Australia’s climate data FAQ

Australian Climate Observations Reference Network – Surface Air Temperature (ACORN-SAT)

August 2015
What is the Bureau’s role in managing temperature data?

The Bureau manages and maintains the equipment that collects the data that makes up Australia’s temperature record. The Bureau also has highly qualified staff with the scientific expertise to collect, curate and analyse the data.

The Bureau of Meteorology has been responsible for collecting the primary observations for Australia’s climate record since 1908. Developing and analysing long-period climate records requires a mix of skills covering climatology, meteorology, metrology, physics, mathematics, computer programming and statistics. The Bureau employs staff with these skills and is the most suitable institution to undertake the necessary analyses. Internationally, it is common for the analysis of climate data to sit with a meteorological or geophysical agency for example Canada, USA, Japan, China, Russia, South Korea, Indonesia, Malaysia and India.

In addition to the national temperature estimate for Australia produced by the Bureau, various international groups independently produce temperature estimates for Australia as part of their own global and regional analyses. Prominent examples include analyses prepared by National Aeronautics and Space Administration (NASA), National Oceanic and Atmospheric Administration (NOAA), Berkeley Earth and the UK Hadley Centre/Climate Research Centre. These analyses generally produce similar results to the Bureau’s analysis of the ACORN-SAT dataset (see Question 15).
What is ACORN-SAT?

The temperature data that comprise Australia’s long-term climate record are known as ACORN-SAT (Australian Climate Observations Reference Network – Surface Air Temperature).

The ACORN-SAT dataset is an analysis of Australian temperature observations since 1910 that provides a record of temperatures that can be compared through time.


The Bureau’s analysis methods for ACORN-SAT www.bom.gov.au/climate/change/acorn-sat/#tabs=Methods have been published in international peer review journals and subject to external independent reviews in 2011 and 2015. These external reviews expressed overall confidence in the Bureau’s practices and found its data and analysis methods to be among the best in the world.
What is homogenisation?

*Homogenisation refers to the method of adjusting temperature records to remove artificial biases, such as the impact of a weather station moving from one location to another.*

Observational climate datasets are regularly updated to include newly digitised historical paper records and improved analysis techniques. This is a complex task conducted using scientifically peer-reviewed processes.

One of the aims of temperature data analysis is to ensure that records can be consistently compared from one time period to another. This is because a large number of factors that are unrelated to climate affect the consistency of the temperature records over time.

For example, while considerable effort is made to keep observational practices consistent, changes in observing methods or technology over time may create artificial ‘jumps’ in the temperature data.

These include artificial jumps due to:

- a shift in the location of the weather station (for example, from a post office to an airport)
- a change in the environment around the station (for example, a tree grows, a structure is built, a lawn is irrigated)
- a change in measurement method (for example, from a manual instrument to a recording electronic instrument).

The Bureau analyses and adjusts the ACORN–SAT temperature data to correct for these non-climate-related influences. Climatologists refer to these adjustments as *homogenisation*. Temperature data that have been adjusted to account for these influences are known as *homogenised* temperature data. Further information on the homogenisation process can be found on the Bureau’s webpage: [www.bom.gov.au/climate/change/acorn-sat/#tabs=Methods](http://www.bom.gov.au/climate/change/acorn-sat/#tabs=Methods)

The Bureau provides its temperature data to researchers in Australia and overseas, and works closely with scientists to ensure that the data meet their research needs. The Bureau makes both adjusted and unadjusted temperature data available to the public.
Why do weather stations move location, and how does the Bureau maintain the integrity of the data?

Weather stations move for a variety of reasons. For example, an observing site at an airport may be required to move to accommodate new buildings or other infrastructure. The Bureau employs standard statistical methods to account for the impact of site moves on the temperature record.

When a site moves, the climate of the old and new site may be slightly different. To maintain a long record for climate monitoring, an adjustment to the data from the older site is required so that it is consistent with the new, operational site. This adjusted data does not replace the old site record—instead, it is appended to the observed record for the new site. In this way, it is possible to create a continuous long record for that location (an area represented by concatenated site records within a particular vicinity).

Since the mid-1990s, it has been standard practice where possible to provision a period of overlapping observations for site moves. This means that observations are taken at both the old and the new stations (preferably for at least two years) to allow the best possible comparison between the two sites. Where suitable overlapping observations exist, these are used to make the adjustments used in the ACORN-SAT dataset.

In cases where no suitable overlap data exists, adjustments in the ACORN-SAT dataset are made using data from a number of closely correlated reference stations. This is done in a two-step process that first matches the old site to the reference station and then the reference station to the new site. Normally a combination of 10 reference stations is used in this process.

A summary fact sheet of temperature adjustments for Deniliquin demonstrates the use of parallel or overlapping observations to adjust for a site move and upgrade to an automatic weather station in 1997. Also summarised is the use of nearby sites to account for earlier site moves in 1984 and 1971 for which no parallel observations were taken. See: www.bom.gov.au/climate/change/acorn-sat/documents/station-adjustment-summary-Deniliquin.pdf

However, there are many cases where a suitable length of comparison data is not available. This may occur when the station was moved without provisioning a period of overlapping observations. This situation is now rare for ACORN-SAT stations but was common up until the 1990s. A lack of comparison data may also occur if there are overlapping observations but they are not representative of the data before or after the overlap period. This can occur if, for example, a building or other infrastructure is built on or near the old site during the overlap period.
How are the temperature data adjusted?

Statistical tests and documentary records are used to identify and correct for artificial biases in the temperature record.

Average temperature can change markedly over relatively short distances. For example, average overnight temperatures can be significantly cooler at the bottom of a valley than at higher elevations. Importantly, however, day-to-day and month-to-month departures from average temperature (the difference between the individual daily or monthly value and the long-term mean, also known as temperature anomalies) are consistent across very large distances.

In other words, a single town’s temperatures are unlikely to start behaving very differently to surrounding locations. A sudden shift in the town’s temperature relationship with its neighbours is more likely to be related to non-climate factors such as a change in instrumentation.

The physical consistency, or covariance, of weather and climate anomalies over wide areas is used to detect artificial jumps in the data when comparing a station to its nearest neighbours. By carefully accounting for the impact of these non-climate factors on the data, it is possible to better characterise real changes in temperature at each location over time.

The standard scientific practice is to detect potential artificial jumps by comparing data from the station of interest (the candidate station) with data from other nearby stations where the suspected artificial jump is absent (reference stations). If there is an artificial jump in the data, this will be reflected in the candidate station warming or cooling relative to other surrounding stations.

This method of detection avoids falsely identifying actual climatic shifts and natural variability (such as that associated with the 1997–98 El Niño) as spurious artefacts in the data. The comparison with neighbours also serves the valuable purpose of largely rendering the test data free of trends.

Occasionally it is necessary to assess the homogeneity of data without the use of reference stations, but using such an approach means that detection and adjustment take place with a much higher level of uncertainty.

This approach is used only in the event that no suitable reference stations exist. Statistical detection using reference stations tests must also take into account the trends in data—otherwise results will be unreliable.

For Australian terrestrial data, there is generally a sufficient observing network to allow reference stations to be identified and compared with target stations for the purposes of detecting inhomogeneities. In the Bureau’s remote islands and Antarctic dataset, for which few or no reference stations exist, adjustments have only been carried out if supported by metadata.

Further information on the detection of inhomogeneities and the adjustment process can be found on the Bureau’s webpage: www.bom.gov.au/climate/change/acorn-sat/#tabs=Methods

The purpose of homogenising temperature records is to remove as many artificial biases in the record as is possible. In this way, the objective statistical tests using reference stations to determine non-climatic discontinuities, described above, are more powerful than relying on metadata alone. This is because some historic changes in observing practices, site moves and changes in exposure are undocumented.

For example, while significant changes in the vegetation or built environment surrounding a weather station may not be included in historical metadata, they may cause significant changes in the exposure of the instruments. It would preferable that such a change is accounted for when homogenising temperature records. The Bureau’s use of statistical tests that are most likely to identify artificial discontinuities in the temperature data, and how they should be applied, are informed by well-established studies on observational climate data.

The science behind the preparation of homogenised temperature data has a long history in the scientific literature, and several climate research centres independently prepare adjusted climate data for use in climate monitoring and research.
Question 6

Does the Bureau provide raw temperature data?

Yes—the Bureau provides the public with raw, unadjusted temperature data for each station or site in the national climate database, as well as adjusted temperature data for 112 locations across Australia. Links to observational data are available on the Bureau’s website by clicking on the map at: www.bom.gov.au/climate/data/

The Bureau does not alter or delete the original temperature data measured at individual stations.

Rather, the Bureau creates additional continuous and consistent (homogeneous) records for locations across the country. This is accomplished by concatenating copies of individual station records and then making appropriate adjustments for artificial (non-climate related) discontinuities or ‘jumps’ in the data. These new datasets are a complement to, not a replacement of, the original data.

The Bureau maintains the unadjusted or ‘raw’ digital data in its national climate database known as ADAM (Australian Data Archive for Meteorology). These data are kept separately from the homogenised datasets created by the Bureau. In addition, the original paper manuscripts are retained, and many of these are also stored as scanned electronic documents allowing for a further check on the raw data.

Access to unadjusted station data, unadjusted gridded temperature data and homogenised temperature data is available through the Bureau’s website—as well as on request from the Bureau’s Climate and Oceans Data Analysis Section: see www.bom.gov.au/climate/data-services/. The Bureau also provides a range of different temperature analyses to fit multiple purposes, and researchers make use of both adjusted and unadjusted data.
Where can I find information on individual stations, for example Rutherglen?

All Bureau observations sites, including ACORN-SAT sites, publish data directly to our website.

These are available for every State and Territory and can be found by clicking to the location from each of the State/Territory landing pages. For example in New South Wales: [www.bom.gov.au/nsw/observations/nswall.shtml](http://www.bom.gov.au/nsw/observations/nswall.shtml). This link provides a table of all stations for New South Wales by location and the latest observations information.

Additionally, you can also access information on ACORN-SAT homogenised station data through the website at: [www.bom.gov.au/climate/change/acorn-sat/index.shtml#tabs=Data-&-network](http://www.bom.gov.au/climate/change/acorn-sat/index.shtml#tabs=Data-&-network). This link provides a map where you can click on individual locations for a record of minimum and maximum data.

The Bureau is also publishing fact sheets on all individual ACORN-SAT locations, including adjustment history. It anticipates these will be available by the end of 2017. Six sites have been published to date including:

- Amberley
- Deniliquin
- Mackay
- Orbost
- Rutherglen
- Thargomindah
Question 8

What are ‘digitised’ data?

Digitised data are observations that have been transcribed from their original paper records to an electronic database.

Modern automatic weather stations (AWSs) take readings that are electronically communicated to a centralised national database, and these were introduced to the Bureau’s network from the 1980s onwards. Nearly all data prior to the 1990s were originally recorded by observers on paper forms. The vast majority of these observations have been subsequently digitised (entered into an electronic database) at the monthly timescale.

Until 2000, very little daily data prior to 1957 were available in electronic form. Since 2000, there has been a major effort to digitise historical climate data as a part of various projects, for example Computerising the Australian Climate Archives (CLIMARC; Clarkson et al., 2001).

Daily digitised data are now available back to 1910 or earlier at 60 of the 112 ACORN-SAT locations, as well as at some non-ACORN-SAT locations. The task of digitising daily records is ongoing (Figure 1) with many daily observations only available in paper form. Approximately 15 ACORN-SAT locations may have paper records of daily temperature data available but which are yet to be digitised. It should be noted that, in most cases where there are known undigitised daily data, the digitised monthly (monthly-mean) data for the period concerned are available through the Bureau’s website.

Figure 1: Number of stations with available data in the Bureau of Meteorology’s database for daily (light blue) and monthly (dark blue) maximum and minimum temperature. The gap between the two represents data which are likely to exist on paper and have the potential to be digitised. (The gap around 1990 is related to changes in data flows and quality control procedures and is not a digitisation issue.)
There is extensive electronic and paper-based documentation that describes historical observing practices for individual stations across the Bureau. This information, or metadata, can extend to more than one hundred pages for individual stations. The station metadata provides information regarding the conditions and practices of temperature observation at the measurement location. Whilst this documentation has generally been recorded electronically since 1997, and many earlier documents have been scanned, a substantial proportion of the documentation remains on paper only, and is stored in the Bureau’s Regional Offices or in various facilities of the National Archives of Australia.

An additional point on available digitised records relates to the discoverability of disparate historical records. Temperature records from the colonial period in particular were recorded in a variety of ways, such as in logbooks, almanacs or newspapers, rather than in a centralised database. These historical accounts were often not catalogued or held as searchable records. This means that such records need to be discovered before they can be digitised and used for scientific research. This process is slow and resource intensive, and has generally advanced through dedicated and collaborative research projects.
Why does the ACORN-SAT dataset start in 1910, and not earlier?

Climate observations prior to 1910 were limited across the Australian continent, being concentrated mostly around settlements and in eastern Australia. Many observations from the pre-federation period were taken with non-standard instrumental configurations, and the accompanying documentation is patchy. This makes it very difficult to reconstruct early national data that is consistent with the modern record.

Instrumental weather observations have been taken in Australia since the start of European settlement. While digitised temperature records (see Question 8) for a number of locations (mainly in eastern Australia) stretch back into the mid-nineteenth century, the Bureau’s national analysis of temperature covers the period from 1910 onward. Earlier observations were taken officially by the colonial governments, as well as by amateur weather watchers. Whilst valuable, there are two reasons why these records are not suitable for reconstructing climate conditions across Australia during the colonial period:

- The observations were limited geographically, covering a small fraction of the continent, with vast regions having no observations at all.
- There is little or no information available regarding the types of instruments used, their calibration and exposures. This makes it difficult to align these early-era observations with the official record that commenced in 1910, soon after the formation of the Bureau of Meteorology.

Figure 2: Map of daily stations with digital reports available for January 1900, indicating the very limited data coverage in Western Australia, the Northern Territory, Tasmania and northern South Australia in digitised form at this time. There are more stations in the west with digitised monthly temperature data at this time, but the daily data are not available in digitised form.
The national daily temperature analysis is a spatially-interpolated (or gridded) surface temperature field that covers Australia. A robust national analysis requires a reasonable distribution of observations across the continent, with a sufficient level of measurement consistency. The criteria for creating such a dataset can only be satisfied by the record starting in 1910. Detail on the early data and the choice of 1910 is provided in the publications of Nicholls et al. (1996) and Trewin (2012, 2013), with further explanatory material at www.bom.gov.au/climate/change/acorn-sat/#tabs=Early-data

The first major limitation in estimating an Australian-mean temperature prior to 1910 is that there was no national network of temperature observations. Temperature records were being maintained around settlements, but there was very little data for Western Australia, Tasmania and much of central Australia (Figure 2). This makes it impossible to derive an Australian-average temperature from a representative national temperature grid that is robust (not subject to very large uncertainties).

However, it is possible to undertake sub-national temperature analyses, particularly for eastern Australia.

The second limitation is that many of these early observations were taken using a variety of observing methods. The Australian Bureau of Meteorology was formed in 1908 by an Act of the Federal Parliament. The formation of a national meteorological agency soon addressed the lack of national standards for instruments and calibrations, as well as limitations on the continental coverage of observations.

The standardisation of instruments in many parts of the country had occurred by 1910, two years after the Bureau was formed. Standard observational practices (such as the use of a Stevenson screen to house the instruments) were in place at most sites in Queensland and South Australia by the mid-1890s, but in New South Wales and Victoria many sites were not standardised until between 1906 and 1908.

Figure 3: Estimates of Australian mean temperature from the 1850s to the present, from the Berkeley Earth dataset (Rohde et al., 2013). Note the large uncertainty shown by the widening grey uncertainty range prior to 1910, and especially prior to 1890.
It is possible to retrospectively adjust temperature readings taken in non-standard ways. However, this task is much more difficult when the network has very sparse coverage and descriptions of recording practices are patchy. This is in contrast to more recent periods where there is both dense network coverage and detailed records of observational practices.

These factors create very large uncertainties when calculating national temperatures before 1910. One assessment of these uncertainties, from Berkeley Earth in the US, is shown in Figure 3. It should be noted that their estimate of uncertainty relates mostly to the spatial sampling, or sparse data coverage. The spatial interpolation of temperature from a sparse network propagates errors in the data over large areas. The Berkeley uncertainty estimates do not include uncertainty from a lack of instrumental standards, are likely to underestimate the true uncertainty in Australian-mean temperature during this early period.

In addition to needing reasonable coverage of observations for gridding the data, the sparseness of the data also makes homogenisation a difficult task. Adjusting the records to remove spurious artefacts becomes increasingly difficult as the network coverage diminishes.

Considering these factors, it is very difficult to create a national gridded temperature analysis that is comparable across the colonial and post-federation periods. There are large uncertainties that make it difficult to evaluate the difference between Australia’s average temperature from the colonial era and that of the immediate post-federation period.

ACORN-SAT and the Bureau’s real-time high-resolution temperature analyses are aimed at providing much more information than just an estimate of Australian annual-mean temperatures. Indeed, the calculation of a national average (whether monthly, seasonal or annual) represents an important but narrow use of the data. The Bureau’s focus in recent years has been in providing a temperature dataset that is resolved at the daily timescale, and is suitable for gridding and area-averaging, and describes recent and current climate events—while still retaining a long-enough record to provide a meaningful historical context. A temperature dataset that is resolved at the daily timescale provides much more detailed information on extreme weather and climate events, such as heatwaves, which are associated with some of the largest weather impacts in Australia.
How do temperatures in the pre-federation period compare to the present?

Southeast Australian observations extending back to 1860 indicate that pre-federation temperatures were very similar to temperatures observed during the period 1910–1950. Temperatures in recent decades are on average warmer than last century.

The Southeastern Australian Recent Climate History project (SEARCH; Ashcroft et al., 2012) demonstrated that temperatures in southeast Australia over the 1860 to 1910 period were similar to those for 1910–1950 (Figure 4), and well below the values seen in the most recent decades.

Comparison with independently measured sea surface temperatures from around Australia and data from New Zealand reinforce conclusions that the 1860 to 1910 period was substantially cooler than recent decades. There is a high degree of consistency in the recent trends in Australian ocean and land surface temperatures (see Question 15), as well as temperatures in the New Zealand region.

The January 1896 heatwave in inland New South Wales is often cited as an indication of a very warm pre-federation period. The SEARCH project dataset suggests that January 1896 was probably one of the ten hottest Januarys in southeast Australia in the last 150 years. This example does not, however, imply that the late 19th century was as warm as the recent climate. As Figure 4 shows, the mid-1890s were unremarkable in terms of annual temperatures in eastern Australia and cooler than some of the early years of the official ACORN-SAT record in the 1910s.

Apparent temperatures at Bourke, New South Wales, during the January 1896 heatwave suggest extreme warmth in that period.

Figure 4: Reconstructed annual temperature anomalies (departure from mean) for maximum (Tmax), minimum (Tmin) and diurnal temperature range (DTR) for southeast Australia for the period 1860–2010, from the Ashcroft et al. (2012) dataset.
While the heatwave was significant, the veracity of extreme temperatures recorded at Bourke can be assessed through a standard statistical test that compares temperatures at Bourke with those recorded at nearby locations (see www.bom.gov.au/climate/change/acorn-sat/#tabs=Methods). It has been demonstrated that Bourke was a particularly poorly exposed site over this period. The SEARCH dataset assessed that the Bourke data for January maximum temperatures differed from that obtained by modern practices by some 3.5 °C and the unadjusted observations (with thirteen consecutive days above 45 °C, available via Climate Data Online: www.bom.gov.au/climate/data/) erroneously exaggerate the severity of the event.

The standard modern enclosure or housing for surface-air-temperature thermometers is the Stevenson screen, which exposes the instruments to the surrounding air but not to heating from direct sunlight or back-scattered longwave radiation. It is worth noting that Charleville (in Queensland), which did have a Stevenson screen by 1896 and is hence comparable to modern practice, had maximum temperatures between 38 °C and 42 °C through most of the 1896 heatwave, with a high of 43.4 °C. For the month as a whole, Charleville was 5.0 °C cooler than the cited estimates for Bourke. This is physically unrealistic in terms of the length-scale of monthly temperatures (see Question 12), with the 1961–1990 mean difference between these sites being just 0.3 °C. Analysing the mean summer maximum temperature differences between Bourke and Charleville, the unadjusted data (Figure 5) indicates that Bourke was, on average, about 2 °C warmer prior to Stevenson screen installation in 1908 than it was in the years following that, with wide year-to-year variations. This reinforces the finding that the colonial-era Bourke temperature data are significantly exaggerated, most likely due to the exposure of the instrument.

It should also be noted that there were both warm and cool extreme events during the 1895–1903 Federation Drought. In addition to the 1896 heatwave described above, the 1897–98 summer was very warm in southeast Australia (including a record number of days over 35 °C at Melbourne). Conversely, notable cold events include the frosts of July 1895, and two significant low-altitude snowfalls, in 1900 and 1901.

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**Figure 5:** Differences in mean summer maximum temperature between Bourke and Charleville (expressed in °C), as represented by the unadjusted data, indicating the impact of a non-standard screen at Bourke prior to 1908 (Charleville is understood to have had a Stevenson screen no later than 1890). The difference series is also influenced by site moves at Charleville in 1914 and 1943, and at Bourke in 1995.
Why do global datasets include Australian data prior to 1910, when such data are not included in ACORN-SAT?

Pre-1910 records are not included in ACORN-SAT because they are insufficient in their continental coverage. Specific international global data analyses use some early temperature data from Australia to construct monthly and annual-mean hemispheric and global temperature averages. This differs from ACORN-SAT, which constructs a continent-wide daily temperature record for Australia. Pre-1910 estimates of Australian annual-mean temperature from just a few sites are very uncertain.

It is currently only possible to construct a daily temperature record, with reasonable national coverage, from 1910 onward (see Question 9). Prior to this time, temperature records in Australia are isolated mostly to eastern Australia, with little data coverage over large areas of central and western Australia. The combination of non-standard instrumentation and sparseness of observations prior to 1910 make it impossible to construct a national mean temperature that is comparable to that derived from the modern network, and not subject to very large uncertainties.

The earlier data that do exist may be used to construct a very uncertain estimate of Australian temperatures, and may also be used for the construction of global and hemispheric temperature averages on monthly and annual time scales. The three main global temperature dataset providers (the UK Met Office–University of East Anglia, the US National Oceanic and Atmospheric Administration (NOAA) National Climatic Data Center and the US National Aeronautics and Space Administration (NASA) have mostly conducted these types of analyses.

The Bureau provides access to all of its digital daily and monthly temperature data holdings to both domestic researchers and international users (accessible via www.bom.gov.au/climate/data/). The Bureau has collaborated with researchers, including the global dataset providers, in analysing some of these data. The constructions of global and hemispheric temperature averages by international agencies are the most prominent use of the early data.

The construction of an annual global or hemispheric temperature average requires a less dense network of stations than is required for a national average. This is because averaging over very large areas smooths out local variations, and because spatial temperature variability is much lower over the oceans. Hence, a relatively small number of observations from Australia can contribute to the construction of a meaningful hemispheric or global average. As the southern hemisphere is largely ocean, southern hemisphere temperature analyses are largely drawn from sea surface temperatures measured from ships. Global dataset providers make their own decisions about which data to include and how to undertake their own data analyses. Many documents in the scientific literature (e.g. Morice et al., 2012; Rohde et al., 2013) provide further details concerning these decisions.

The sparseness of the early networks is reflected in the large uncertainties reported in the available datasets. The UK Met Office–University of East Anglia (Morice et al., 2012) assessed the uncertainty in annual temperature values for the southern hemisphere in the most recent version of their dataset (HadCRUT4) at approximately ± 0.5 °C in 1850, reducing to ± 0.3 °C in 1900. The Berkeley Earth group (Rohde et al., 2013) has provided an analysis of early Australian temperature data. This reveals a 95% confidence (or uncertainty) range of colonial period decadal-average Australian-mean temperatures near 0.5 °C. These large uncertainties reflect the very sparse available data. For example, before the 1870s, no temperature data of any kind was available from Western Australia, Queensland, or the Northern Territory, with analyses for those States either being considered as missing or extrapolated from sites in southeast Australia.
International assessment of the pre-1910 data from Australia have revealed issues consistent with the Bureau’s assessment of the data. As part of their assessment of the HadCRUT4 dataset, the UK Met Office–University of East Anglia group carried out a sensitivity test (reported in Jones et al., 2012) in which the global analysis of land areas was re-run with all Australian data deleted. This test found that the ‘no-Australia’ southern hemisphere temperature was typically 0.10–0.15 °C cooler than the full southern hemisphere dataset between about 1878 and 1893, suggesting that Australian temperature observations incorporated into the HadCRUT4 dataset were likely to be unrealistically warm during this period. Differences were minimal after 1893 (by which time Stevenson screens were in widespread use for observations except in New South Wales and Victoria, a small area in the context of a global dataset), and before 1878 (when there were limited Australian observations of any kind and most of the continent was considered to be missing data in the HadCRUT4 dataset).

Global dataset developers (e.g. Brohan et al., 2006) acknowledge that those 19th century temperatures on land are likely to be warm-biased in many locations. This is chiefly due to the variety of instrument shelters that were in use, with a possible overall impact on global averages of up to 0.2 °C (Parker, 1994). An Australian example is the comparison between a Stevenson screen and a Glaisher stand carried out between 1887 and 1947 at Adelaide (Nicholls et al., 1996), which found that maximum temperatures in the Glaisher stand were about 0.6 °C warmer than those in the Stevenson screen as an annual average, with differences of about 1 °C in summer. A number of alternative approaches have also been used to try and quantify this impact, including seeking to recreate historical instrument shelters for comparison with modern standards (e.g. Böhm et al., 2010; Brunet et al., 2011). The results generally reinforce the conclusion that historical thermometer exposures tended to be biased warm relative to modern standards, especially during daytime and in the warmer months.
Are trends in Australian annual-mean temperature affected by changes to the observing network over time?

*No—the Bureau’s method for analysing Australian temperature records accounts for changes in the observing network over time.*

Australia’s national temperature observing network has changed significantly over time. Temperature observations were initially concentrated around major settlements. Additions to the network have included warmer locations across central and northern Australia, as well as some colder locations in elevated and alpine regions. These network changes need to be accounted for when analysing changes in temperature over time.

The process for calculating temperature averages over a region starts with calculating, at each location, the *difference* in each time period (day, month, year) between the temperature at a location and that location’s climatological average for a standard 1961–1990 reference period. The climatological average is referred to as the *climatology*. This difference between actual temperatures and climatology is referred to as a *temperature anomaly*.

Temperature anomalies have certain physical properties that are useful when analysing and adjusting temperature data for artificial biases. In particular, anomalies have very long *length scales* or distances over which anomalies are spatially coherent. Length scales are typically hundreds of kilometres, corresponding to the spatial scale of weather systems, known as the *synoptic scale* in meteorology. When it is warmer than the climatological average (and therefore a positive temperature anomaly) in a particular location, it is generally also warmer than average over hundreds of kilometres—corresponding to the mean synoptic weather pattern—even though the actual temperature may be quite different from location to location. This is particularly true when daily temperatures are averaged over a month or longer.

The use of anomalies also reduces the impact of stations with different mean temperatures dropping out of, or being added to, the network over time. The difference in climatology from one location to the next is accounted for in the anomaly calculation itself—since anomalies are the departure from the mean temperature, and since the mean temperature is defined from a standard climatological period. ACORN-SAT locations have been selected such that they all have enough data during the 1961–1990 period to produce stable climatology estimates. The anomaly-based process is adopted specifically to prevent network changes introducing biases into national and regional means.

Once calculated, these station anomalies are interpolated to a spatial surface, in the form of a regular grid, using the Barnes successive correction technique (Koch et al., 1983), and national and regional means are calculated from averaging these grid-point values. The technique has the effect of weighting each location value according to how large its ‘footprint’ is. The footprint reflects the relative influence that a single station has on the national dataset as a consequence of its remoteness or proximity to neighbouring stations. Locations in regions with widely spaced observations (mostly remote areas) have a larger footprint in the analysis than locations in more densely observed areas. Alternative methods, such as the Thiessen polygon method, exist for area-weighting location values, but the grid-point-based value is used by the Bureau because of its flexibility in allowing calculations to be made for any specified region as opposed to regions that depend on the distribution of stations. The limited ability of sparse networks to capture spatial variability and the resultant larger uncertainty in large-area averages is inherent in any gridding calculation. This is reflected, for example, in the increasing uncertainty going back in time in the Australian region means (see Question 9). Hence, the data sparseness during the early period of record is the major source of underlying uncertainty in the surface temperature estimates.
Where absolute temperature values (rather than anomalies) are quoted as an area average for Australia or a region, this is done by first calculating the anomaly as above, and then adding that to a fixed estimate of the area average for the standard 1961–1990 reference period.

A related issue is that of the reference period used as the basis for calculating temperature anomalies. The Bureau currently uses the 1961–1990 period, which follows the World Meteorological Organization’s definition of climatological standard normals (WMO, 2007). Some other international agencies use different reference periods for their global datasets (e.g. US National Oceanic and Atmospheric Administration (NOAA) use 1901–2000, and National Aeronautics and Space Administration (NASA) 1951–1980).

Using a different reference period shifts all anomaly values up (or down) by a constant amount. So, for example, recent data will show smaller positive anomalies with respect to the 1981–2010 reference period than it will with respect to a (cooler) 1961–1990 reference period, but this has no effect on trends (as illustrated in Figure 6).

![Graph showing annual maximum temperature anomalies at Wagga Wagga](image)

**Figure 6:** Annual maximum temperature anomalies (departure from mean) at Wagga Wagga and linear trend lines for 1943–2014, using reference periods of 1961–1990 (red lines) and 1981–2010 (grey lines). The difference between the two series is constant through time and both show a trend of +0.25 °C/decade.
Question 13

What are the differences between adjusted and unadjusted trends?

Adjustments ensure that trends in the climate record can be accurately attributed to changes in temperature—and not due to changes in the site or the equipment used to take the measurements. The current trend in Australia’s temperatures is evident in both adjusted and unadjusted temperature data, and is similar to the global warming trends published by many other agencies.

Warming trends over Australia are evident in both adjusted and unadjusted temperature datasets. Over the past 60 years, which is the period that Australia has warmed most rapidly, the adjusted and unadjusted temperatures show virtually identical trends. There is also generally close agreement between the ACORN-SAT national temperature series and international analyses that incorporate Australian data, particularly after 1950 (see Question 15).

From 1910 to approximately 1950 there are small differences—generally less than 0.2 °C—in annual-mean Australian temperatures between adjusted and unadjusted datasets. There are no trends in temperatures over this period and the inherent uncertainty in the data is largest at this time due to a sparser observing network.

From the context of relative comparison of temperatures from one period to another—it should be noted that ‘raw’ temperature data are not pristine instrumental observations that are more ‘real’ than the adjusted data. Each temperature recording is the result of a series of decisions related to the observation of surface temperature, including: the time of observation; the type of instrument used; the calibration of the instrument; the type of enclosure used to house the instrument; the positioning of that instrument within the enclosure; and the positioning of the enclosure with respect to its local environment (i.e. its exposure). All of these elements can be considered a function of time, since observing practices and equipment have changed over time. For example, the introduction of automatic weather stations saw the replacement of mercury-in-glass or alcohol-in-glass thermometers with platinum resistance probes. The temperature observations made with these differing instrumental configurations can all be considered ‘raw’, while having differences that may need to be reconciled for consistency of comparison.

In this way, the unadjusted or ‘raw’ temperature data contains spurious artefacts (including artificial ‘jumps’ in the data in individual site records) from non-climatic factors that are likely to bias derived trends. The apparent trends calculated from unadjusted or ‘raw’ temperature data cannot therefore be considered as the truth against which the adjusted data trends should be evaluated.

Rather than asking ‘how much have adjustments changed the underlying trend?’ the question should be ‘which preparation of the data will best characterise real changes in temperature over time?’. The answer to that question is the homogenised or adjusted dataset.

Site moves—that is, a change in the position of a weather station—are one of the more common reasons that raw data need to be adjusted, and present a good illustration of why homogenised data are more likely to best characterise real changes in temperature over time. References to ‘raw’ station data as the baseline against which to compare other analyses may imply that the raw station data are unbiased continuous readings from a single site. In reality, the raw data describe ‘as-read’ temperature readings from single stations across multiple sites, for varying timespans, and using multiple instruments over time. As such, ACORN-SAT reconstructs a continuous temperature record for a location—typically made up of multiple station records within a vicinity, and adjusted to account for that concatenation as well as changes in instruments and exposures.
Figure 7: Annual temperature differences (expressed in °C) for Australia between the unadjusted and ACORN-SAT datasets for maximum (top) and minimum (bottom) temperature.
In fact, almost all of the ACORN-SAT locations in the dataset have sites that moved at least once in their history, and hence there is no continuous ‘raw’ temperature time series available for these locations. Instead, a combined time series taken from two or more stations that operated in proximity must be used to create a continuous span of temperature data. (It only became standard practice to associate a significant site move with a change in the identifying station number in the 1990s. Prior to the 1990s, station numbers were normally only changed if the old and new stations operated simultaneously. Many substantial moves took place without a change in station number—hence a continuance of a single station number does not guarantee that the station location has remained fixed.)

Considering all of these factors in creating long, continuous temperature records for individual locations, there is only one ACORN-SAT site that requires no subsequent adjustment for factors such as site moves, changes in observing practices, instruments and instrument exposures: Learmonth, which opened in 1975, the shortest record in the ACORN-SAT dataset. An example of the influence of non-climate factors on the temporal continuity of ‘raw’ records can be found in the temperature data for Orbost in Victoria (see our Orbost factsheet: www.bom.gov.au/climate/change/acorn-sat/documents/station-adjustment-summary-Orbost.pdf).

While the above illustrates the challenges associated with comparing ‘raw’ data taken at stations to the long-term time series for locations, the Bureau can show some comparisons at the national scale.

The adjusted ACORN-SAT data may be compared with an unadjusted gridded daily and monthly temperature dataset derived from the Australian Water Availability Project (AWAP) dataset—which draws on the full Australian network without accounting for temporal inhomogeneities. The AWAP data is spatially analysed onto a high-resolution national grid dataset (Jones et al., 2009). (It should be noted that the AWAP dataset starts in 1911, rather than 1910.)

Australian mean temperature change over the last century is best represented by a bilinear model, with a period of relatively no change from 1910 through to 1950, followed by a period of relatively rapid warming from 1950 to present. When characterised this way, both adjusted and unadjusted data show virtually identical warming over this latter period.

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**Figure 8:** Proportion (expressed as a percentage) of operating ACORN-SAT stations situated in built-up areas by year, showing a decrease through time as the quality of the network improves.
A simple linear trend shows that Australia warmed by around 0.92 °C from 1950 to 2014 in the ACORN-SAT data, compared with a change of 0.85 °C in the AWAP data—a difference of around 0.07 °C over 65 years.

The bulk of the differences between the two datasets, and associated uncertainties, relate to Australian national temperatures prior to 1950, when there is no significant trend in the data. In this way, the difference between the two datasets is perhaps better characterised as a difference in the climatology (the average climate) from 1911 to 1950. Averaged over Australia, the unadjusted AWAP data are generally about 0.2 °C warmer than the homogenised ACORN-SAT data in the decade from 1911 to 1920. This difference falls to 0.11 °C when averaged over 1911–1950 (and falls to near zero from 1950 onward).

While there is no trend prior to 1950, the difference in the adjusted and unadjusted climatologies for this period causes differences in the overall temperature change from 1911 to 2014. Taking a simple linear trend, Australia warmed by around 0.99 °C from 1911 to 2014 in the ACORN-SAT data, compared with a change of 0.77 °C in the AWAP data—a difference of around 0.22 °C over 113 years.

As mentioned previously, and guided by the scientific literature (e.g. Brohan et al., 2006), an adjusted dataset is more likely to capture true physical changes in temperature during the early period, when the network is sparser. This is one of the main reasons why the Bureau uses ACORN-SAT for estimating the national, long-term trend in surface air temperature. However, the differences between adjusted and unadjusted data, and the differences between ACORN-SAT and international datasets, can be considered a reflection of the underlying uncertainties during this early period.

The early difference between ACORN-SAT and AWAP appears to arise from the combination of two factors. First, network changes have caused stations to move from climatologically warmer sites to climatologically cooler sites nearby over time. Second, individual changes have occurred at some key locations in remote, data-sparse areas with large ‘footprints’ in the national average.

With regard to the shifts in sites within the network, the early period temperature network was relatively sparse and many sites were reporting from the centre of small towns or coastal locations.

Figure 9: Annual maximum temperature differences (expressed in °C) for South Australia between the area-averaged unadjusted and ACORN-SAT datasets (1911–2014).
Subsequently, these sites were shifted to climatologically cooler locations, most often to airports or aerodromes. This shift is shown by the proportion of all ACORN-SAT sites that were located in built areas (regardless of population) having decreased from around 70% in 1930 to 10% now (Figure 8). When data from multiple individual sites are combined to form a long temperature record for a given location, it is necessary to adjust that record to account for the climatological differences in those sites.

With regard to changes at key locations—some individual sites have a proportionally higher impact on the national average because they are located in data sparse regions. This means that errors in the data at those locations, such as non-climate related ‘jumps’ in the temperature record, carry more weight when calculating Australian mean temperature. The most prominent example is Alice Springs, where there is a well-documented site move in 1932 from a site in an enclosed courtyard, surrounded by white-painted stone walls, to a much more open site. As Alice Springs effectively contributes about 10% of the calculation of national mean temperature anomalies in 1932, the adjustment for this move (−0.6 °C for maximum temperature, −1.1 °C for minimum temperature) has a noticeable impact on national anomalies.

While the warming trends over the last century for Australia as a whole are slightly stronger in the ACORN-SAT dataset than they are in the AWAP dataset, this is not necessarily true for all the States and Territories taken as separate geographic regions. For instance, in South Australia, AWAP maximum temperatures are substantially cooler than ACORN-SAT in the earlier years of the dataset, especially before 1939 (Figure 9). This was strongly influenced by a site move in 1939 from Farina to Marree, which is further north and at a lower elevation, and was therefore warmer.

For New South Wales, AWAP minimum temperatures are consistently about 0.2 °C cooler than ACORN-SAT minimum temperatures from the mid-1990s to the present, as a result of a large number of site moves from town to airport sites in the 1990s (Figure 10). Many site moves of this type took place in the 1990s, due in combination to the Bureau’s roll-out of the automatic weather station network and the corporatisation of Australia Post, which made post offices a less viable proposition as observation sites. Such moves were especially common in New South Wales.

Figure 10: Annual minimum temperature differences (expressed in °C) for New South Wales between the area-averaged unadjusted and ACORN-SAT datasets (1911–2014).
How does the urban heat island effect impact the climate data?

The urban heat island effect can increase surface-air temperature at urban locations. While studies have found the effect has minimal impact on global long-term temperature trends, urban sites are not included in the Bureau’s assessments of temperature trends across Australia.

It is well known that urbanisation raises surface air temperature. The increase in temperature is particularly pronounced at night and under conditions of light winds and clear skies. This is due to a number of factors, including: the different thermal properties of urban surfaces (paved surfaces and buildings release some of the heat they absorb during the day into the surrounding environment during the evening); the presence of artificial heat sources; and the rapid removal of surface moisture via drainage systems. A good review of the topic is presented by Parker (2010).

Sites significantly influenced by urbanisation were identified as part of the process when developing the ACORN-SAT dataset. Initially, locations were classified as clearly urban (that is, within the built-up part of a town with a population of 10 000 or greater), urban fringe (near the boundary of such a town, or within the town but in a non-built-up area, such as a park or airport grounds), or clearly non-urban. In a second stage, those locations which were classified as urban fringe, and those which were formerly urban but are no longer (e.g. where a station has moved out of a town), were tested for minimum temperature trends which were anomalously large relative to non-urban sites in the region. If anomalous trends were found, these sites were classified as urban-influenced.

As a result of this process, four ACORN-SAT locations (Sydney, Melbourne, Adelaide and Hobart) were defined as urban in the initial classification, and four more (Laverton, Victoria; Richmond, New South Wales; Townsville and Rockhampton, Queensland) as urban-influenced as a result of anomalous trends being identified at those sites. It is worth noting that the Laverton, Richmond and Townsville sites are all near urban growth corridors—in particular, the appearance of an urban signal at Laverton is recent and probably linked to the construction of the new suburb of Williams Landing to the west of the site from 2008 onwards.

These eight locations remain a part of the ACORN-SAT dataset, as they are important for monitoring changes in the climates in which many Australians live. However, they are not included in assessments of the warming trend across Australia or the calculation of national and State averages.

It is also worth noting that urbanisation will only produce anomalous trends at a location if the nature of the urban influence on that location is changing over time. In the case of Sydney, there is no evidence of urbanisation trends over the post-1910 period relative to non-urban sites in eastern New South Wales. A reasonable interpretation of this result is that whatever urban influence exists on temperature observations at the Observatory Hill site (which is in a part of Sydney that was heavily built up) was already fully developed by 1910. A similar lack of anomalous warming over the last century has been noted in well-established urban centres such as London and Vienna (Jones et al., 2008; Jones and Lister, 2009). Some other urbanisation signals may also manifest themselves as step changes related to specific changes in a site environment (e.g. the 1996 construction of a new building across the street from the Melbourne site) and are detected and adjusted for as part of the normal ACORN-SAT homogenisation process.
International studies (Peterson, 2003; Jones and Wigley, 2010) have generally found that the impact of urbanisation on temperature datasets at national to global scales is marginal to non-existent. Urban to non-urban temperature differences of several degrees reported in numerous case studies are typically taken under optimal conditions for urban heat island development, with differences reduced considerably in long-term averages. Urban to non-urban differences are also typically largest during the evening, decline slightly by the time of minimum temperature in the early morning and are much smaller during the day (Figure 11).

In some cases, such as cities with heavy particulate pollution, the city can even be slightly cooler during the day, owing to reduced solar insolation. Finally, it should be noted that estimated global and regional warming trends over land compare well with those from sea surface temperature data, which includes no influence from urbanisation (see Figure 13).

![Figure 11: Average temperature differences (expressed in °C) between Melbourne and Laverton by time of day (in hours), July 2006.](image)
Question 15

How do the trends in ACORN-SAT compare to other datasets?

The trends in the Bureau’s temperature data are in close agreement with trends derived independently by other agencies. Warming in Australian surface temperature closely matches warming seen in the oceans surrounding Australia and in the Pacific Islands.

A comparison of Australian mean temperature from a range of different datasets—including local and international datasets (which use different methods of data selection, preparation and analysis) and both station-based and satellite data—is provided below (Figure 12).

This is an extension of work originally reported at the time of the ACORN-SAT release in 2012 (Fawcett et al., 2012).

Figure 12: Annual mean temperature anomalies (departure from mean) for Australia (1911–2014), using the ACORN-SAT dataset and a range of other local and international land-only (LO) and blended (BL) land/ocean datasets based upon surface-based instruments. While not directly comparable to surface temperature, the average temperature of the lower troposphere (TLT) from remotely sensed satellite data is also included. Anomalies are with respect to 1981–2010.

Notes on Figure 12: Datasets from the Bureau of Meteorology (BoM) include the operational whole-network (unhomogenised) dataset (AWAP) and the Australian Climate Observations Reference Network-Surface Air Temperature (ACORN-SAT) dataset. Datasets from the United Kingdom (UK) are obtained from the University of East Anglia’s Climatic Research Unit (UEA CRUTEM). Their LO datasets are merged with the UK Met Office Hadley Centre’s sea surface temperature (SST) analyses to create the HadCRU BL datasets. Dataset version 4 is shown for UK UEA CRUTEM, both with (v) and without variance adjustment. Datasets from the United States (US) National Aeronautics and Space Administration (NASA) Goddard Institute for Space Studies (GISS) are available in two analysis scales (250 km and 1200 km), courtesy of the US National Oceanic and Atmospheric Administration (NOAA) Earth System Research Laboratory’s (ESRL) Physical Sciences Division (PSD). The Global Historical Climatology Network (GHCN) version 3.2.2 dataset was obtained from the NOAA National Climatic Data Center (NCDC). The Japan Meteorological Agency (JMA) land only dataset comprises of the GHCN dataset to 2000 and CLIMAT messages since 2001. The TLT datasets (1979–2014 only) were obtained from the University of Alabama in Huntsville’s (UAH) National Space Science and Technology Centre (NSSTC) and Remote Sensing Systems (RSS).
Overall, the level of agreement between datasets is very high, with all showing warming over Australia. To the extent that there are differences, this provides an estimate of the uncertainty in estimating a national Australian annual temperature and suggests that it is the period from 1910 to 1940 that has the greatest uncertainty.

The reasons for the differences between the national values from these datasets, both those with and without homogenisation, over the period 1910 to 1940 are complex. These differences are due to a number of factors, chief amongst them uncertainty introduced by a sparse observing network and the greater difficulty in obtaining an estimate of an Australian annual temperature (see Question 9).

The warming trends evident in the ACORN-SAT dataset compare very well with those revealed in Australian-region sea surface temperatures since 1910. Both have increased by about 1 °C (Figure 13). The sea surface temperature observations are independent measurements of regional temperature.

Figure 13: ACORN-SAT land surface air temperature anomalies (departure from mean) for Australia (red) and Australian region sea surface temperature from the NOAA ERSST v3 dataset (grey) across the period 1910–2014. Anomalies are with respect to the 1981–2010 reference period. Trend lines are the quadratic fit.
How do the adjustments in the ACORN-SAT dataset affect the representation of extreme temperatures?

*Temperature data adjustments make almost no difference to the characterisation of extreme temperatures or the change in extreme temperatures over the past 100 years.*

The change in hot and cold extreme temperatures over the last century is consistently characterised by both adjusted and unadjusted data maintained by the Bureau. As an example, Figure 14 shows a comparison between unadjusted and adjusted temperature data for the national percentage area of annual mean temperature that is above the 5th and 95th percentiles. The two datasets yield similar estimates for these national percentage areas, and consequently similar estimates of the trend behaviour—percentage areas above the 95th percentile have increased markedly in recent years (since around 1980 onwards). As the percentage areas above the 5th percentile have similarly increased, we conclude that the percentage areas below the 5th percentile have decreased markedly across the past 100 years.

When adjusting temperatures based on correlations with other sites, the general approach in ACORN-SAT is to assume that inter-site relationships for all values above the 95th percentile are the same as those for the 95th percentile (and analogously for values below the 5th percentile). Evaluations carried out as part of the ACORN-SAT project (Trewin, 2012) found that this gave more reliable results across the network as a whole than deriving relationships using more extreme values (e.g. the 1st and 99th percentiles). More extreme values involve only a small number of data points (e.g. in a 5-year overlap, the 1st percentile for a season is between the 4th and 5th lowest value), and are hence somewhat susceptible to issues affecting individual observations and harder to statistically analyse.

![Figure 14: National percentage area for which annual mean temperature is above the 5th and 95th percentiles as estimated from the unadjusted and adjusted (ACORN-SAT) monthly analyses (1911–2014). Unadjusted percentiles are calculated using all available years (1911–2014). ACORN-SAT percentiles likewise (but 1910–2014).](image-url)
At a small number of locations, this assumption of consistent relationships at the extreme ends of the distribution breaks down, and hence there are a small number of ACORN-SAT locations where certain extremes cannot be satisfactorily homogenised. This most commonly occurs where an ACORN-SAT location moves from a coastal to inland location (or vice versa) on a coast with a strong summer sea breeze influence. Typically in such situations the coast–inland temperature difference will increase with increasing temperature, before reducing to near zero on the very hottest days when offshore winds are strong enough to override the sea breeze. An example at Albany is shown in Figure 15.

To account for these issues, a separate check was carried out on the homogeneity of time series of the highest and lowest value of each year for maximum and minimum temperature. Where major inhomogeneities were detected in this series, the data were considered unable to be homogenised at that location for that variable.

This was found to be the case for four locations—Albany and Port Macquarie (high maximum temperatures), Eucla (high minimum temperatures) and Horn Island (low minimum temperatures). Data from these locations are not included in ACORN-SAT-based extremes analyses for the relevant variable. However, as the number of observations involved is very small, impacts on mean temperatures are minimal (for example, even a 5 °C error which affected 1% of observations would only alter mean temperatures by 0.05 °C) and the stations are still useful in assessment of those.

Figure 15: Differences (expressed in percentile points) of summer maximum temperatures between Albany Airport (inland) and town (on coast) during an overlap period from 2002 to 2009.
When was Australia’s warmest year on record?

Australia’s warmest year on record was 2013 according to multiple datasets, regardless of whether they were adjusted or not.

Most of the major area-averaged records that are reported by meteorological agencies, such as continental or global annual-temperature records, are consistently characterised across multiple datasets (see Question 15).

There are multiple independent estimates of Australian mean-annual temperature based on the work of a number of institutions and temperature analysis methods. The uncertainty in temperatures for any particular year means that it is rare for all datasets to agree on absolute values, however ranks may be more similar.

Figure 16 shows that 2013 was the warmest year on record for Australia in several datasets, including the Bureau’s unadjusted dataset (AWAP) and the adjusted dataset (ACORN-SAT). The Bureau’s statements are based on its own analyses that make use of the best Australian information for surface air temperature.

2013 was not the warmest year in some satellite records of the temperature of the lower troposphere (also known as MSU-lt; microwave sounding unit–lower troposphere). However it should be noted that satellite-based estimates of temperature are a less appropriate measure of land surface temperature than those derived from ground-based stations. Satellite data provide a bulk estimate of temperature in the height range of one to ten kilometres above the surface, and so are not directly comparable to temperatures at the surface.

Figure 16: ACORN-SAT and unadjusted (AWAP) annual mean temperature anomalies (departures from mean) for Australia compared with results for the average temperature of the lower troposphere over the Australian region from three satellite-based datasets. The comparison is only available from 1979 when satellite data commence. The anomalies are calculated with respect to the base period 1981–2010.
A significant source of difference between the surface data and the MSU-lt data is that they behave differently in response to wet and dry conditions. Typically the surface is cooler than the lower troposphere during wet years, and warmer than lower troposphere during dry years. This difference reflects the respective changes in the rate of temperature decrease with altitude (or lapse rate), which is in turn influenced by the amount of moisture in the atmosphere. This out-of-phase variation between the surface and troposphere has been known in the scientific literature for many years (e.g. Drosdowsky and Williams, 1991). In Australia a consequence of this is that ACORN-SAT is generally cooler than satellite MSU-lt during wet La Niña years such as 2010 and 2011, and warmer during prolonged dry El Niño conditions such as those which prevailed in the early 1990s. A comparison of MSU-lt (satellite) and surface data is shown in Figure 16.
Why do some days in the ACORN-SAT dataset have maximum temperatures that are cooler than minimum temperatures?

This is an artefact of the adjustment process at some locations. The maximum and minimum temperatures are analysed independently, so on a very small number of days where there is little difference between the overnight minimum temperature and the daytime maximum temperature, the small adjustments can mean the minimum temperature is slightly higher than the maximum after analysis. It has no impact on trends derived from the dataset.

An artefact of the ACORN-SAT homogenisation process is that maximum temperatures very occasionally fall below the minimum. This occurs on individual days of very low diurnal temperature range, at individual locations, and affects less than 0.03% of the records in the dataset. It has no bearing whatsoever on temperature trends.

Maximum and minimum temperatures are analysed entirely independently for the ACORN-SAT dataset. This is to ensure that the respective time series are as temporally homogeneous as possible. Since they are analysed and corrected independently, and use a quantile-matching algorithm to perform a distributional adjustment, the situation can arise where the corrections to either maximum or minimum temperatures, or both, result in the maximum being very slightly below the minimum on an individual day. This is possible on days where there is little difference between the overnight minimum temperature and the daytime maximum temperature. These days of low diurnal temperature range occur naturally from time to time at individual locations. This is related to specific weather and rainfall conditions, typically either rainy days, or days when the temperature falls sharply near 9:00 am after the passage of a cold front or trough (so the highest temperature of the day occurs near 9:00 am). This small number of cases where maxima fall below minima are a result of the adjustment combined with the adjustment uncertainty.

It is possible to correct for this in the analysis, such as by placing a limit on the difference between maximum and minimum temperatures, however this would mean that respective time series are not independently adjusted. This type of targeted correction would likely introduce a small but systematic bias to the record. In other words, by solving one issue—a very small number of negative diurnal temperature ranges—we could create another—introducing a small bias into the mean temperature and diurnal temperature range. Taking in a broad consideration of the issues, such as the benefit of treating maximum and minimum temperatures independently, it was decided that the instances of maximum being below minimum in the analysis should be left in the record as a known issue for the first version of ACORN-SAT.

This issue will be addressed in the next version of ACORN-SAT. In cases where the adjusted maximum is less than the adjusted minimum, both the maximum and minimum will be set to be equal to the mean of the two values. In doing so, no bias to the mean temperature is introduced.

It is worth noting that the Bureau carried out extreme temperature analysis, namely the frequency of record-setting daily temperatures, while excluding all negative diurnal temperature range results. We found that these instances did not impact on the extremes analysis. Over the last 100 years, record warm observations have increased in frequency while record cold observations have decreased in frequency (see the State of the Climate 2014).
Question 19

How is data from ACORN-SAT used in climate models?

*Climate models typically do not use any observational climate data such as surface temperature observations. Hence, datasets like ACORN-SAT are not used to produce projections of possible future climates, such as those reported by the International Panel for Climate Change (IPCC).*

Climate models, also known as *general circulation* models of the climate system, are used to investigate and understand climate variability and change. For example, a climate model may be used to understand the impact of a change in solar radiation on the Earth’s climate system. When used in this way, climate models represent the fundamental physics and chemistry alone, and are not fed information from instrumental observations of the climate system over time—such as the change in atmospheric temperature. The models do include empirical bulk parameterisations for sub-grid or small-scale processes such as cloud formation, as part of their underlying physics.

The only direct real-world inputs to these models, in a climate change simulation context, are changes in atmospheric chemistry and composition (such as increasing greenhouse gases, or changing volcanic aerosols) and changes in solar radiation. These changes may be based on observed changes in those quantities or future projections of possible changes, and are often expressed as changes in radiative forcing.

The extent to which model outputs and observed data agree or otherwise is a result of the skill of the model projections, the observational uncertainty in all observational datasets, and which radiative forcings are included in the simulations. Comparisons undertaken by the Bureau between Australian observational temperature datasets and 30 model simulations from the Coupled Model Intercomparison Project 5 (CMIP5)—including all historical radiative forcings—show close agreement over the observational period.

![Figure 17: Projections of Australian-annual mean temperature anomalies (departure from mean) from 30 simulations from the Coupled Model Intercomparison Project 5 (CMIP5) using a mid-level emissions scenario (RCP4.5). ACORN-SAT observations are represented by the yellow line, and the unadjusted temperatures are represented in green. The Ashcroft et al. (2012) reconstruction of temperatures for southeast Australia only (and hence not directly comparable to the Australian-mean) are represented in blue.](image)
**Why are there differences between satellite data and observations using surface thermometers?**

The satellite data and surface thermometers do not measure the same thing. Satellites measure the average temperature between the surface and three to ten kilometres above the surface. Ground-based thermometers measure the surface-air temperature, typically taken 1.5 m above the ground.

Satellites do not measure temperature directly. Instead, satellites measure radiation across various wavelengths and infer temperatures from these using a mathematical algorithm. The satellite data most commonly compared to surface thermometers is actually the derived average temperature through the lowest several kilometres of the atmosphere. By contrast, surface temperatures are measured by thermometers placed 1.5 metres above the ground. Surface temperatures and temperatures in the lower atmosphere are often similar—but they are not the same—and can at times differ significantly.

The satellite-based *microwave sounding unit* (MSU) temperature record provides recent estimates of temperatures over Australia, with records starting in the late-1970s. Satellite data has one advantage over surface-based observations in that it has total coverage over the Australian continent.

However, satellites have several disadvantages, when it comes to climate monitoring. The satellite temperature records are of comparatively short duration—only dating back to 1979. They do not measure surface air temperature—rather they measure an average temperature of the lower atmosphere or troposphere. They are not global—for example high elevations and polar regions require interpolation or extrapolation. Individual satellites and satellite sensors tend to have a short lifetime and so temperature records require the piecing together of data from numerous satellite missions.

A major source of potential inconsistency in the satellite record comes from this piecing together of data from multiple satellite missions over time. Each satellite mission has different instrumentation. Missions may have different orbital characteristics, and slight changes in the orbits of satellites over time have been shown to introduce inconsistencies in the data.

The satellite record is complementary to all other temperature data, and the Bureau and climate scientists compare these records routinely. The Bureau’s surface air temperature measurements for Australia compare well with the remotely sensed satellite record in terms of area-averaged variability and warming trends. These have been published in the papers found on the ACORN-SAT website (Fawcett et al., 2012).

Because the satellite data measure an average temperature through a depth of several kilometres in the atmosphere, they would be expected to compare better with upper-air measurements taken using weather balloons and radiosondes than they would with measurements at the surface. A long-term dataset of upper-air temperatures for Australia, measured using radiosondes, is currently being prepared by the Bureau.

Globally, recent studies have shown that the satellite data are warming at a similar rate to both the surface observations, and radiosonde records. This is also the case over Australia, where warming trends since 1979 are very similar for satellite and surface data.
Some differences between the satellite record and the surface thermometers are understood and to be expected—being directly related to the difference between the climate of the air near the surface and that of the lower troposphere. This is particularly true over Australia during El Niño events or particularly dry and hot periods, such as the 2012–13 summer. One of the main reasons for this is that the rate at which temperatures cool with increasing altitude (known as the lapse rate) is greater in dry air than it is in moist air. This means that during hot summers (which in most cases will also be dry), the rate at which temperatures cool with altitude will normally be greater than normal. Hence temperatures will be less hot—relative to normal—in the upper atmosphere at a given altitude than they will be at the surface.

The reverse is true during cool and wet summers, when the magnitude of cooler than normal temperatures at the surface is not matched in the upper air. (Also see Question 17.)

In short, record summer temperatures in Australia are less likely to be matched by records higher in the atmosphere. These differences are well documented (e.g. Drosdowsky, W.; M. Williams, 1991).


Trewin, B.C. 2012. Techniques involved in developing the Australian Climate Observations Reference Network – Surface Air temperature (ACORN-SAT) dataset. There are a small number of ACORN-SAT locations where certain extremes cannot be satisfactorily homogenised. *CAWCR Technical Report 49*, Centre for Australian Weather and Climate Research, Melbourne.

