April 1939 the Bureau of Meteorology established a meteorological office and started taking daily observations covering rainfall, temperature, wind and cloud. The observation site was relocated in December 1954 to the eastern side of the island. Another relocation of the observation site occurred in November 1988, when it was moved to near the airport runway. At the same time an automatic weather station (AWS) was installed which was replaced in 1994.

Both Norfolk and Lord Howe islands are situated at similar latitudes (29.0°S and 31.3°S), which results in a similar regime of the prevailing winds throughout the year. Hence, maximum and minimum temperature series from Norfolk Island (starting in 1944) were used as a reference series for testing the homogeneity of the Lord Howe Island maximum and minimum temperature series respectively. In addition, averages of Norfolk Island and Whenuapai Aero, New Zealand (36.8°S, 174.6°E), Port Macquarie (31.4°S, 152.9°E) and Yamba Pilot Station (29.4°S, 153.4°E) temperature series (see Fig. 1(b)) and SSTs near Lord Howe Island were used as reference series.

Prior to 1939 observations were performed by non-Bureau staff and very little metadata is available. Hence it was decided that only Lord Howe Island temperature series from 1940 (as data for 1939 were incomplete) would be considered in this study. Results obtained by the objective statistical test showed that maximum temperature series had a discontinuity around the time of the December 1954 station move. The minimum temperature series had four potential inhomogeneities (in 1943, 1965, 1977 and 1983) though these were not supported by metadata.

The maximum temperature series was adjusted for the site change in 1954 (data were adjusted for each month separately, with an annual adjustment of –0.3 °C). For minimum temperature no adjustments were applied, due to the lack of support in the metadata. Original and adjusted annual maximum temperature series are shown in Fig. 3. After adjustment of the maximum temperature series, the correlation coefficient between maximum and minimum temperatures increased from 0.43 to 0.62 providing further evidence that the data quality is improved when account is made for the change in station location in 1954, as would be expected.

The minimum temperature data and homogenised maximum temperature data reveal statistically significant warming trends for minimum (0.12 ± 0.05 °C/decade) and maximum (0.08 ± 0.04 °C/decade) temperatures resulting in a total rise of 0.8 and 0.6 °C since 1940 (Fig. 2). We note that the trends are stronger than those at Norfolk Island which lies to the northeast. In recent decades SSTs have warmed faster in the western Tasman Sea than in the eastern Tasman Sea (CSIRO 2007) and this difference in warming is evident when comparing the two stations.

The increase in maximum temperature at Lord Howe Island has occurred in all months and in all seasons, with the largest rise occurring in winter and spring and the smallest in autumn. The increase in minimum temperature has also occurred in all months and in all seasons, with the largest rise occurring in summer and smallest in winter. As at Norfolk Island, maximum and minimum temperatures at Lord Howe Island show relatively small day-to-day and seasonal variations, owing to the moderating influence of the surrounding warm oceans. Interannual variations in mean air temperature (calculated as an average of maximum and minimum temperatures) and SSTs at Lord Howe Island follow a similar pattern (correlation coefficient 0.78), and trends are of the same magnitude (0.10 ± 0.04 °C/decade) over the period 1940–2009.

Homogeneity of the rainfall data series for Lord Howe Island was tested using rainfall series for Norfolk Island and average rainfall for Cape Moreton Lighthouse (27.0°S, 153.5°E) and Yamba Pilot Station (29.4°S, 153.4°E). All rainfall data series were logarithmically transformed prior to testing. Total cloud amount (from 1940) at Lord Howe Island was also used as a reference series. Results showed that rainfall data had a statistically significant inhomogeneity in 1949. As there was nothing in the historical information (metadata) to explain the inhomogeneity, data were not adjusted but to minimise the possible impact of an inhomogeneity, the data were truncated at 1950.

Like Norfolk Island, Lord Howe Island rainfall shows strong year-to-year variability, with large fluctuation in the annual amounts with a substantial rainfall trend. The linear trend shows a decline of 23 ± 43 mm/decade since 1950 amounting to a total decline of about 140 mm (or about nine per cent of the annual mean for the indicated period of measurements). Since 1970 the rainfall decline has been even steeper, at a rate of 53 mm/decade. Figure 4 shows a scatter diagram of annual rainfall at Lord Howe Island against total cloud amount for the 1950–1969 and 1970–2009 period highlighting a decline in both rainfall and cloudiness in the past 40 years. As in the case of the Norfolk Island, the decrease in rainfall is potentially linked to pressure and circulation changes that have impacted on rainfall in some regions of Australia (CSIRO 2007; Timbal et al. 2010).

Willis Island

Willis Island (16.3°S, 150.0°E) is a small coral atoll in the Coral Sea, some 450 km east of Cairns (Fig. 1(a)). It is aligned northwest to southeast and is about 500 m long by 150 m wide, rising to about 9 m above the mean sea level at its highest point.

Willis Island experiences a dry season from May to November and a wet season from December to April. Mean annual rainfall is 1100 mm, most of which falls during the wet season. Mean cloud amount and humidity are also higher during the wet season. The weather in the dry season is characterised by prolonged dry periods and dominated by southeast trade winds, interspersed with the occasional tropical disturbance (Bureau of Meteorology 2002).

The monitoring of weather at Willis Island began in 1921 with the main purpose of providing advanced meteorological warning services for tropical cyclones near the Queensland coast. Observations were performed by Amalgamated Wireless Australia (AWA) staff, i.e. mainly by radio operators. From 1939 one member of the Willis Island crew was from the Bureau of Meteorology, and from 1967 Willis Island was completely staffed by professional Bureau

Fig. 2. Comparison of mean annual temperatures and annual rainfall for Norfolk and Lord Howe Islands.

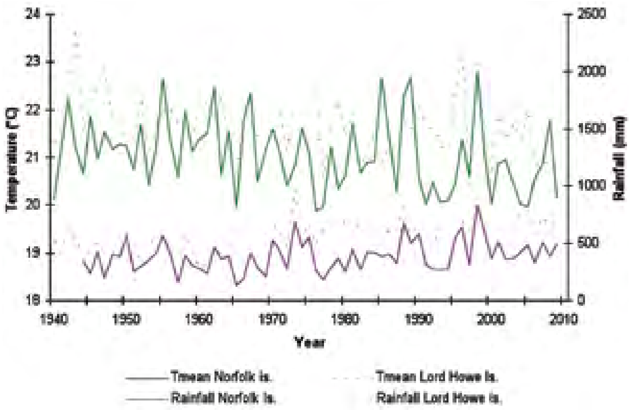


Fig. 3. The original and adjusted maximum temperature series for Lord Howe Island. Vertical line shows year in which data were adjusted.

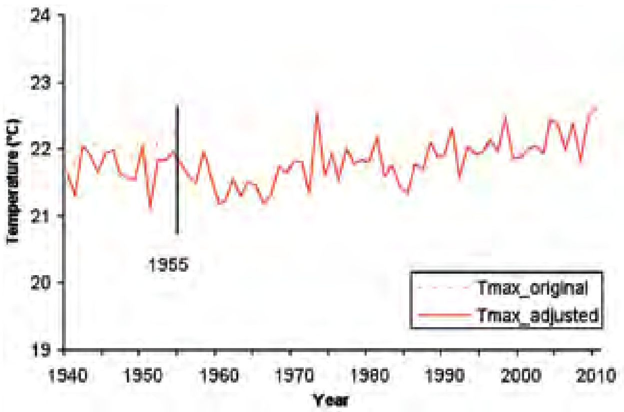
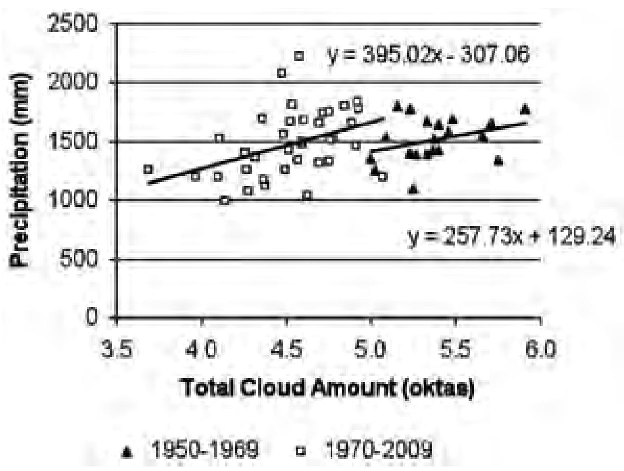


Fig. 4. Scatter plot showing annual rainfall against total cloud amount (TCA) at Lord Howe Island for two periods: 1950–1969 and 1970–2009.



observers. Observations included rainfall, temperature, wind and cloud. An AWS was installed in June 1991, while between June 2004 and November 2005 the station was closed for a major upgrade to facilities. For this project it was decided to use temperature data from 1939 only, as prior to that time temperature data are incomplete (with gaps in 1927, 1933–1934 and 1936–1938), and were taken by non-Bureau personnel with no evidence of training.

We used Cairns Aero (16.9°S, 145.8°E) and Townsville Aero (19.3°S, 146.8°E) high-quality temperature data series as reference series for detecting inhomogeneities in the Willis Island maximum and minimum temperatures (Fig. 1(b)), We also used the average of Cairns Aero and Townsville Aero maximum (minimum) temperature, as well as SST in the vicinity of Willis Island. Results obtained by the objective statistical test indicate that the maximum temperature series has two change points, in 1966 and around 1987 (Fig. 5). These change points are not confirmed by the metadata about the site, although it is known that there were slight changes in the observation site which are not reported in the station's files, but may have affected the observations (Zillman et al. 1989). Visual inspection of the maximum temperature anomalies series also confirmed change points detected by the statistical test. Consequently, maximum temperature was adjusted for changes in 1966 and 1987.

Unlike the case for Willis Island maximum temperature, where two change points were (strongly) indicated by the statistical test using two independent reference series (surface temperature and SST), results of the objective statistical test for the Willis Island minimum temperature showed that the timing of detected change points were different (and depended on the choice of reference series). Consequently, minimum temperature was not adjusted as the homogeneity test did not provide consistent guidance.

Maximum temperature was adjusted for changes in January 1966 (annual adjustment –0.1 °C) and January 1987 (annual adjustment –0.1 °C). Original and adjusted maximum temperature series for Willis Island are shown in Fig. 6. After adjustment, the correlation coefficient between maximum and minimum temperatures increased from 0.44 to 0.59, providing further evidence of improvement in data quality when the inhomogeneities are corrected.

Maximum temperature at Willis Island has increased slightly, by about 0.1 °C in total since 1939, while minimum temperature has increased by about 0.7 °C since 1939. The rate of change in night time and daytime temperatures are therefore 0.1 ± 0.05 °C/decade and 0.01 ± 0.05 °C/decade respectively over the full period. Annual maximum, minimum and mean temperature for Willis Island are shown in Fig. 7, together with local SSTs. Interannual variations in mean air temperature at Willis Island are highly correlated with sea surface temperature (correlation coefficient 0.72),

Fig. 5. Output of the RHTest for Willis Island maximum temperature with (a) an average of Cairns and Townsville high-quality temperatures and (b) sea surface temperature as a reference series.

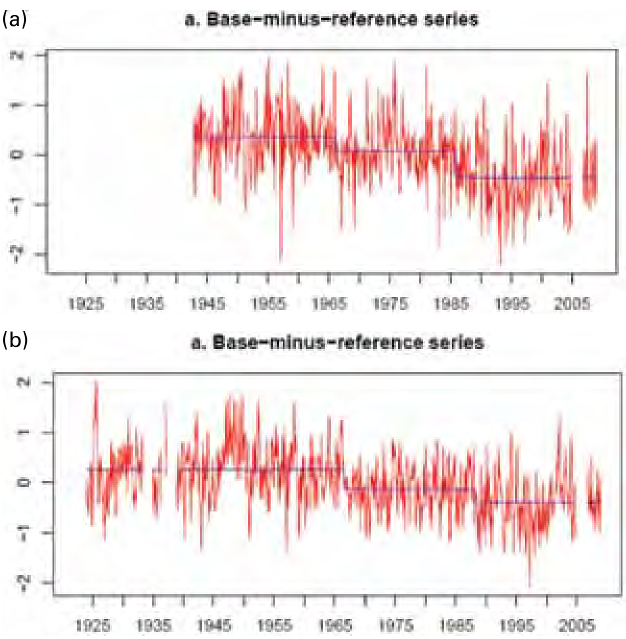


Fig. 6. The original and adjusted maximum temperature series for Willis Island. Vertical lines show years in which data were adjusted.

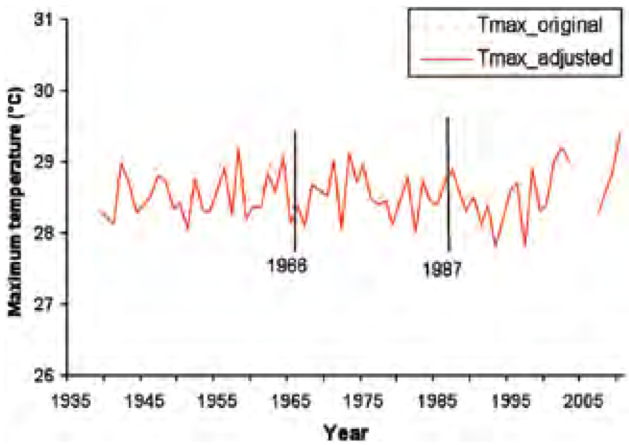
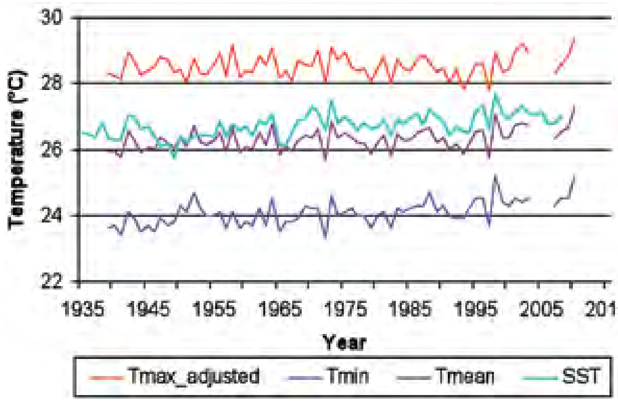


Fig. 7. Annual maximum, minimum and mean temperatures at Willis Island. Also shown is SST calculated from the NOAA ERSST in the vicinity of Willis Island.



although the rate of increase in sea surface temperature is higher (0.1 °C/decade) than for the mean air temperature (0.05 °C/decade) during the same period of time. This result is in contrast to Lord Howe and Norfolk islands where the trend over land is slightly greater than for the surrounding waters. It is not clear whether this difference is due to the subtropical versus tropical locations or something else.

Willis Island rainfall shows strong year-to-year variability. Homogeneity of the rainfall data series was objectively tested using log-transformed annual rainfall series from Cairns and Townsville, and total cloud amount at Willis Island as a second, independent reference series. Results suggested that the rainfall data were homogeneous from 1924 onward. The rainfall at Willis Island shows essentially no change over the period of observations, with a very slight upwards linear trend of 4 ± 40 mm/decade (or about 2.5 per cent of the annual mean for the indicated period of measurements). The lack of a trend stands in contrast to the situation on the Queensland coast further west (Climate Change in Australia 2007). At least part of the explanation for the lack of trends may be the very large rainfall variability at Willis Island which makes detecting trends very difficult.

Cocos (Keeling) Islands

The Cocos (Keeling) Islands (12.2°S, 96.8°E) are a group of 27 coral islands in a pair of atolls in the eastern Indian Ocean (Fig. 1(a)). The islands were first permanently inhabited in the early 19th century, and have been a territory of Australia since 1955. The islands are low-lying, typically 1.5 to 3 m above the mean sea level, with the highest point having an elevation of 11 m.

The Cocos Islands have a tropical maritime climate, with little diurnal or seasonal temperature variation and a distinct wet (January to July) and dry (August to December) season. Mean annual rainfall is 1950 mm, while mean rainfall during the wet season is about 1450 mm. The average cloud amount and relative humidity remain high and easterly or southeasterly winds predominate throughout the year (Bureau of Meteorology 2002).

Measurements of precipitation at Cocos Islands began in 1901 at a site on Direction Island. A meteorological office was opened in September 1943 by the Royal Australian Air Force at the airport (located on West Island), but closed in August 1946. It was reopened in February 1952, with observations taken by trained Bureau of Meteorology observers. Observations performed included rainfall, temperature, wind and cloud. A new office building was completed in May 1980 and some changes in instrumentations were made, as well as the relocation of the observation site (the change was made in 1979; personal communication G. Jemmeson). In July 1993 an AWS (Micromac) was installed at the existing enclosure site; it was then replaced by a Vaisala Milos AWS in October 1997.

Obtaining reference series for Cocos Islands has been somewhat problematic due to the remoteness of the islands. The one site close to Cocos Islands, located at Christmas Island, contains a series of inhomogenities and is not of a sufficient quality for the purpose. The homogeneity of the maximum and minimum temperature series was objectively tested using SSTs as a reference series for the both temperature series separately. The statistical test was also applied for the daily temperature range (DTR) with total cloud amount (TCA) at Cocos Islands (from 1952) as a reference series. Three possible change points were identified in the maximum temperature series and two of these were confirmed by the metadata (1979 and 1997). The third change point, not confirmed by the metadata, was in 1958. To avoid the impact of a possible inhomogeneity in 1958 on the calculated trends and variability, it was decided to use only data from 1960 onward. In the minimum temperature data only one change point (1979) was identified by the objective test coinciding with the site relocation. Visual inspection of the maximum and minimum temperature anomalies series also confirmed change points detected by the statistical test. Consequently, maximum temperature was adjusted for changes in 1979 (annual adjustment –0.2 °C) and 1997 (annual adjustment +0.5 °C), while minimum temperature was adjusted for a change in 1979 (annual adjustment +0.4 °C) with adjustments leading to a reduction in the warming trend compared to the raw data. Original and adjusted annual maximum and minimum temperature series are shown in Fig. 8. After adjustment, the correlation coefficient between maximum and minimum temperatures increased from 0.65 to 0.74, suggesting improvement in the data quality.

Since 1960, maximum temperature at Cocos Islands has increased slightly, by about 0.15 °C (0.03 ± 0.06 °C/decade) while minimum temperature has increased by about 0.5 °C (0.10 ± 0.06 °C/decade). Increases in maximum temperature have occurred during the wet season (January–July), while in the dry season maximum temperature has slightly decreased. The increase in minimum temperature has occurred during both seasons, with slightly more warming during the wet season. As with the other tropical islands, the inter-annual variations in mean air temperature (calculated as the mean of maximum and minimum temperatures) at Cocos Islands show a high association with sea surface temperature (correlation coefficient 0.65), although the rate of increase in sea surface temperature is slightly higher (0.10 °C/decade) than for the mean air temperature (0.07 °C/decade) during the same period of time.

Cocos Islands rainfall exhibits strong year-to-year variability. Homogeneity of the rainfall data series was objectively tested using TCA at Cocos Islands as a reference series (from 1953). The objective test was also applied for the case without a reference series for the whole length of the rainfall series. Results indicated that the rainfall data were likely to be homogeneous from 1916. The very high interannual variability of rainfall means that the downwards trend, that led to a total decline of 160 mm since 1916, is not statistically significant (17 ± 50 mm/decade, or about eight per cent of the annual mean for the indicated period of measurements). Since 1970 the decrease in rainfall is much stronger, with an average rate of 130 ± 190 mm/decade, and with low rainfall in all years from 2002 to 2009. Cocos Island is in the vicinity of the eastern pole of the Indian Ocean Dipole (IOD, Saji et al. 1999) in a region which experiences suppressed rainfall during positive IOD events (Abram et al. 2008). The declining rainfall at Cocos Islands in recent decades coincides with a shift of the IOD towards more frequent positive events (Cai et al. 2009) and sits in contrast to the marked rainfall increases that have occurred over northwestern Australia over the same time (Jones et al. 2009).

Macquarie Island

Macquarie Island (54.3°S, 158.6°E) is a long, narrow, steep-sided island forming a plateau, 34 km long and 5.5 km wide at its broadest point, lying approximately in a north–south direction (Fig. 1(a)). It has a history of human presence from the early 19th century. The current meteorological station was established by the Australian National Antarctic Research Expeditions (ANARE) in March 1948 and is situated on the northern isthmus of the island, 6 metres above MSL (Gibbs et al. 1952).

Macquarie Island has a maritime climate characterised by high total cloud amount (TCA), persistent strong west to northwesterly winds, mean rainfall of about 960 mm/year and a high number of days with precipitation throughout the year. The diurnal, seasonal and annual variations in temperature are small (Bureau of Meteorology 2002).

The first study of Macquarie Island's climate was probably made by Gibbs et al. (1952), who analysed the observations of the first year of the Australian National Antarctic Research Expeditions in 1948. Adamson et al. (1988) analysed mean annual surface temperature at Macquarie Island and found that it had a marked upward trend in the period 1949–1986, while Streten (1988) described the general characteristics of the climate.

Observations that commenced in 1948 included temperature (using dry bulb, maximum and minimum thermometers, as well as thermograph, all mounted in a Stevenson screen), atmospheric pressure (using mercurial barometer and barograph), precipitation (using a 203 mm rain gauge and pluviograph), hours of sunshine (using Stokes Campbell sunshine recorder) and visual observation of cloud amount (Gibbs et al. 1952). An AWS was installed but manual readings are still taken as the primary observations and used in this study.

There was a change of enclosure (but no relocation) in 1979. Temperatures recorded by thermometers were regularly checked against values recorded by the thermograph. Similarly, precipitation amounts measured with the rain gauge were compared regularly to amounts recorded by the pluviograph. Frozen precipitation is common at the site, though rain is the dominant form of precipitation. A snow gauge was installed in 1996 in addition to the rain gauge.

A study by Adamson et al. (1988) found that Macquarie Island's temperature record is more similar to the area east and southeast of New Zealand, rather than Tasmania. Consequently, the average of mean surface temperatures from Invercargill, New Zealand (46.7°S, 168.6°E) and Campbell Island, New Zealand (52.5°S, 169.2°E) was used as a reference series (Fig. 1(b)) for detecting inhomogeneities in the mean temperature for Macquarie Island. As a second (independent) reference series we used SST in the vicinity of Macquarie Island. We note that based on annual averages the correlation between mean temperature at Macquarie Island and SST is 0.83.

Results obtained by the objective test, as well as careful investigation of the metadata, suggested that maximum and minimum temperature data for Macquarie Island were homogeneous. Both maximum and minimum temperatures warmed by around 0.45 °C over the period of observations, with maximum temperature increasing slightly faster (0.08 ± 0.06 °C/decade) than minimum temperature (0.07 ± 0.06 °C/decade). Both trends are statistically significant (see Table 2). Increases in maximum temperature have occurred in all months and all seasons, with the largest warming in summer and autumn, and the smallest in winter. Similarly, increases in minimum temperature have occurred in all months and

Fig. 8. The original and adjusted maximum and minimum temperature series at Cocos Islands. Vertical lines show years in which data were adjusted.

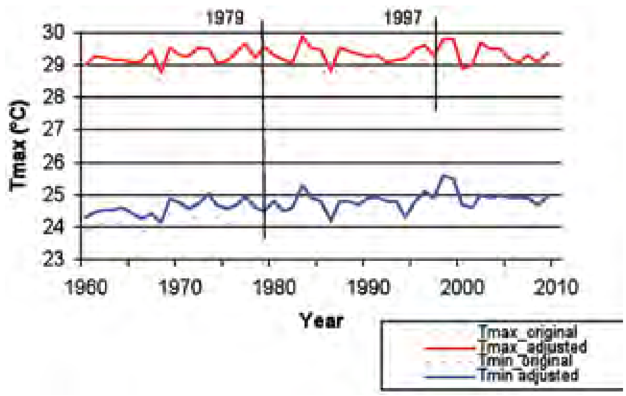
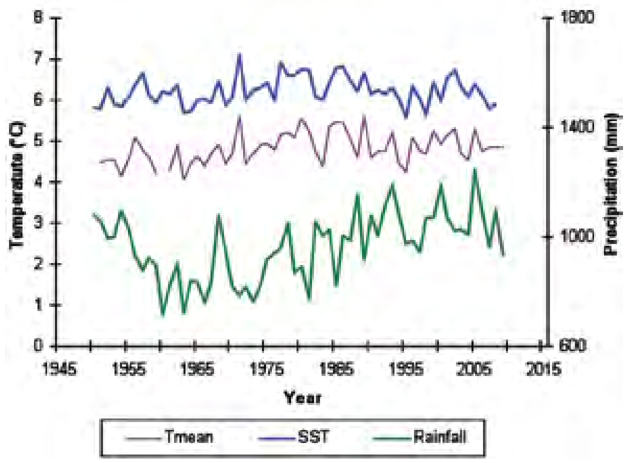


Fig. 9. Mean air temperature (Tmean), SST and precipitation at Macquarie Island.



in all seasons, with the largest rise in minimum temperature occurring in autumn and the smallest in winter. We note that the warming trend in SSTs near Macquarie Island is much slower than over the island, being at the rate of just 0.02 °C/decade (Fig. 9). The slow rate of warming largely reflects a lack of warmer SSTs in the last 20 years. While we expect ocean temperatures to warm more slowly than land temperatures on average, one would expect this effect to be less clear for small and remote islands. Hence the difference in trends is a potential caveat for the reliability of SST data around Macquarie Island or undetected inhomogenieities in the land based record.

The homogeneity of the total precipitation data series was objectively tested using TCA and mean sea level pressure (from 1948 and 1952 respectively) as reference series at Macquarie Island. Statistical tests with these two reference series showed two (common) points of discontinuity (in 1956 and 1982). Neither of these discontinuities have support in the metadata. Additional checks performed using RClimDex software (Zhang and Yang 2004) suggested that the changes were due to an increase in the number of 'heavy' raindays (rainfall greater than 10 mm). Consequently, it was concluded that Macquarie Island precipitation data series was homogeneous and that the change points probably reflected real and abrupt changes in the local climate.

In contrast to southern Australia which has experienced a rainfall decline (Climate change in Australia 2007; Timbal et al. 2010), Macquarie Island has experienced a marked increase in rainfall at the rate of 30 ± 18 mm/decade amounting to a total rise of nearly 200 mm since 1948 (or about 20 per cent of the annual mean for the whole period of measurements). The increase has occurred in all seasons, with the largest rise occurring in autumn and winter and the smallest in summer. Over the last four decades, since 1970, the rate of increase in annual precipitation is even higher, being 65 mm/decade. The increase in annual total precipitation also suggests a change in regional atmospheric circulation patterns, possibly related to the Southern Annular Mode (Trenberth 2007) which has been trending more positive in recent decades.

Mawson

Mawson (67.6°S, 62.9° E) is Australia's oldest Antarctic station and the oldest continuously inhabited station south of the Antarctic Circle (Fig. 1(a)). It was opened in February 1954 and is located on a rocky outcrop on the Antarctic coastline. Behind the station, the continental ice sheet slopes upwards towards a high plateau, resulting in strong katabatic winds. The temperatures at Mawson are generally very cold with an average annual mean maximum of –8.3 °C and annual mean minimum of –14.4°C.

The observation of maximum and minimum temperatures at Mawson station started in March 1954. A dry bulb thermometer and thermograph were mounted in a Stevenson screen; the thermograph was used to obtain the daily temperature extremes. In early 1973 the Fielden (remote temperature sensors and display) was introduced at the station and was used for maximum and minimum temperatures as well. From January 1992 those temperatures were obtained from the maximum and minimum thermometers mounted on the anti-vibration supports. An AWS was installed in January 1994 (Micromac) and was replaced by another AWS (Almos) in April 2004.

Homogeneity of the daily temperature range (DTR, the difference between maximum and minimum temperature) was tested using TCA (from 1955) observed at the station as a reference series. This indicated inhomogeneities in DTR at about the time when the Fielden was installed (1973) and when it was replaced by the maximum and minimum thermometers (1992). One more change point was detected in 1984 but this change point was not confirmed by the metadata. As there are no other stations with suitable data series (starting in 1954), for further testing it was decided to use only Mawson maximum and minimum temperature data from 1958 (as Davis' data started at that time). The homogeneity of the maximum temperature series at Mawson station was also objectively tested using the average of Davis (68.6°S, 78°E) and Molodeznaya (67.7°S, 45.9°E) mean temperatures as a reference series (Fig. 1(b)). The same tests were repeated for minimum temperature. The outputs of the statistical tests were evaluated and it was concluded that maximum temperature data were homogeneous, while minimum temperature had two inhomogeneities. This result can probably be explained by the fact that Mawson is known for strong katabatic winds that exhibit a strong influence on the measurements of minimum temperature. Mawson minimum temperature was adjusted for changes in February 1973 (annual adjustment –0.2 °C) and January 1992 (annual adjustment –0.1 °C). Original and adjusted annual minimum temperatures, as well as annual maximum temperature, are shown in Fig. 10. After adjustment, the correlation between annual maximum and minimum temperatures increased from 0.91 to 0.94.

Maximum temperature at Mawson increased by 0.5 °C (0.09 ± 0.1 °C/decade), while minimum temperature increased by about 0.3 °C (0.05 ± 0.2 °C/decade) over the period 1958–2009. Warming in maximum temperature has occurred in autumn and winter, while in spring and summer maximum temperature shows decreasing trends. For minimum temperature, increases have occurred in all seasons, with the largest rise in minimum temperature occurring in autumn.

Davis

Davis (68.6°S, 78°E) is the most southerly Australian station (Fig. 1(a)), and was opened in January 1957. It is situated on the coast of the ice-free Vestfold Hills that shield the station from the katabatic winds that are normally associated with the East Antarctic coast. Davis is a key Australian site, supporting the largest population of scientists during the summer season. The temperatures at Davis are generally very cold with an average annual mean maximum of –7.4 °C and annual mean minimum of –13.3 °C.

The observation of maximum and minimum temperatures at Davis started in February 1957. A dry bulb thermometer and thermograph were mounted in a Stevenson screen. The thermograph was used to obtain the daily temperature extremes, as it was suggested that maximum and minimum thermometers were unsuitable because of strong wind conditions vibrating the mercury thermometers. In January 1965 Davis was temporarily closed to allow the diversion of the Australian Antarctic Division's resources for the building of Casey station. It was reopened on the 15 February 1969 at the same site. Since the thermograph itself experienced some problems in the harsh Antarctic conditions and since, on some occasions, it was impossible to visit the screen, a Fielden (remote temperature sensors and display) was installed in February 1970. As stated in the *1976 Annual Report for Davis* (station history files), the Fielden equipment was generally accurate, and usually all temperatures were taken from it, including maximum and minimum temperatures. From January 1992 maximum and minimum thermometers on anti-vibration supports were installed and utilised. From December 1992 all observations were performed at a new site, due to the building of a new meteorological office and a balloon complex. An AWS (Micromac) was installed (as a replacement for the Fielden) in May 1994 and in January 2004 it was replaced by an Almos AWS.

Homogeneity of the DTR was objectively tested using TCA (from 1957) observed at the station as a reference series. This indicated an inhomogeneity in monthly DTR at the time when the Fielden instrumentation was installed. Homogeneity of the maximum and minimum temperature series at Davis station was objectively tested using the average of Mawson (67.6°S, 62.9°E) and Mirnyi (66.5°S, 93.0°E) mean temperatures as a reference series (Fig. 1(b)). From the output of the statistical tests it was concluded that the minimum temperature data were homogeneous, while maximum temperature had an inhomogeneity in 1972. Since it was found that maximum temperature data series at Mawson station was homogeneous, a difference series between Davis and Mawson was produced; it indicated a discontinuity around the beginning of 1970. Davis' maximum temperature was adjusted for the change in February 1970. The annual adjustment was +0.6 °C. Original and adjusted annual maximum temperature series are shown in Fig. 11. After adjustment, correlation between maximum and minimum temperatures increased from 0.94 to 0.96.

Maximum temperature at Davis has increased by 0.6 °C (0.11 ± 0.3 °C/decade), while minimum temperature has increased less, by about 0.3 °C (0.05 ± 0.3 °C/decade) over the period of observations. The increase in maximum temperature has occurred in all seasons, with the largest rise in maximum temperature occurring in autumn and winter. Similarly, increases in minimum temperature have occurred in all seasons, with the largest rise occurring in spring. We note however that all trends lack statistical significance.

Fig. 10. The original and adjusted minimum temperature and maximum temperature for Mawson station. Vertical lines show years in which minimum temperature data were adjusted for inhomogeneities.

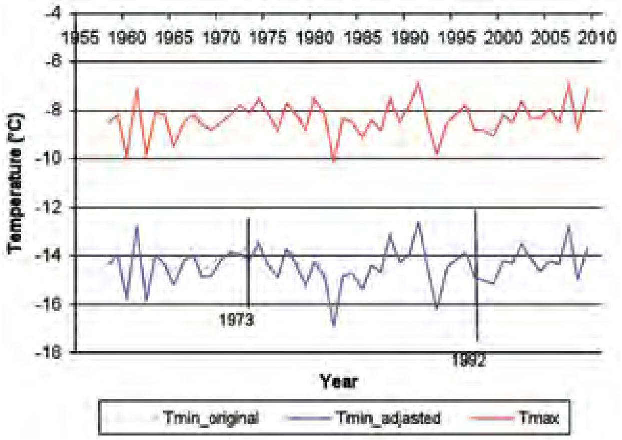
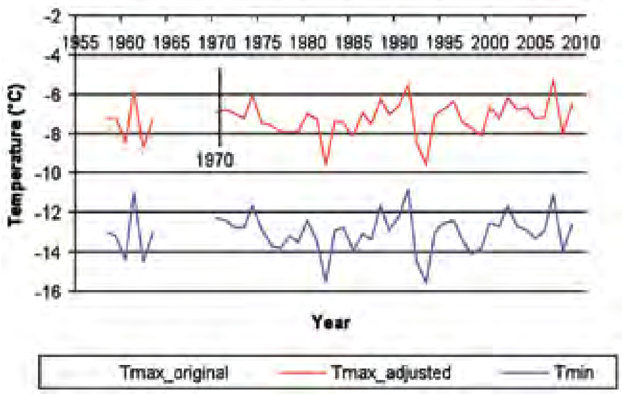


Fig. 11. The original and adjusted maximum temperature, and minimum temperature for Davis station. Vertical line shows year in which maximum temperature data were adjusted.



Casey

Casey station (66.3°S, 110.5° E) is located close to the now abandoned Wilkes station, established by the United States of America during the International Geophysical Year in 1957–1958 (Fig. 1(a)). Australia took over responsibility of Wilkes station in 1959, and it was used by Australian National Antarctic Research Expeditions from 1960 to February 1969. The first Casey Base (The Tunnel) was built a few miles away, on the opposite side of the bay from Wilkes, but had to be abandoned due to the build-up of ice around buildings. The same problem forced another relocation to the current more elevated position of Casey Base, at which observations commenced in 1 January 1989. The temperatures at Casey are very cold with an average annual mean maximum of –5.6 °C and an annual mean minimum of –12.3 °C.

The observation of maximum and minimum temperatures at Wilkes started on 1 February 1960. Temperatures were obtained from liquid in glass or electrical resistance thermometers mounted in a Stevenson screen and a continuous record was obtained from a thermograph or a recording electrical resistance thermometer. Maximum and minimum temperatures were obtained from the thermograph trace. In 1972 a Fielden was already operational, most likely installed after the 1969 opening of the Casey Base. Temperatures were taken from the maximum and minimum thermometers in the screen, except if the screen was inaccessible due to wind, when temperatures were obtained from the Fielden. It is not clear exactly when maximum and minimum thermometers replaced the thermograph at Casey. In January 1994 an Micromac AWS was installed. It was replaced with an Almos AWS in March 2003.

Because of the lack of metadata for the period before Casey Base (The Tunnel) was opened, only data from March 1969 onwards are used in the homogeneous record. The homogeneity of the DTR was objectively tested using TCA (from 1960) observed at the station as a reference series. Obtained results suggested that the DTR series was homogeneous. Similarly, homogeneity of the maximum and minimum temperatures was tested using the average of Mirnyi (66.5°S, 93.0°E) and Dumont D'Urville (66.7°S, 140.0°E) mean temperatures as reference series (Fig. 1(b)). Results obtained by the objective tests indicated change points in January 1973 (for maximum temperature) and August 1974 (for minimum temperature). These change points are not supported by the metadata, and as the DTR series was found to be homogeneous, it was concluded that Casey Base maximum and minimum temperature series were likely to be homogeneous.

Maximum temperature at Casey decreased about 0.2 °C (–0.06 ± 0.3 °C/decade), while minimum temperature decreased about 0.1 °C (–0.03 ± 0.3 °C/deacde) since 1969. It is interesting to note that the decreases in both maximum and minimum temperatures have occurred in all months except April, July, August and September. The strongest decrease in both temperatures occurred in May, while the strongest increase occurred in September. We note however that all trends lack statistical significance.

Conclusions

In this study we presented a brief history of observational changes that occurred at Australia's remote island sites (located at Norfolk, Lord Howe, Willis, Cocos and Macquarie islands) and Antarctic sites (Mawson, Davis and Casey Bases located in the east Antarctic). These eight sites now have records of maximum/minimum temperatures and precipitation that are long enough to enable reliable analysis of trends. Christmas Island also has a sufficiently long data record, but it was not included in this study due to many changes in the location of the observing site that resulted in a poor quality of data including a move in elevation by some 250 m.

Climate data are considered homogeneous if variations in the data are a result only of variations in weather and climate (Conrad and Pollak 1962). In practice, it is very rare to have a long, homogeneous, raw data record. To detect and reduce (or remove, if possible) the impact of non-climatic factors on climate data series, different methods have been developed based on metadata only, statistical homogeneity tests only or a combined approach when both metadata and statistical tests are used.

In this work we applied information obtained from both metadata and objective statistical tests, and developed a new method of evaluating inhomogeneities (change points) in the data series using statistical tests based on two or more independent reference series. Due to the stations' remoteness, we were often forced to use temperature (precipitation) records from sites that were far away from candidate sites to generate reference series, assuming that monthly temperature (precipitation) means fluctuate in a similar way over geographical areas with uniform climatological characteristics. For the most part the results we have found are consistent, and the same change points often appeared in the outputs of the objective tests when different (independent) reference series were used.

Generally, it was found that, out of eight sites, only one site had homogeneous records (Macquarie Island). Other sites had typically one or two inhomogeneities in the data series, though in many cases the detected change points are relatively small. Data were adjusted when the change points were supported by the metadata, resulting in the homogeneous maximum and minimum temperature and precipitation time series, which were further analysed. Consistency checks between the data, for example comparing maximum and minimum temperature correlations revealed that homogenisation did improve the quality of records overall.

Analysis of the homogenised time series showed that the overall temperature increase at all island sites fits the warming of SSTs in their vicinity and is consistent with larger scale warming trends that affect the globe. It is interesting to note that all tropical and sub-tropical sites show faster warming in minimum temperature than in the maximum temperature. Mean surface air temperatures increased by between 0.3 to 0.7 °C since about 1940 at Norfolk, Lord Howe and Willis islands, and 0.3 °C since 1960 at Cocos Islands. Macquarie Island also showed an increase in the mean surface air temperature of about 0.4 °C since 1950. In contrast, at Antarctic sites Davis and Mawson the maximum temperature increased faster than the minimum temperature. At Davis the mean surface air temperature increased by about 0.5 °C since 1958, while at Mawson the increase was about 0.4 °C over the same period of time. These rates of warming are fairly similar to that estimated for East Antarctica as a whole (Steig et al. 2009). At Casey the mean surface temperature showed a decreasing trend of –0.05 ± 0.3 °C/decade since 1970, resulting in a temperature decrease of 0.2 °C over the 1970–2009 period. The decreasing trend in temperature at Casey station is most likely related to decreases in stratospheric ozone which, over the period 1971–2000, resulted in cooling over parts of the Antarctic interior, though large warming in the Antarctic Peninsula region was observed (IPCC 2007). Temperature trends for all three Antarctic sites are not statistically significant, due to large interannual temperature variability, and it is vital that measurements continue to determination of longer-term warming trends given the very large size of Antarctic ice sheet.

Apart from Lord Howe Island, precipitation was found to be homogeneous at all remote island sites. This is perhaps not too surprising given the relatively slight topography near the gauges and the consistent use of manual gauges through the period of record. Norfolk, Lord Howe and Cocos islands recorded substantial decreases in precipitation, while Macquarie Island recorded a substantial increase. Decreased precipitation is associated with decreases in total cloud amount that are observed at all tropical/subtropical island sites.

The rainfall declines at Norfolk and Lord Howe islands are consistent with broader trends seen in parts of southern and eastern Australia, and consistent with a general intensification of the subtropical ridge of high pressure and associated declines in baroclinicity (Timbal et al. 2010). The declines at Cocos Islands are consistent with the recent positive trends in the Indian Ocean Dipole. The large rainfall increases which we have found at Macquarie Island stand in contrast with declines affecting mainland southern Australia in recent decades. Further, we note that the largest increases are evident during autumn–winter, which is also the period when rainfall has most consistently declined over southern Australia. These trends are consistent with a southward contraction of the polar westerlies (Trenberth 2007).

It is important to stress again the value of observations from these remote sites for both the day-to-day analysis of hemispheric weather and for the long-term monitoring of changes in climate, as they are largely unaffected by industrial activities and urbanisation. Despite the introduction of the new observational techniques, such as remote sensing from meteorological satellites, the observations from these sites provide the longest available instrumental records and baseline data for calibration by other techniques. It is also important to stress the necessity of preserving each observing site in its current state, particularly those that are located in inhabited surroundings (Norfolk, Lord Howe and Cocos islands).

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