Australian Government
Bureau of Meteorology

Review of the Bureau of Meteorology's Automatic Weather Stations

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1 Executive Summary

The Bureau of Meteorology's (the Bureau) observations network is extensive. It includes 695 Automatic Weather Stations (AWS) across Australia and collects over 2.5 million temperature readings each day. Data from this network underpins all of the services the Bureau delivers, enabling more than 500,000 public forecasts, and nearly 15,000 weather and ocean warnings to be issued each year.

In July 2017, the Bureau identified problems with the performance of some AWS equipment at very low temperatures which meant that some temperature data was not recorded at two sites; Thredbo Top Station (Thredbo) and Goulburn Airport (Goulburn).

Initial quality assurance investigations undertaken by the Bureau found that the AWS equipment installed at Thredbo in 2007 and at Goulburn in 2003 was not fit for purpose. The type of data acquisition equipment (specifically, a hardware card) fitted in those locations was unable to operate at temperatures below -10.4°C. This occurred on one day at Goulburn and on six days at Thredbo.

When the Bureau became aware of the problem in July, it took immediate action to replace the data acquisition equipment at Thredbo and Goulburn, avoiding any reoccurrence. The Bureau also worked quickly to replace the same equipment at four other sites deemed at risk of experiencing temperatures below -10.4°C. These were in Tuggeranong (ACT), Fingal (Tasmania), Butlers Gorge (Tasmania) and Mt Baw Baw (Victoria).

The Bureau's initial investigations confirmed that Thredbo and Goulburn were the only sites where temperature recordings had been affected by the inability of some Bureau AWS to read temperatures below -10.4°C.

Furthermore, the Bureau determined that these failures at below -10.4°C had no impact on the official temperature record used for monitoring long-term temperature change; the Australian Climate Observations Reference Network – Surface Air Temperature (ACORN-SAT). The Goulburn and Thredbo AWS are not part of the ACORN-SAT, and the loss of data during the events described above had no impact on the ACORN-SAT record, either directly or indirectly through quality assurance of other ACORN-SAT sites.

Given the criticality of ensuring ongoing community confidence in the integrity of the Bureau's observations, the CEO and Director of Meteorology commissioned a formal review to confirm the circumstances surrounding the equipment failures at Thredbo and Goulburn, to evaluate whether these failures were likely to manifest in other sites within the Bureau's AWS network and to identify any learnings from the events experienced at Thredbo and Goulburn. The following Terms of Reference (ToR) were defined for the Review:

1.1 The Review's Terms of Reference

With regard to: all automatic and manual quality processes applied to the Automatic Weather Station data flow, including ingest and product generation rules for the Australian Data Archive for Meteorology (ADAM), the Automated Surface Observation System (ASOS), the Australian Integrated Forecasting System (AIFSDB) and the Real Time (RTDB) databases.

1. Evaluate the Bureau of Meteorology's land-based Automatic Weather Station observation network and air temperature data flow with respect to the suitability of the:
   a) Equipment, including supporting hardware, power supplies and wireless and wired data transfer networks;
   b) Approaches and methods for Automatic Weather Station data capture, transmission, and data quality assurance and quality control, including ingest and product generation rules for the Australian Data Archive for Meteorology (ADAM), the Automated Surface Observation System (ASOS), the Australian Integrated Forecasting System (AIFSDB) and the Real Time (RTDB) databases;
   c) Processes for recognising and acting on equipment failure and erroneous observations, including down-stream quality assurance and control processes;
   d) Maintenance practices, verification and return to service applied to each network tier, including data required for ACORN-SAT purposes;
   e) Data flows from observation through to end products; and
   f) Manual and automated processes in the quality control system.

2. Assess the implications of any instances of failure of an AWS to read temperatures below -10^0C on the integrity of the ACORN-SAT record.

3. Recommend any improvement necessary to maintain the robustness and resilience of the Automatic Weather Station observation network and associated data flow and data quality assurance and quality control processes.

1.2 Summary of Findings and Recommendations

A panel comprising three external independent technical experts and two senior officers from the Bureau was commissioned to undertake the review. The independent experts are professionals of national and international standing with expertise relevant to the scope of the Terms of Reference.

The panel supported the Bureau's initial diagnosis that outages at temperatures below -10.4°C at Thredbo and at Goulburn were the result of equipment in those locations not being fit for purpose.

The panel confirmed that the ACORN-SAT dataset has not been compromised directly or indirectly by the inability of some Bureau AWS to read temperatures below -10.4°C.

The panel found that, across the AWS network, the Bureau's verification process, quality checks, and processes for finding and acting on equipment failure all achieve their purpose.

The panel found that the Bureau's data quality control processes work well, flag errors appropriately, and that the Bureau's practices are of a high standard, and are in line with accepted practice for meteorological services worldwide.

Notwithstanding the soundness of the Bureau's data quality control, there were clearly failures in some of the Bureau's internal processes dating back to the mid-1990s that allowed equipment that was not fit for purpose to be installed at a small number of locations. Inadequate process, documentation and communication meant that some field officers were unaware of the different capabilities of similar pieces of equipment.

While the Panel considers that the current Bureau AWS network is fit for purpose, it has made a number of recommendations to prevent a reoccurrence of the issues that manifested at Thredbo and Goulburn.

The Panel's findings and recommendations for each of the Terms of Reference are as follows:

1.2.1 Terms of Reference 1:

Evaluate the Bureau of Meteorology's land-based Automatic Weather Station observation network and air temperature data flow with respect to the suitability of the:

a) *Equipment, including supporting hardware, power supplies and wireless and wired data transfer networks:*

The Review Panel found that:

- the Bureau's observing equipment for surface air temperature is suitable for its intended purpose, with the exception of sites where temperatures can reach less than -10°C and at which a particular equipment configuration exists—the Almos AWS with a MSI1 hardware card;
- there are two sites, Goulburn and Thredbo, where the equipment was not fit-for-purpose and failures have occurred at temperatures lower than -10°C;
- the MSI1 cards are not suitable to be installed at sites where temperatures below -10°C could be recorded as the card ceases reporting temperatures below -10.4°C;
- as a priority, the Bureau has replaced the MSI1 cards at six sites where temperatures below -8°C have previously been recorded. These are Goulburn, Thredbo, Tuggeranong, Mount Baw Baw, Butlers Gorge and Fingal; and
- recent developments in sensor and data acquisition technology provide the opportunity for the Bureau to replace its existing AWS to increase reliability and provide additional remote diagnostic and quality control information.

Recommendation 1: At all Almos AWS sites, where there is a reasonable risk that temperatures below -10°C could be recorded, the Bureau should replace the MSI1 hardware.

Recommendation 2: As the Bureau progressively replaces assets in its AWS network, it should ensure the ongoing integrity of the climate record in accordance with WMO recommendations, whilst leveraging new technology to improve reliability.

Recommendation 3: Before being deployed, new or replacement equipment installed at ACORN-SAT sites should undergo environmental testing across the full range of temperatures possible to be experienced in the field, to ensure that equipment is fit-for-purpose.

b) *Approaches and methods for Automatic Weather Station data capture, transmission, and data quality assurance and quality control, including ingest and product generation rules for the Australian Data Archive for Meteorology (ADAM), the Automated Surface Observation System (ASOS), the Australian Integrated Forecasting System (AIFSDB) and the Real Time (RTDB) databases:*

The Review Panel found that:

- the Bureau's methods for data capture, transmission, quality assurance and quality control are suitable for their intended purpose;
- the Bureau's data quality control processes do not have any negative impact on the data the Bureau publishes. The processes work well, and automatically capture errors that could affect downstream products;
- the Bureau has most of the documentation and systems in place to meet the International Organization for Standardization (ISO) 17025 standard for its measurement processes and would benefit from the discipline that full accreditation under the standard would bring;
- the documentation of the Bureau's automated quality control tests and processes is not readily accessible, as evidenced by the time taken to investigate the root cause of the data loss at Goulburn AWS; and
- the gaps in the Bureau's formal documentation of its automated processes mean that there is a risk of technical expert knowledge being lost.

Recommendation 4: The Bureau of Meteorology should seek accreditation of its laboratories and measurement processes under the ISO 17025 standard, and extend its existing ISO 9001 certification to include AWS management, operation and maintenance, and associated data management.

c) *Processes for recognising and acting on equipment failure and erroneous observations, including down-stream quality assurance and control processes:*

The Review Panel found that:

- processes for recognising and acting on equipment failure are robust and suitable for their intended purpose;
- procedures for following up on sensor failures or system failures exist but would benefit from formal documentation. This is addressed under Recommendation 4;

- standard procedures exist for dealing with identified or flagged errors and these are sufficient for all but a small number of instances, where the error is unique or the root cause is difficult to identify.

Recommendation 5: The management of data quality issues, where the error is unique or the root cause is difficult to identify, should be strengthened to ensure that such non-standard cases are be treated as exceptions, escalated for rectification and added to standard procedures where appropriate.

d) Maintenance practices, verification and return to service applied to each network tier, including data required for ACORN-SAT purposes:

The Review Panel found that:

- the Bureau failed to adequately communicate the limitations of the MSI1 card to its field staff;
- overall, the Bureau's field practices are of a high standard, and reflect accepted practice for meteorological services worldwide; and
- some documentation has not been updated for some time. This is addressed under Recommendation 4.

e) Data flows from observation through to end products; and

The Review Panel found that:

- the Bureau's data flows from AWS to end products have developed over time and have evolved increasing complexity;
- the quality tests applied to the data as it passes through the Bureau's systems, whilst effective, are also very complex;
- the current data flow architecture creates situations where data can be delivered to, and displayed on, the Bureau's website via multiple pathways and this can be potentially inconsistent and confusing for end users; and
- the planned refresh of the Bureau's central IT systems is an opportunity to redesign and implement a simplified data flow whilst maintaining current data quality standards.

Recommendation 6: Future investment in supporting IT systems should, as part of their design and system architecture, streamline and improve efficiency and consistency in data flows.

Recommendation 7: The Bureau of Meteorology should ensure that thresholds and criteria for data quality checking are held, controlled, and monitored in a central repository. The redesign should ensure consistency in the checks throughout the process.

f) Manual and automated processes in the quality control system.

The Review Panel found that:

- the Bureau's manual and automated processes for quality control are suitable for their intended purpose;
- the Bureau's quality control systems are effective in capturing those errors which would have a negative impact on downstream products, such as the calculation of monthly climate statistics, being accepted as a record value, or being displayed on the Bureau's Climate Data Online pages;
- the Bureau has processes in place to ensure that staff undertaking data quality control are competent and trained to do so, but the formalised competency assessment documentation is in need of updating and the training is not integrated with the Bureau's broader competency framework;
- the most recent version of the quality management system software was released before the documentation was brought up to date.

Recommendation 8: Documentation for the quality management system needs to be updated, to reflect the current version, and future revisions should adhere to the Bureau's standard version control practices.

Recommendation 9: The competency assessment for staff doing data quality control in the quality management system should be formally documented and integrated with the Bureau's broader staff competency framework.

1.2.2 Terms of Reference 2:

Assess the implications of any instances of failure of an AWS to read temperatures below -10°C on the integrity of the ACORN-SAT record.

The Review Panel found that:

- the issues relating to the inability of some Bureau AWS to read temperatures below -10°C have only affected sites at Goulburn and Thredbo;
- the ACORN-SAT dataset has not been compromised by the inability of some Bureau AWS to read temperatures below -10°C;
- there has been no impact of these failures on the ACORN-SAT data set;
- no ACORN-SAT station has been affected directly by the inability of some Bureau AWS to read temperatures below -10°C; and
- the homogenisation of ACORN-SAT time series has not been affected by the inability of some Bureau AWS to read temperatures below -10°C.

2 Background

2.1 Context for this Review

On 7 August 2017, the CEO and Director of Meteorology, Dr Andrew Johnson, put in place a review of the Bureau's Automatic Weather Stations (AWS).

The review evaluates the integrity of the AWS network, from the initial automatic recording of temperatures and observations to the final data logged into the record, and assesses whether data quality across the entire process meets its intended purpose, whether it can be traced and audited, and whether its quality is fully understood.

The review was instigated after the Bureau of Meteorology found equipment in Goulburn and Thredbo had malfunctioned following exposure to very low ambient temperatures. Case studies on these incidents are provided at Appendix A.

The review also sought to examine the impact on the Australian Climate Observations Reference Network Surface Air Temperature (ACORN-SAT) dataset, to make sure the error had not affected the integrity of the ACORN-SAT database. ACORN-SAT itself has been independently reviewed on several occasions, and found to be a sound and trustworthy dataset.

In 2011, a panel of internationally recognised independent experts reviewed the processes and methods used in developing the ACORN-SAT dataset. It ranked the Bureau's procedures and data analysis as being among the best in the world.

In January 2015, the then Parliamentary Secretary to the Minister for the Environment, the Hon Bob Baldwin MP, established a Technical Advisory Forum, as recommended by the 2011 independent peer review.

Comprised of leading scientists and statisticians, who were appointed for a total of three years to meet annually. The forum advises the Bureau on the development and operation of the ACORN-SAT dataset, and comments on further possible developments.

The forum has released two reports in 2015 and 2016, which are publicly available at: www.bom.gov.au/climate/change/acorn-sat/#tabs=Technical-Advisory-Forum and the 2017 report will be published soon.

2.2 Background on Bureau Processes

2.2.1 The Bureau's Observation Network

The Bureau of Meteorology operates a diverse observations network to provide weather forecasts, weather warnings, climate services, water information services, and ocean services.

Spread across Australia, this network includes 58 weather radars, sea level stations, rainfall stations, and tsunami and drifting buoys, as well as 695 AWS, which record temperature, humidity, pressure, rainfall, and wind.

The Bureau's observations network is one of the foundations for all of the services it delivers to the public, and to specific sectors, such as aviation, agriculture, transport, and defence. Each year, this network enables the Bureau to issue more than 500,000 public forecasts, and nearly 15,000 weather and ocean warnings.

2.2.2 Automatic Weather Stations

Beginning in the 1980s, the Bureau gradually started replacing manual observing stations with automated systems. AWS offered reliable and accurate observations at much greater frequency, and much lower cost than human observers.

Automation has greatly improved measurements and delivery, from less than 10 messages per day from manual observing stations, to about a million measurements per day through the AWS network.

AWS can be configured in different ways to meet various needs; some just measure wind speed and direction, while others measure surface air temperature, relative humidity, wind speed, wind direction, atmospheric pressure, soil temperature at various levels below ground, sea level, and lightning, or a combination of all these parameters.

As well as the sensors, each AWS has a data acquisition system that interprets the sensor signals, and converts them to quantities with appropriate units (for example, degrees Celsius for surface air temperature), as well as a communication component to direct messages to the Bureau's central system.

2.2.3 Quality Systems

Quality systems are the methods by which the Bureau ensures that its observations are of a known quality, and are traceable. Traceability means that a measurement can be traced back to an international standard, and its relationship to that standard demonstrated. Quality systems incorporate the physical laboratories and their staff, procedures, documentation, processes, and capabilities.

The observations requirements of the World Meteorological Organisation (WMO) stipulate that measurements must be traceable. To meet these requirements, the Bureau maintains measurement laboratories and reference standards used to verify and calibrate the AWS systems and sensors. The standards are then used in the field to verify the observations taken at individual AWS. The laboratories are regularly audited, most recently in 2017 and serve to provide traceability and calibration for other meteorological services in the Asia–Pacific region.

ISO 9001 is a widely-used system published by the International Organization for Standardization (ISO) to certify management tools and procedures, in this case management tools and procedures. This standard does not explicitly require people to have technical competence for making measurements. In comparison, ISO 17025 is an accreditation system, which accredits people for making measurements. Under this standard, technical competence is an explicit requirement, as is traceability for all measurements.

The Bureau has quality system certification in place (ISO 9001) for its aviation forecasting activities, to conform with the regulations of the International Civil Aviation Organization. This certification covers the management tools and processes ensuring that all the 80 or so meteorological products the Bureau produces meet client needs. The certification does not extend to measurement quality, including AWS data and messages, nor to the associated derived quantities and data streams.

To address measurement quality, the WMO recommends that national meteorological agencies have ISO 17025 accreditation of key measurement processes. Accreditation covers the technical procedures and processes that ensure the traceability and integrity of measurements, as well as the technical competence of the staff making the measurements. While the Bureau does not currently hold ISO 17025 accreditation, it has internal processes, technical procedures, and measurement traceability and integrity that are largely in accordance with ISO 17025 requirements.

2.2.4 Changes to Observing Methods

The Bureau has processes and procedures in place to make sure that changes to the observing systems and network are controlled, and their impacts understood. Any change to observing systems must be signed off at the General Manager or Manager level to avoid or minimise potential impacts on quality and delivery. The controls around ACORN-SAT are particularly rigorous, requiring a minimum two-year overlap between sites or systems when observing equipment is changed or relocated, or techniques are changed. System changes, and any other events that might have an impact on data records, are documented in the Bureau's station metadata repository SitesDB, in accordance with WMO requirements.

In 2011, the Bureau's methods for providing surface air temperature measurements were documented in a public report, as part of an independent peer review of ACORN-SAT. The Bureau provided additional supporting information on observing methods to this first of two independent reviews into ACORN-SAT (with the second Technical Advisory Forum extending over three years).

The ACORN-SAT measurement report documents the change from manual measurements of surface air temperature by observers using mercury-in-glass thermometers, to using platinum resistance sensors and associated electronics within AWS. The report also shows how the traceability of surface air temperature measurements, conforming with the international standards, was maintained over more than 100 years.

2.2.5 Tiering of Observing Networks

Historically, the Bureau operated a uniform AWS network in terms of its quality, with consistent maintenance and quality practices for all stations. But with a large network of stations, it is inefficient to manage all of them to the highest standard of quality when end-user applications do not require it. Due to the increasing diversity in weather and climate products that use AWS data, the growing number of AWS, and growing community interest in weather measurements, the Bureau shifted to a tiered AWS network in 2016 (Refer Table 1).

The highest tier is made up of the 91 AWS, which are used to generate the ACORN-SAT products. The ACORN-SAT requires both lowest uncertainty in an AWS message and shortest down-time after a failure or fault.

The second tier is the 417 AWS used for commercial aviation and severe weather response. Requirements for this tier of AWS are based on the more modest uncertainty requirements of International Civil Aviation Organization, but also with strong requirement to minimise down-time.

The third tier is the remaining AWS, which are used for public weather information, tracking severe weather and input into numerical prediction models.

The main difference between the highest two tiers and the third tier is the length of time it takes to respond to equipment failure and restore data communications.

The Bureau makes exceptions to this tiered priority during a major localised weather or water event (such as a tropical cyclone, a large bushfire, or a significant flood), where priorities are adjusted to ensure that local AWS that may be important for situational awareness are given priority.

3 Review Methodology

For this review, the Bureau established a five-member Review Panel, comprising three external experts and two senior Bureau officers.

The Review Panel met regularly, using telephone and video conferencing to cater for the two external panel members who are based overseas. Meetings were held on 11, 14, 15, 16, 18 and 23 August. Before and during these meetings, the external Review Panel members sought information from the Bureau's team of experts.

At the 15 August meeting, the Review Panel interviewed an expert about the Bureau's measurement activities, including surface air temperature. On 16 August, the Review Panel interviewed two Bureau experts on the processes used for generating the ACORN-SAT dataset, and specifically on any potential impact of the issues relating to the reading of low temperatures.

One of the external panel members visited the Bureau on 15 August 2017 to review the metrology laboratories. Using material provided to the Review Panel, and a series of questions from the other external panel members, this panel member performed a comprehensive investigation process similar to that used for auditing accreditation under ISO 17025, looking at the processes used, and determining the suitability of the quantities produced.

The external panel member conducted a vertical audit of the measurement chain from field-station verification (for Thredbo, Goulburn, and several other sites) to national standards of measurement, covering clauses 4 and 5 of ISO 17025 (which includes recordkeeping, methods, equipment, and staff competency).

Members involved in the data quality management system review were interviewed to confirm that actual practices aligned with documented procedures.

The Review Panel considered more than 50 technical documents, and posed more than 100 written questions, with answers provided with supporting documentary evidence.

Following this process, the Review Panel agreed on their findings and recommendations. These are included in this report, against each of the sections relating to the sub-points of the terms of reference.

4 Terms of Reference 1: Suitability of the Bureau of Meteorology's Land-Based Automatic Weather Station Network

4.1 Suitability of Equipment

4.1.1 Introduction

There are 695 stations in the Bureau's AWS network. Of these, 563 measure surface air temperature. As well as temperature, these measure humidity, pressure, rainfall, and wind speed and direction. Aviation AWS have additional sensors for cloud height, visibility, and present weather. The network is tiered (see Section 2.2.5), and the top tier sites, those within the ACORN-SAT network, are used to monitor long-term climate variability and change.

AWS follow a standard layout (Figure 1), which complies with WMO requirements, and includes:

- a Stevenson screen for measuring temperature and humidity;
- a separate rain gauge; and
- a 10-metre wind mast.

Figure 1: Bureau AWS (with Stevenson screen on left)

Observations from AWS are automatically delivered in real time to the Bureau's central computing system, where various tests and analysis occur before the measurements are used in downstream products, such as the Bureau's public website.

The Bureau uses platinum resistance probes to measure surface air temperature at AWS, and these are connected to the Data Acquisition System (DAS) located at AWS sites. The temperature measurement is derived by converting a measured resistance to a temperature by the known relationship between temperature and the resistance of platinum.

A known point of failure for this type of sensor is a connection point between the sensor and the DAS, as each connection point can potentially cause a change in resistance, resulting in a less accurate temperature. However, the Bureau's routine maintenance of its AWS has shown that faulty connections are very rare, and that once new sensors have been installed in the field, they are very reliable.

The testing procedure for AWS during routine maintenance visits is designed to identify any issues, so that corrective action can be taken immediately. The Bureau records all maintenance actions in a corporate database called SitesDB, and Bureau users of AWS data can access this information to help their assessment of the quality of products that were derived from AWS surface air temperature measurements.

The AWS surface air temperature measurements are monitored by specially trained and competent staff, who will flag any potential issue, triggering an action in SitesDB, which goes to the relevant operational area for investigation.

Two models of DAS are used in the Bureau's AWS network for surface air temperature: the Almos AWS and the Telmet 320 AWS.

4.1.2 Almos Data Acquisition System

The Almos was introduced in 1993, when the AWS network was initially expanded, after a tender process and trial of different DAS models and sensors.

In 2007, after another tender process that used the experience gained with the Almos DAS, the Telmet 320 was selected as the next generation of DAS to eventually replace the Almos. As the use of proprietary designs and intellectual property for both DAS are owned by the vendor, the only changes the Bureau can make are the site details, sensor configuration, and, in some cases, message formatting.

There are 397 Almos DAS in the Bureau's surface air temperature AWS network. The Almos DAS consists of proprietary modules that provide processing, measurement and communications functions using technologies available before 1993. It uses

custom firmware (both operating system and application), which is provided by the vendor, and stored physically on the processing module using erasable programmable read-only memory. As a result, remote updates of the firmware are not possible.

The measurement module is designed for a fixed number and pre-defined type of meteorological sensors (including platinum resistance probes). System configuration can be accessed and changed via the serial port (locally and remotely). The Almos DAS can provide one-second, one-minute, and 10-minute messages, as well as various other standard format meteorological messages.

A key component of the Almos AWS is the data acquisition card, which converts the resistance of the platinum resistance probe to a temperature value. The initial model of this card (designated MSI1) was provided with the initial purchases of Almos DAS units in 1993.

Testing of the MSI1 card at the Bureau's metrology area and the vendor's facility in 1994 determined that the card would not report temperatures where the resistance was equivalent to a temperature below –10.4°C. Subsequently, a new model card (MSI2) was developed and procured from the vendor, with testing at the Bureau's metrology area in 1999 showing this card could operate accurately and successfully at temperatures down to –25°C.

4.1.3 Telmet 320 Data Acquisition System

In 2007, the *NextGen AWS Project* was initiated with the intention to replace the AWS network DAS, move to 3G and satellite communications for remote AWS, and establish a centralised message generation model using one-minute or one-second messages.

The Bureau selected the Telmet 320 as the replacement DAS. Between 2008 and 2014, the NextGen AWS project progressively rolled out Telmet 320s, and converted all AWS to sending one-minute messages, which is now the default message frequency. There are now 165 Telmet 320 AWS in the Bureau's surface air temperature network.

Bureau staff perform station configuration using vendor-provided software, which creates a configuration file that can be remotely uploaded to the station. Bureau staff can modify or update the configuration file only; all other modifications must be provided by the vendor. As a more modern unit, the Telmet 320 had considerably more storage than the Almos, and could store up to two years of one-minute messages, although the default is currently set at 30 days of one-minute messages.

As the Telmet 320 was deployed in the Bureau's network, it proved to be less reliable than the Almos. The proprietary nature of the software in the device did not allow timely upgrades or modifications that were necessary for several new measurement programs in the Bureau. In addition, resources to maintain each Telmet 320 were significantly higher than for the Almos. For example, between 5% and 10% of the storage cards used in the Telmet 320 AWS network failed each year, and several of the units regularly locked up, and had to be restarted.

Testing of a Telmet 320 by the Bureau's metrology area in 2011 confirmed the Telmet 320 DAS meteorological measurements satisfied the Bureau's measurement requirements. But given the likely down-time of individual Telmet 320, it was not deemed a suitable replacement DAS and messaging system for use at ACORN-SAT sites.

Almos is still the preferred DAS for ACORN-SAT sites, and the Bureau has not been yet procured a suitable replacement. As a result, the MSI2 cards have been prioritised for ACORN-SAT sites in alpine areas and other locations where temperatures are likely to fall below zero. To ensure enough Almos DAS are available for ACORN-SAT sites until a new and appropriate DAS is available, the Bureau has been replacing Almos DAS at lower-tiered sites with Telmet 320 units.

4.1.4 Power

Reliability of power supply and electrical interference are significant issues for any real-time messaging system. The Bureau uses battery power supplies charged by either mains power at sites with suitable infrastructure, or by solar power at remote sites that are off the main power grid.

At solar powered sites, the power requirements of the DAS, sensors, and satellite communications can be difficult to meet during long cloudy periods, and on rare occasions battery voltages can drop below the level required to achieve uninterrupted observations and effective messaging. The DAS monitors battery supply voltage, which is reported in the one-minute messages. This information is then available as inputs to Bureau QA and QC procedures. Of the 563 Bureau AWS sites currently recording temperature, 178 rely on solar power.

For sites with mains supply, a rare disruption of power supply will result in switching to battery backup. Typically, sites can operate for three to five days on battery backup, which is enough to cover most outages.

4.1.5 Communications

A key challenge for getting data from remote sites is digital communications. While cellular networks and fixed-line services are common in built-up areas, coverage across remote areas of Australia is very limited. The AWS network uses a combination of both wired and wireless methods to deliver data to the Central Message Switching Service. The communication method used at each site is determined by its location, service category, and the availability and reliability of commercial data communications services.

Where a station is identified as critical or important (for example, cyclone, fire, key aviation, and extreme weather forecasting/monitoring), two or three data communications methods will be used at once, to ensure continued communication should one of the services fail. For critical stations, the Bureau ensures that the availability of communications systems is 99.9%.

Most of the AWS network sites use a Telstra 3G/4G wireless service as primary communications (627 sites), with a Broadband Global Area Network satellite service as secondary communications for critical or important sites (373 sites).

A Broadband Global Area Network satellite system is used as a second communications service across the network, with services delivered via the Inmarsat-4 network, which has a 99.9% satellite and ground network availability.

4.1.6 Testing

The Bureau has factory-acceptance testing for equipment it uses in the field, and equipment that is used for traceable measurements is extensively tested and verified against references before being deployed. Any equipment the Bureau buys must meet its quality and accuracy performance specifications, which are set out in tender documents.

4.1.7 Findings and Recommendations

The Review Panel found that:

- the Bureau's observing equipment for surface air temperature is suitable for its intended purpose, with the exception of sites where temperatures can reach less than -10°C and at which a particular equipment configuration exists—the Almos AWS with a MSI1 hardware card;
- there are two sites, Goulburn and Thredbo, where the equipment was not fit-for-purpose and failures have occurred at temperatures lower than -10°C;

- the MSI1 cards are not suitable to be installed at sites where temperatures below -10°C could be recorded as the card ceases reporting temperatures below -10.4°C;
- as a priority, the Bureau has replaced the MSI1 cards at six sites where temperatures below -8°C have previously been recorded. These are Goulburn, Thredbo, Tuggeranong, Mount Baw Baw, Butlers Gorge and Fingal; and
- recent developments in sensor and data acquisition technology provide the opportunity for the Bureau to replace its existing AWS to increase reliability and provide additional remote diagnostic and quality control information.

Recommendation 1: At all Almos AWS sites, where there is a reasonable risk that temperatures below -10°C could be recorded, the Bureau should replace the MSI1 hardware.

Recommendation 2: As the Bureau progressively replaces assets in its AWS network, it should ensure the ongoing integrity of the climate record in accordance with WMO recommendations, whilst leveraging new technology to improve reliability.

Recommendation 3: Before being deployed, new or replacement equipment installed at ACORN-SAT sites should undergo environmental testing across the full range of temperatures possible to be experienced in the field, to ensure that equipment is fit-for-purpose.

4.2 Approaches and Methods for Automatic Weather Station Data Capture, Transmission, Quality Assurance, and Quality Control

4.2.1 Introduction

The process from observation through the Bureau's various systems is documented in Section 4.5. This has numerous steps of quality control, with data passing through multiple IT systems before being used in applications such as forecasting or climate.

The AWS used in the Bureau's surface air temperature network, the Telmet 320 and Almos (both MSI1 and MSI2 cards), all have the same basic measurement design.

4.2.2 Data capture and transmission

The process from sensor to output message for measuring surface air temperature has 3 main steps:

- analog to instantaneous temperature value;
- instantaneous temperature value to one-minute value; and
- formation and transition of one-minute values in the data message.

4.2.3 Analog to instantaneous temperature value

The Bureau uses platinum resistance thermometers to measure surface air temperature, and only those that conform to an accepted standard (BS 1904:1984)[1], when compared to a reference standard are used in the field.

The resistance is sampled at least once a second, and a temperature (sample) value calculated. The four-wire measuring technique is used to measure the resistance, and the maximum excitation current is limited to 0.2 mA so that the sensor heating is within acceptable limits.

[1] Equipment specification A2671: provision of an automatic weather station type 1 v4.0, 1991 p77. The BS 1904:1984 Standard is equivalent to IEC 60751:2008.

4.2.4 Instantaneous temperature value to one-minute value

The Almos and the Telmet 320 DAS capture, test, and process data in different ways.

4.2.4.1 Almos (internal quality control)

The Almos AWS has two key data validation tests: a range test and a rate test:

- The range test checks that the one-second temperature value that is measured is within the range –50°C to +70°C at all stages in the process. If a value does not fall within this range, it is replaced with a marker (or flag) denoting that the value is unavailable; and
- The rate test checks that the difference between the current measurement and the previous one is no greater than 0.4°C. If the difference is greater, the measurement is replaced with a marker denoting that the current value is unavailable.

All valid one-second temperature values within the minute interval are assembled into an array. If there are more than nine valid one-second temperature values within the minute interval, then a range of one-minute statistics are generated from these values. These include:

- an instantaneous air temperature is the last valid one-second temperature value in the minute interval;
- one-minute maximum air temperature is the maximum valid one-second temperature value in the minute interval; and
- one-minute minimum air temperature is the minimum valid one-second temperature value in the minute interval.

If there are less than 10 valid one-second temperature values within a minute interval, then the instantaneous air temperature and all one-minute temperature statistics are marked as being unavailable.

4.2.4.2 Telmet 320 (internal quality control)

The Telmet 320 AWS implements a larger suite of data validation tests, reflecting its more modern technology compared with the Almos.

The range and rate tests are similar to the Almos, except that the one-second temperature value measured must be between –70°C and +60 °C. Temperature values that do not pass the tests are marked (flagged) as unavailable. The threshold number of temperature values needed to calculate the three main temperature statistics is also the same as an Almos.

On passing the two key data validation tests, an average and standard deviation are calculated for the sample set. Note that second pass statistics[2] are not done on any temperature measurements.

The Telmet 320 also incorporates an extended reporting mechanism[3] for the number of valid samples used to generate the statistical values.

4.2.5 Formation and Transmission of One-Minute Values in the Data Message

Once the temperature statistics are calculated, they are formed into data messages for transmission. The Almos uses the one-minute data format[4], which includes groups for instantaneous air temperature, and the one-minute values for the maximum and minimum temperatures.

The Telmet 320 uses the name value/pair format[5], which includes groups for instantaneous air temperature, one-minute averages and standard deviations, one-minute maximum and minimum values, and optional quality flags.

4.2.6 Quality Control Rules for AWS Temperature

Quality control for temperature data occurs at several points along the process to ensure the final record is accurate, or otherwise flagged. This occurs within the following key systems:

- Automatic weather stations (AWS):
  - data loss rule
  - temperature range tests
- Automated Surface Observation System-Central System (ASOS-CS)
  - data loss rule
  - temperature range tests
- Australian Data Archive for Meteorology (ADAM) ingest
  - temperature range tests

2 commonly termed outlier tests

3 This uses additional message content to reflect the sample size. Reports data validation variables (as above).

4 One-second data and one-minute data format description V1-1, 2017.

5 One-minute name value pair data message: content description V1 2017, and One-minute name value pair data message: format description V1–10, 2017.

- ADAM database quality management systems (see Section 4.6)
    - Climate test
    - Three-hourly test
    - Maximum and minimum test
    - Spatial test
    - Flatline test
    - Period gap test
    - Large period test
    - diff.MaxAirTempDiffTest

In addition, data distribution rules deliver data and information to targeted channels to the following systems to:

- Central Messaging Switching System;
- Services and Information Management System; and
- Climate Data Online.

4.2.6.1 Data Loss Rule for Daily Temperature Extremes

Daily temperature statistics such as daily temperature extremes are created in one of two key systems, the Bureau's automated surface observation system (ASOS-CS) or specific Almos AWS sites.

The one-minute data streams from most of the Almos AWS and from all Telmet 320 AWS are delivered via the Bureau's central message switching system to ASOS-CS, where they are then processed into daily temperature products.

At specific Almos AWS, where manual data input is needed, or where data communications are poor, daily temperature statistics are automatically calculated on site then transmitted via Central Messaging Switching System for distribution and further processing. This route does not involve ASOS-CS.

When six or more consecutive one-minute samples are invalid or missing, data loss is recorded. In such an event, the daily statistics are stored, but are not transmitted beyond ASOS-CS, unless manual validation has occurred. Where the daily statistics are automatically calculated at the Almos AWS, these events mean that no daily statistics (such as daily temperature extremes) are calculated.

4.2.6.2 Temperature Range Rules

The temperature ranges for valid measurements differ between the key systems (see sections 4.2.4.1 and 4.2.4.2).

The valid temperature range in the ASOS-CS system matches that of the Almos AWS (–50°C to +70°C). Antarctic stations use an Almos AWS with a MSI2 sensor interface card. These are capable of the extended range. The Australian Antarctic Division (AAD) AWS sites are predominantly coastal and therefore do not experience the –50°C observed further inland. Davis has remained operational down to -41.3°C using the Almos MSI2 system as recently as August 2013.

The ADAM ranges for Australia (Table 2) are primarily determined by the following site classifications:

- Alpine (1000 metres and above mean sea level)
- Standard (less than 1000 metres).

If a temperature measurement is outside of the range for ADAM, it is diverted to a holding table to be manually checked by Bureau staff. On 12 July 2017, the Bureau expanded the temperature ranges in each classification as an interim measure while the Goulburn AWS issue was being investigated.

The threshold placed upon the ingest prevents any data that exceeds this value from being ingested directly into the appropriate table, rather it gets placed into a holding table. However, this data can subsequently be retrieved during the Quality Control process.

The quality management system in ADAM contains several quality control tests, as well as algorithms that flag potential quality issues (see also Section 4.6). Within the quality management system, all AWS stations have a unique minimum temperature threshold, which varies from month-to-month based on the likely temperatures in each location.

The Bureau's Climate Data Online[6] uses data quality flags (see Section 4.6) before data is published. Flagged data is checked against threshold flag values, and if the data is found to be of poor quality, it is not published. Different Climate Data Online

6 Climate Data Online provides public access to various statistics, recent weather observations, and climate data from ADAM

products, such as Daily Weather Observations and Climate Data Online daily values have different thresholds for publication (see Section 4.5).

ADAM also prioritises the data it retains, so that more specific data is selected over less specific data. So that lower precision weather data (known as Surface Synoptic Observation) (expressed as an integer value for temperature) enters ADAM before higher precision weather data (known as meteorological data format) (expressed as a decimal value for temperature) enters ADAM second. The higher precision data overwrites the lower precision data. For example, a value of –5.5°C overwrites a value of –5°C.

4.2.7 Australian Integrated Forecasting System

The Australian Integrated Forecasting System (AIFS) regional system generates the latest weather products. These products appear on the website, including on the Latest Weather Observation pages, MetEye, and Bureau weather based web applications.

The AIFS products and data do not contribute to the climate information workflow, so do not influence the climate record. As these products provide the latest weather intelligence, they have different quality control requirements to that of the Bureau's more stringent climate quality control processes. AIFS receives AWS temperature data from Central Messaging Switching System, which has ingested data directly from specific Almos AWS or ASOS-CS (see Section 4.2.6.1).

The AIFS system does several syntax checks to ensure that incoming data has the correct format. If the checking system stops for any reason, data up to that point is retained. Following the syntax checks, validation checks are done. If the temperature values do not satisfy these checks, the data is unchanged, but a warning is generated so that it can be checked manually. AIFS also checks for internal consistency within data messages. If data is not consistent, it is manually checked (see Section 4.3).

All valid data that goes through AIFS, the Central Messaging Switching System, and the Services and Information Management System is unchanged. Rather, these systems alert Bureau staff of anything unusual, so that data can be manually checked.

4.2.8 Findings and Recommendations

The Review Panel found that:

- the Bureau's methods for data capture, transmission, quality assurance and quality control are suitable for their intended purpose;

- the Bureau's data quality control processes do not have any negative impact on the data the Bureau publishes. The processes work well, and automatically capture errors that could affect downstream products;
- the Bureau has most of the documentation and systems in place to meet the International Organization for Standardization (ISO) 17025 standard for its measurement processes and would benefit from the discipline that full accreditation under the standard would bring;
- the documentation of the Bureau's automated quality control tests and processes is not readily accessible, as evidenced by the time taken to investigate the root cause of the data loss at Goulburn AWS; and
- the gaps in the Bureau's formal documentation of its automated processes mean that there is a risk of technical expert knowledge being lost.

Recommendation 4: The Bureau of Meteorology should seek accreditation of its laboratories and measurement processes under the ISO 17025 standard, and extend its existing ISO 9001 certification to include AWS management, operation and maintenance, and associated data management.

4.3 Processes for Recognising and Acting on Equipment Failure and Erroneous Observations

4.3.1 Introduction

The Bureau has several controls in place to identify equipment failure and erroneous observations, and to do real time, initial quality assurance and control.

Bureau staff are automatically notified of incidents, and have protocols in place to prioritise and rectify faults, and return equipment to service as fast as possible. Real time and post event processes for monitoring the AWS network ensure robust oversight.

4.3.2 Real time (and near real time) monitoring

Real time monitoring of AWS data maintains data resilience, and enables staff to find and fix faults quickly, and get data flows back on track.

Real time monitoring is typically done using one or more of the following:

- **Network monitoring tool**—this system provides a web interface and monitoring capability, and alerts staff of possible sensor anomalies, and of data from an AWS that might have been processed incorrectly by downstream systems (for example, clock drift alerts to ensure one- minute data is not lost).
- **One-minute data application**—this software monitors real time AWS data. It displays the current minute only, and alerts staff of abnormal system behaviour.
- **AIFS (see Section 4.2.7) consistency checker**—this system alerts staff in capital city airports of inconsistencies between stations' observations that need investigating.
- **COMMS GUI** (part of the AIFS application)—this tool alerts staff of 'message syntax' and 'parameter out of range errors'. It can also be used to edit data messages for distribution to downstream systems.
- **External bulletins**—these are messages transmitted to users, such as aviation, defence, and other meteorological centres. They can be used to notify staff of data gaps, which can be caused when:
    - observations are not sent
    - data are missing for more than six consecutive minutes
    - 20% of the data are missing over the 24 hours to 9am.

4.3.3 Data corrections and flagging

Bureau staff can correct air temperature errors in near real time using the following tools:

- **Web Electronic Field Book**—this system sends messages on behalf of manual observer locations or is used to generate AWS messages where sufficient data exists (for example, where an outage is unlikely to affect the daily maximum, minimum, or cumulative rainfall). Messages from this system typically contain the text 'regional observer' in the plain text field.
- **COMMS GUI** —This system interfaces directly into AIFS to correct messages for syntax and out-of-range errors.

To document any changes made to data, staff are required to email the Quality Control Group, so they can investigate the changes, using the quality management system. Staff will also notify Observing Operations Hub Technical Officers to investigate equipment faults or errors, using SitesDB.

Quality Control Operators verify any changes made by Communications Desk staff. When the maximum or minimum temperature data are removed from the MDF message via the COMMS GUI, the ADAM database keeps the original value, rather than removing the data. However, this process prevents the data from appearing on the Bureau's website.

Where Communications Desk staff can't recover the missing data, Quality Control Operators will try to recover it via either the MDF message or the one-minute data stream.

Data that is recoverable is flagged as either corrected (QF2) if recovered by the MDF message, or estimated (QF3–5) if recovered via the one-minute data. Where the data is not recoverable, the value is left as null in the ADAM database.

Where data is determined to be incorrect, Quality Control Operators will try to recover the correct value. Where incorrect temperature data is encountered, and the correct value is not recoverable, the data is retained, but assigned a quality flag of 'suspect' (QF6 or greater). All corrections or modifications done on data are logged in the respective audit table, to ensure probity and traceability of the data chain.

Where a station has multiple occurrences of equipment failure or erroneous observations, a SitesDB action is lodged, so that Bureau field staff can investigate.

4.3.4 Findings and Recommendations

The Review Panel found that:

- processes for recognising and acting on equipment failure are robust and suitable for their intended purpose;
- procedures for following up on sensor failures or system failures exist but would benefit from formal documentation. This is addressed under Recommendation 4;
- standard procedures exist for dealing with identified or flagged errors and these are sufficient for all but a small number of instances, where the error is unique or the root cause is difficult to identify.

Recommendation 5: The management of data quality issues, where the error is unique or the root cause is difficult to identify, should be strengthened to ensure that such non-standard cases are be treated as exceptions, escalated for rectification and added to standard procedures where appropriate.

4.4 Maintenance Practices, Verification and Return to Service

To maintain and operate its large observing network, the Bureau has a workforce of technical officers across Australia. These staff perform field work, visiting AWS and other observing sites where they work on various tasks - from clearing vegetation to verification checks, and scheduled maintenance. They carry with them tools to repair faults, and sophisticated testing equipment to validate the measurements being taken by the AWS. These officers visit sites at least once a year, but more often for higher tiered sites.

4.4.1 Program Requirements

In doing maintenance, inspection, verification, and return to service activities on AWS, Bureau staff operate under the guidance and instruction of key documents:

- the *Inspections handbook*[7], which provides instructions on inspection and verification procedures;
- the *Surface observations handbook*[8], which detail the procedures for maintenance;
- a series of engineering documents[9], which detail the procedures for maintenance; and
- the *Program of maintenance*[10], which provides direction to local managers on levels of service for business-as-usual observing operations activities (maintenance, inspection, verification, and return to service) to be done in a given year for all of the Bureau's observing networks. This document notes that only staff with the appropriate training and competencies should do maintenance, inspection, verification, and return to service work.

The handbooks and engineering documents are amended as required to reflect system and process changes, while the Program of Maintenance is updated each year, and is linked to the setting of annual operational budgets.

7 Inspections handbook 2010. Bureau of Meteorology. Internal document 60/3317.

8 Surface observations handbook, 1989. Bureau of Meteorology. Internal document 60/452

9 Technical engineering documents held in the Bureau's engineering document management system, which contain the instructions and manuals for all the physical and electronic components of the AWS system.

10 Programme of maintenance 2017–18.

4.4.2 Inspection visits

The inspection visit checks standards and practices for observations, exposure and siting, instruments and sensors, documentation, station facilities and safety, communications, metadata, and training.

The Inspection visit is designed to ensure that:

- the quality of an observation product meets or exceeds a required minimum standard; and
- maximum efficiency is achieved in the production process.

During an inspection visit, the performance of each observing instrument is verified, both on arrival and on departure. If the performance is within documented limits, it is recorded in SitesDB as being within calibration. If it fails calibration, and on-site rectification is not possible, then a return-to-service action is lodged in SitesDB. The exposure of the instruments is also checked against observations specifications[11]. The station metadata is updated in the database, which includes photographs and site layout diagrams. A safety check is also completed.

More detail can be found in the Inspections Handbook[7], in particular on:

- field tolerances of AWS sensors (Chapter 3.2, Point 42, page 11); and
- procedures for performance checks on sensors (Part 4 Annexes).

4.4.3 Maintenance Visits

The tasks done during a maintenance visit include:

- Checking the physical state of the measurement station via a visual inspection;
- In-situ calibration check against higher level measurement standards;
- replacing and upgrading equipment, communications, and physical infrastructure;
- completing outstanding actions logged in the station database (SitesDB);
- checking the integrity of power supply, batteries, components, cabling, and earthing; and
- assessing equipment performance since the previous visit.

11 Observations specification 2013.1

All of these and other tasks are detailed in the Surface observations handbook and several technical engineering documents.

4.4.4 Return to Service Visits

During a return-to-service visit, the faulty equipment is replaced or repaired. Performance checks are done on arrival and on departure for all equipment where a fault has been reported. Where time permits, a full inspection is also done. All changes are recorded in the station database, SitesDB.

In some cases, return to service can be achieved through remote access. When this occurs, information is recorded in SitesDB, but no sensor verification checks are done. Prioritisation of return to service is guided by the *Program of maintenance*[12].

4.4.5 Calibration and Repair of Sensors

Faulty sensors are replaced with new or refurbished units, then returned to central stores to be refurbished, calibrated, or disposed of. AWS air temperature sensors that are returned to the Bureau's Regional Instrument Centre for testing are compared to the working references. The working references are calibrated using documented procedures[12,13]. All air temperature sensors, whether new or brought back from field deployment, are verified against criteria[14], and only pass the testing if they are within acceptable limits. As the air temperature sensors cannot be adjusted, a failed sensor is either disposed of, if it is brought back from the field, or returned to the manufacturer, if it is part of a new batch.

The field inspection devices for air temperature, which are used to verify the air temperature sensors in the AWS, are calibrated annually using documented procedures[15].

12 Calibration of working reference SPRT and IPRT 2016. Document RIC-TP-WI-002, version 3.0.

13 Calculation of uncertainty for temperature working references 2016. Instrument test report 709.

14 Calibration of industrial platinum resistance thermometers and Agromet probes (IPRTs) 2003. Standard procedure number Pt100_02SCP01.

15 Verification of field IPRT (inspection and field) 2016. Document RIC-TP-WI-004, version 3.0.

4.4.6 Findings and Recommendations

The Review Panel found that:

- the Bureau failed to adequately communicate the limitations of the MSI1 card to its field staff;
- overall, the Bureau's field practices are of a high standard, and reflect accepted practice for meteorological services worldwide; and
- some documentation has not been updated for some time. This is addressed under Recommendation 4.

4.5 Data Flows for Surface Air Temperature from Automatic Weather Stations

4.5.1 Introduction

The data flows for automatic measurements of temperature are complex. The high-level AWS data flow diagram provided at Appendix C shows key systems (applications and databases), connections, and data rules that AWS data goes through.

The key components of the data flow are described in Table 3. These components include the applications, databases, archives, and user interfaces, together with a brief description of the data rules for these components, and the main data types relevant to this data flow.

The weather and climate data flow split at the real time database. The weather applications data flow that deals with latest observations go back though Central Meteorological Messaging System to the AIFS systems, where products are generated, stored, archived, or dispatched. The weather systems do not include complex quality management system, as their purpose it to provide weather data in near real time.

The climate data flow continues from the real time application to ADAM applications and systems, including the quality management system and climate data online. The climate data flow requires manual steps, so is not a near real time data flow.

4.5.2 Findings and Recommendations

The Review Panel found that:

- the Bureau's data flows from AWS to end products have developed over time and have evolved increasing complexity;
- the quality tests applied to the data as it passes through the Bureau's systems, whilst effective, are also very complex;
- the current data flow architecture creates situations where data can be delivered to, and displayed on, the Bureau's website via multiple pathways and this can be potentially inconsistent and confusing for end users; and
- the planned refresh of the Bureau's central IT systems is an opportunity to redesign and implement a simplified data flow whilst maintaining current data quality standards.

Recommendation 6: Future investment in supporting IT systems should, as part of their design and system architecture, streamline and improve efficiency and consistency in data flows.

Recommendation 7: The Bureau of Meteorology should ensure that thresholds and criteria for data quality checking are held, controlled, and monitored in a central repository. The redesign should ensure consistency in the checks throughout the process.

4.6 Manual and Automated Processes in the Quality Control System

All maximum and minimum surface air temperature data pass through the quality monitoring system application, which includes a set of validation tests and analysis tools used to quality control observational data before it enters the climate database. The quality monitoring system testing consists of a series of automated tests, followed by manual check, when flagged.

The climate test listed in Table 2 is run as soon as the data is recorded, and the remaining automated tests run 72 hours after the day on which data has been recorded. As a result, manual quality control processes for maximum and minimum temperatures do not occur until at least 3 days after the data has been recorded.

A full list of the automated tests done on maximum temperatures is provided in Table 6, and those done on minimum temperature are in Table 7. When an observation fails an automated validation test, it is listed in a 'suspect queue' for a manual check by a QC operator.

Manual verification involves analysing the meteorological data format message submitted and the one-minute data stream, then comparing those with the temperature observations at surrounding stations. Several additional sources of information are available to help the QC operator in that assessment, including access to the action history at a station and its metadata from SitesDB. All corrections or modifications done on the data are logged in the respective audit table, to ensure provenance and traceability of the data chain.

Once the analysis is completed, the observation is assigned a quality flag by the trained QC operator, based on the confidence level in the observation. The full list of quality flags used in the QC process is listed in Table 8. Once flagged, suspect or erroneous temperature data is not deleted from the ADAM database, but the flag might prevent it being used to generate unreliable products in some downstream applications.

The original WMO reference for the quality control of climate data was published in 1986[16]. These guidelines have recently been updated, but not yet published. A peer review process is under way, with a final version likely by end of 2017, and

16 The Guidelines for the quality control of surface climatological data, 1986

publication expected in early 2018. This will then be the new definitive WMO reference for quality control of surface climate data.

The guidelines present a description of the principles, requirements, and techniques used, along with a detailed description (including algorithms) of recommended quality control tests. The Bureau's quality management system aligns with these, particularly in relation to the following:

- The initial screening process for incoming data is completely objective.
- The quality control system testing algorithms and quality monitoring parameters are scientifically and statistically sound in accordance with WMO guidelines and other relevant sources. They are also well documented, including version control where algorithms change. While all algorithms comply with the WMO guidelines, the quality management system has some additional algorithms.
- By applying a variety of tests in the QC process, it is highly likely that data will be flagged if it:
    - appears in any way inconsistent in time or space with other data
    - falls outside the range of historically recorded values
    - is internally inconsistent (for example, rainfall observed with no cloud, minimum temperature higher than maximum).
- Further investigation then enables an expert to assess the likelihood of the recorded value being incorrect. As an example, an extremely high temperature value near the climatological extreme at a particular location would be flagged, and verified only if there was supporting evidence, such as similarly extreme values at surrounding stations.
- Details of the QC process, and all available quality information, are accessible to data users.
- Any alterations to the measured or observed values are required to be documented and flagged, and an audit trail generated, so that the history of changes to the data, including who made the change, when, and why are documented.
- Values that have been changed are not deleted, but are stored in ADAM, including their quality assessment.

4.6.1 Findings and Recommendations

The Review Panel found that:

- the Bureau's manual and automated processes for quality control are suitable for their intended purpose;
- the Bureau's quality control systems are effective in capturing those errors which would have a negative impact on downstream products, such as the

calculation of monthly climate statistics, being accepted as a record value, or being displayed on the Bureau's Climate Data Online pages;

- the Bureau has processes in place to ensure that staff undertaking data quality control are competent and trained to do so, but the formalised competency assessment documentation is in need of updating and the training is not integrated with the Bureau's broader competency framework;
- the most recent version of the quality management system software was released before the documentation was brought up to date.

Recommendation 8: Documentation for the quality management system needs to be updated, to reflect the current version, and future revisions should adhere to the Bureau's standard version control practices.

Recommendation 9: The competency assessment for staff doing data quality control in the quality management system should be formally documented and integrated with the Bureau's broader staff competency framework.

5 Terms of Reference 2: Impacts on ACORN-SAT

5.1 Background

The temperature data that comprises a key part of Australia's long-term climate record is 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, providing a record of temperatures that can be compared through time.

Weather stations move for a variety of reasons. For example, an observing site at an airport might 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. For example, when an observing site moves, the climate of the old and new site might be slightly different. To maintain a long-term record for climate monitoring, the data from the older site needs adjusting, so that it is consistent with the new, operational site. This adjusted data does not replace the old site record, but ensures comparability with the new site data.

The science used to prepare datasets like ACORN-SAT has a long history in the scientific literature, and several international climate research centres independently prepare adjusted climate data for use in climate monitoring and research, work that is endorsed by the WMO.

The Bureau's analysis methods for ACORN-SAT have been published in international peer review journals, and was subject to external independent reviews in 2011 and from 2015 to 2017. These reviews expressed overall confidence in the Bureau's practices, and found its data and analysis methods to be among the best in the world.

A fact sheet summarising ACORN-SAT at: www.bom.gov.au/climate/change/acorn-sat/documents/About_ACORN-SAT.pdf

5.2 Impact of the –10°C issue on the ACORN-SAT Record

No AWS used as part of the ACORN-SAT has ever failed to read a valid temperature below –10°C.

In fact, no ACORN-SAT site has reached temperatures of –9°C or lower since AWS were installed. Inspection of time-series has confirmed that the true minimums have been recorded and that there are no instances of equipment failure, where temperatures below –10°C have occurred, but failed to be recorded by the AWS.

While there have been no instances of temperatures below –9°C at ACORN-SAT sites since AWS installation, ACORN-SAT sites at Butlers Gorge, Cabramurra, Canberra, and Inverell have in the past reached –10°C or below as manual sites. Following the internal review of the Goulburn and Thredbo incidents, the MSI1 cards at these locations have been replaced with MSI2 cards, except for Inverell, which remains a manual site.

There are only two instances outside of the ACORN-SAT network where the AWS failed to read valid temperatures below –10.4°C, Goulburn and Thredbo. These instances have not affected any ACORN-SAT data. The only use of the Goulburn AWS (where only one observation in 2017 was affected) in an ACORN-SAT adjustment was between 2001 and 2010, for a 2006 adjustment at Canberra.

Thredbo has not been used in any ACORN-SAT adjustments since AWS installation. In any case, the ACORN-SAT method is designed to be robust enough not to be materially affected by a small number of suspect or incorrect values at reference sites.

Data used for ACORN-SAT (both for the ACORN-SAT stations themselves and for reference stations used in the ACORN-SAT process) are drawn from ADAM. Data entered into ADAM is subject to quality control steps that are outside of the ACORN-SAT analysis process. Those quality control steps applied to apparent readings below –10°C from AWS (whether subsequently determined to be valid or invalid observations) have not biased the ACORN-SAT analysis.

5.3 Failure to Read Temperatures Below –10°C at Reference Stations

The analysis underpinning the ACORN-SAT data set uses temperature data from nearby stations to assess 'temporal inhomogeneities' (artificial influences, such as due to instrument changes) at its 112 locations. These neighbouring sites are known as reference stations in the ACORN-SAT context. While there is no identified case of failed –10°C or below readings occurring at reference stations at times that would affect homogeneity adjustments in ACORN-SAT, the method of detecting and

adjusting homogenisation is relatively insensitive to outliers in the daily temperature record.

This includes the use of a quantile matching algorithm for adjusting ACORN-SAT data. The quantity of missing/suspect data in a reference station needs to be substantial to have a material impact on the ACORN-SAT analysis.

The methods used for ACORN-SAT are fully documented and described in the technical report by Trewin B (2012)[17], which is the key document for informing scientists working on ACORN-SAT in the Bureau.

The methods have also been published in the peer reviewed literature.

5.4 Additional Quality Control Applied Downstream of the Observing and Data Management Systems

The daily temperature observations are subject to numerous QC processes. QC is applied through the observing system, which assesses values in the data stream from the instrument.

Quality control is also applied through the data management system when data is archived in the national database. The data management QC processes that would have identified the extreme low temperature reading issue at Goulburn are described in this report.

Separately, and somewhat independently, the ACORN-SAT analysis provides a retrospective quality control process.

In this context, a minimum temperature close to –10°C is currently a very rare event in the ACORN-SAT network. This type of extreme temperature, and any missing data associated with the event in key locations, is typically independently scrutinised by Bureau staff.

17 Trewin B (2012). Techniques involved in developing the Australian Climate Observations Reference Network – Surface Air Temperature (ACORN-SAT) dataset, CAWCR Technical Report No.49

5.5 Comparison of ACORN-SAT data with unadjusted data

The Bureau regularly compares temperature trends derived from ACORN-SAT with international analyses of Australian data, and with unadjusted temperature data.

The key companion dataset to ACORN-SAT is the whole-of-network, unadjusted, and gridded *daily* and *monthly* temperature that is derived from the Australian Water Availability Project, which draws on the full Australian network without accounting for temporal inhomogeneities. The Australian Water Availability Project data is spatially analysed onto a high-resolution national grid dataset[18].

This comparison forms one of several measures taken to ensure that ACORN-SAT is not affected by biases due to such things as network selection. It also provides insight into how sensitive derived climate statistics are to homogenisation adjustments, with the robust conclusion that the magnitude of the warming trend observed over Australia is relatively insensitive to inhomogeneities in the temperature record.

The derived trends and climate statistics are very similar to those analysed by international agencies, who take a raw data feed from the Bureau and apply their own quality control (in some instances) and homogenisation of the data independently of the Bureau.

Material on the comparison of ACORN-SAT to other datasets is in the technical report by Fawcett R.J.B et al (2012)[19] .

5.6 Previous international and independent reviews of ACORN-SAT data and methods

The Bureau ensures that all its datasets, and the methods used to develop them, are rigorously reviewed. The ACORN-SAT methods are subject to the expert peer review process required for publication in scientific journals.

Recognising the importance of the integrity of long-term homogenised datasets as the basis for climate change analysis, the Bureau initiated an additional international peer review of the ACORN-SAT processes and methods.

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18 Jones DA, Wang W & Fawcett RJB (2009). High-quality spatial climate data-sets for Australia. *Aust. Met. Oceanography. J.* 58:233–48

19 Fawcett RJB, Trewin BC, Braganza K., Smalley RJ, Jovanovic B., Jones DA (2012).On the sensitivity of Australian temperature trends and variability to analysis methods and observation networks, CAWCR Technical Report No.050.

In August 2011, a panel of world-leading experts convened in Melbourne to look at the methods used to analyse the Bureau's temperature data. This included taking in submissions and presentations from the scientists developing ACORN-SAT, as well as examining the Bureau's observations practices, station selection methodology, data homogenisation, data analysis methods, and communication.

After reviewing all of the processes the Bureau uses to maintain a homogenised temperature record the panel was satisfied with the methods used by the Bureau to develop ACORN-SAT. It ranked the Bureau's procedures and data analysis as among the best in the world.

In January 2015, the Parliamentary Secretary to the Minister for the Environment, the Hon Bob Baldwin MP, announced the establishment of a Technical Advisory Forum, in response to one of the recommendations of a 2011 independent peer review of the ACORN-SAT dataset. The forum members were appointed for a three-year period to meet annually and advise the Bureau on the development and operation of the ACORN-SAT dataset. This advisory panel process ran from 2015 to 2017.

The forum's third and final communiqué from May 2017 concluded that:

"As outlined in our two previous annual reports which are available on the Bureau's website, we have found the dataset is well maintained, and is an important part of Australia's climate record. We have no reason to question the accuracy of the dataset".

5.7 Findings and Recommendations

The Review Panel found that:

- the issues relating to the inability of some Bureau AWS to read temperatures below -10°C have only affected sites at Goulburn and Thredbo;
- the ACORN-SAT dataset has not been compromised by the inability of some Bureau AWS to read temperatures below -10°C;
- there has been no impact of these failures on the ACORN-SAT data set;
- no ACORN-SAT station has been affected directly by the inability of some Bureau AWS to read temperatures below -10°C; and
- the homogenisation of ACORN-SAT time series has not been affected by the inability of some Bureau AWS to read temperatures below -10°C.

5.8 ACORN-SAT website and FAQs

In response to public interest, the Bureau developed a website for ACORN-SAT, including documentation of the methods used, network descriptions, and an extensive FAQ section, at http://www.bom.gov.au/climate/change/acorn-sat.

Appendix A: Case Studies

Case study 1: Goulburn Airport Automatic Weather Station

Background

The Goulburn Airport (Goulburn) AWS is not part of the ACORN-SAT network. The specific circumstances examined in this case study have only occurred once in the history of this AWS site, and have not affected ACORN-SAT (see Section 5.0).

In September 2002, an Almos AWS was installed at Goulburn, with an MSI2 sensor interface card, which was appropriate for capturing the range of temperatures likely to be experienced at this site. The card is a critical piece of equipment, which converts the resistance of the platinum resistance probe to a temperature.

A few weeks later, a fault in the AWS led to the replacement of several components. At this point the MSI2 card was replaced with an MSI1 card. This replacement was made by Bureau field officers who were unaware of the difference in temperature range capabilities of the two cards. The MSI2 can record temperatures over a broader range (nominally –25°C to +55°C) than the MSI1 (nominally –10°C to +55°C). The MSI1 card stops recording when the temperature drops below –10.4°C.

Key events as they unfolded in July 2017

In July 2017, several independent factors came together in unique circumstances, leading to a number of different minimum temperature values for Goulburn being published on the Bureau's website.

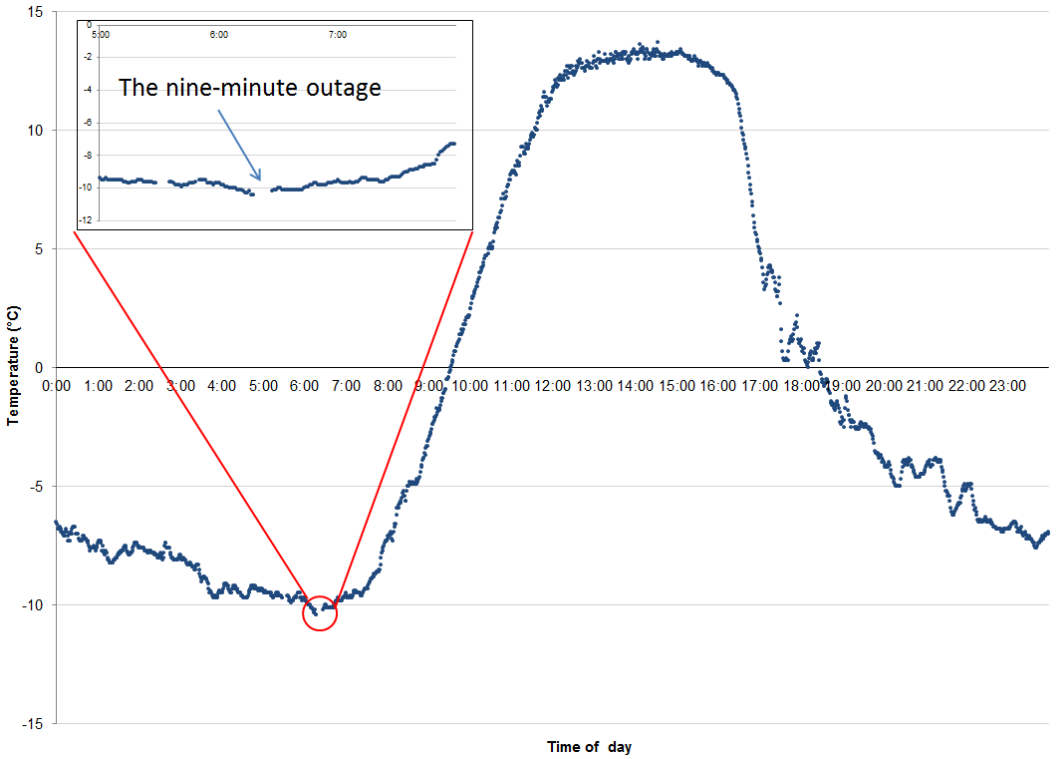
These factors were a combination of hardware limitations (the MSI1 card) and quality control processes. The following describes the key events over the three-day period from Sunday 2 July 2017.

At 6.17am on Sunday 2 July 2017, the temperature at Goulburn reached –10.4°C. Due to the temperature range capability of the MSI1 card, the Goulburn AWS stopped recording temperature observations for nine minutes (Figure 2). As a result, the last reading at 6.17am was –10.4°C. Observations restarted at 06.27am, with a reading of –10.2°C, and were displayed on the Goulburn latest weather observations[20] web page. The Bureau drew public attention to the exceptionally cold temperature by issuing a tweet at 9.21am. It was the coldest July temperature since records began at

[20] http://www.bom.gov.au/products/IDN60801/IDN60801.95716.shtml

Goulburn Airport in 1988 and the third coldest minimum temperature overall. As a result of this nine-minute data gap, automatic quality control processes (which are used to identify potential quality issues) flagged that the data needed a manual check. The flagging meant that, from 9am on 2 July, the Climate Data Online web page presented no value for Goulburn's daily minimum temperature. This is because any time six or more consecutive one-minute results are invalid or missing, statistics are not displayed until the data has been manually inspected for accuracy (see Section 4.2).

Figure 2: Temperature measured over 24 hours at Goulburn Airport AWS on 2 July 2017



Mid-morning on 2 July, Bureau staff in the Bureau's New South Wales office identified the missing daily minimum temperature, and tried to manually reinstate the –10.4°C value. This manual entry followed normal procedures, through a visual inspection of the one-minute data from Goulburn AWS, and accompanied by a notification, which was sent to the quality management system as part of normal quality control procedures. The reinstatement of the minimum temperature value satisfied local news bulletin requirements for New South Wales.

However, for sites below 1000 metres elevation such as Goulburn, the database that supplies the Climate Data Online web page (the Australian Data Archive for Meteorology or ADAM) places temperatures outside of the range of –10°C to +50°C into a holding table for subsequent manual quality control. ADAM also requires lower precision weather data to be entered first, and higher precision data to be entered second. This is so that the more exact data (for example, –5.5°C) can overwrite the less exact data (for example, –5°C).

For Goulburn AWS, on 2 July, the higher precision value of –10.4°C did not overwrite the lower precision value of –10 °C, because it was outside of range of –10°C to +50°C. Instead, the higher precision value of -10.4°C was placed in ADAM's holding table for quality checking and the lower precision value of –10 °C was displayed on the Climate Data Online web page.

Storing the –10.4°C value in the holding table meant that this value could be reviewed and finalised, according to the Bureau's standard quality control processes.

On the afternoon of 4 July, Bureau management requested quality control procedures[21] to be initiated for the outage event in Goulburn on 2 July. This was one day ahead of the normal onset of standard climate data quality procedures, which normally take three days, but was prompted by heightened media interest in the record low July temperature.

Had this management request not been made, normal quality control procedures would have been triggered a day later (5 July) by the fact that the –10 °C temperature was lower than the expected July minimum temperature threshold for Goulburn AWS of –9.3 °C.

Even if the observation had not been the lowest recorded at that site for July, and even if the manual reinstatement by Bureau staff on 2 July had not occurred, normal quality control procedures would have started on 5 July via another trigger, the period gap test. This test checks whether there is a daily minimum (or maximum) temperature value for two consecutive days. If a daily minimum temperature is missing when comparing the two consecutive days, a manual quality control

[21] When an observation fails an automated validation test, it is listed in a suspect queue for a manual check. This typically involves inspecting the one-minute data stream, and comparing the temperature trends (minute-by-minute) with surrounding stations. Various additional tools are also available to help the manual operator, including the action history and station metadata (describing, for example, maintenance that might have been carried out at the site) that is stored in a separate database. All corrections or modifications done on the data are logged in the respective audit table, to ensure probity and traceability of the data chain. Once the analysis is completed, the observation is given a quality flag based on the confidence level in the validity of that data (see Appendix B, Table 8).

assessment is triggered. For Goulburn, the period gap test would have identified a missing daily minimum temperature value on the 2 July, which would have triggered normal quality control procedures.

On 4 July, the quality control inspection of the one-minute data stream determined that the likely daily minimum for Goulburn on 2 July was –10.4°C, so this value was moved from the holding table to the main table in the database.

At that point, the data was given a quality flag that prevented it being published on parts of the public Climate Data Online web page. However, this did not prevent it being shown on the Goulburn daily weather observation page[22], which is subject to less strict data quality controls, as its primary purpose is for visualising temperatures in real time, whereas Climate Data Online is a portal for downloading data that has been quality controlled. As a result, on 4 July, –10.4°C appeared on the Goulburn daily weather observations web page, but not on the Climate Data Online web page.

The quality flags were again reviewed on 5 July, and, based on further assessment of the unique circumstances surrounding the measurement at Goulburn during this period, the quality flag was changed, allowing the minimum temperature (–10.4 °C) to be displayed on the Climate Data Online web page.

A timeline of events is provided at Figure 4, following Case Study 2.

[22] http://www.bom.gov.au/climate/dwo/201707/html/IDCJDW2049.201707.shtml

Case study 2: Thredbo Top Station Automatic Weather Station

Background

The primary purpose of the Thredbo Top Station (Thredbo) AWS is to provide real-time weather information to support recreational activities in the local Alpine area. The station is not part of the ACORN-SAT network.

The Bureau installed the first AWS at Thredbo in April 1997. In 2003, an Almos AWS with a MSI2 sensor interface card was installed. A large storm in 2007 caused such damage that the AWS became unserviceable, and in May 2007, the AWS was replaced with an Almos unit incorporating an MSI1 card. As with the previous Case Study, this replacement was made by Bureau field officers who were unaware of the difference in temperature range capabilities of the two cards.

The Thredbo AWS is located in a very exposed and harsh environment. As a result, it is subject to data outages from numerous causes, including high winds, lightning strikes, power outages and data communications outages. Accessing the site for maintenance or return-to-service visits can also be challenging due to local weather conditions, such as strong winds and/or snow. These factors make the site unsuitable for climate monitoring.

Due to the significant variation in local topography at Thredbo, the Bureau also employs a local resident to take manual meteorological observations at Thredbo village. These observations include 9am and 3pm temperatures, and 24-hour maximum and minimum temperatures.

Key events in July 2017

On 13 July 2017, Bureau staff identified that outages of temperature data at the Thredbo AWS had occurred on 12 July 2017. An instruction was placed into the Bureau's station database for this to be fully investigated by technical officers.

On 16 July, as a result of multiple outages on the Thredbo AWS, the daily minimum temperature for that day was not displayed on the Bureau's webpages.

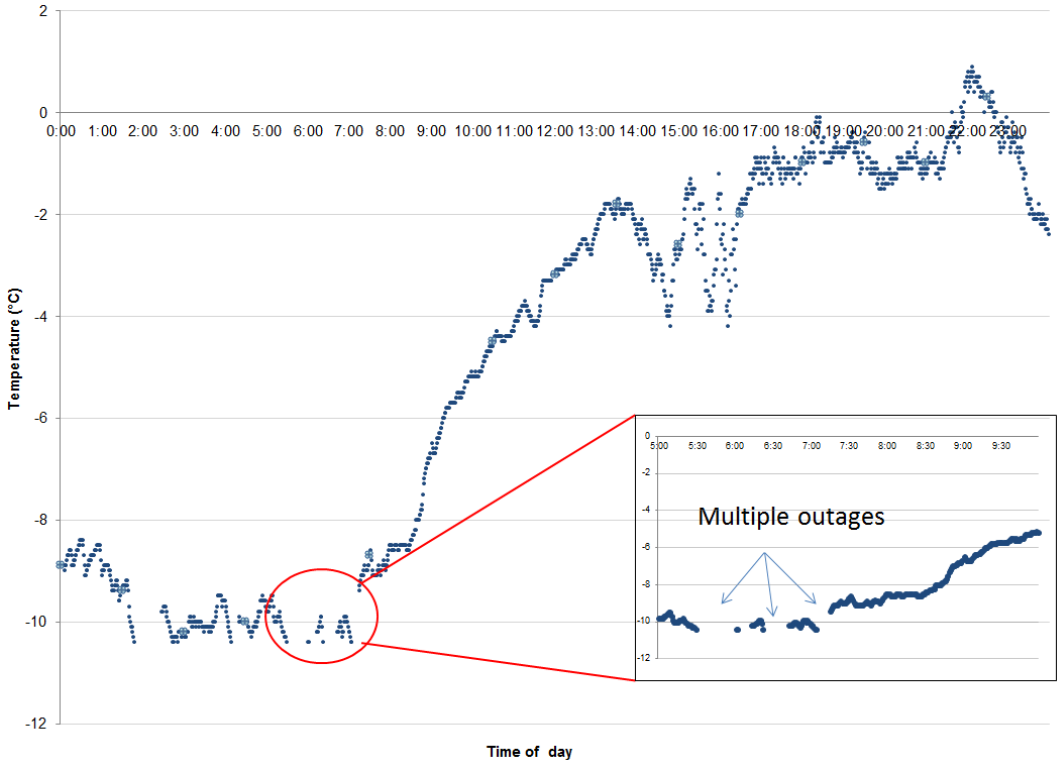
During the investigation into the recent low temperature outages at Goulburn, it was identified that the likely cause at Thredbo was also the MSI1 card. Bureau field officers were instructed to investigate and replace the card at the Thredbo AWS with an MSI2 card.

Further investigation identified that, since 2007, there have been six separate days (including 12 July 2017) when the AWS stopped operating at temperatures below -10.4°C. The MSI1 card was the cause on all of these occasions.

On 20 July, the Bureau's automatic quality control process found that a daily minimum temperature had not been generated for 16 July, and manual quality control procedures were initiated. These determined that the daily minimum temperature could not be recovered, due to the amount of missing data.

Overall, there were seven individual outages in the one-minute data from the Thredbo AWS (Figure 3), some of which lasted for considerable periods, and these outages were close to when the lowest recorded temperature for the day can be expected to occur.

Figure 3: Temperature measured over 24 hours at Thredbo AWS on 16 July 2017



The majority of the outages on 16 July occurred precisely when the temperature dropped to –10.4°C. Between 1.47am and 7.26am, there were seven outages in the one-minute data. The length of each outage was as follows:

- 1.47am—40 minutes
- 4.09am—11 minutes
- 5.29am—31 minutes (data returned for 2 minutes before dropping out again)
- 6.02am—10 minutes
- 6.22am—20 minutes
- 7.04am—10 minutes
- 7.23am—1 minute

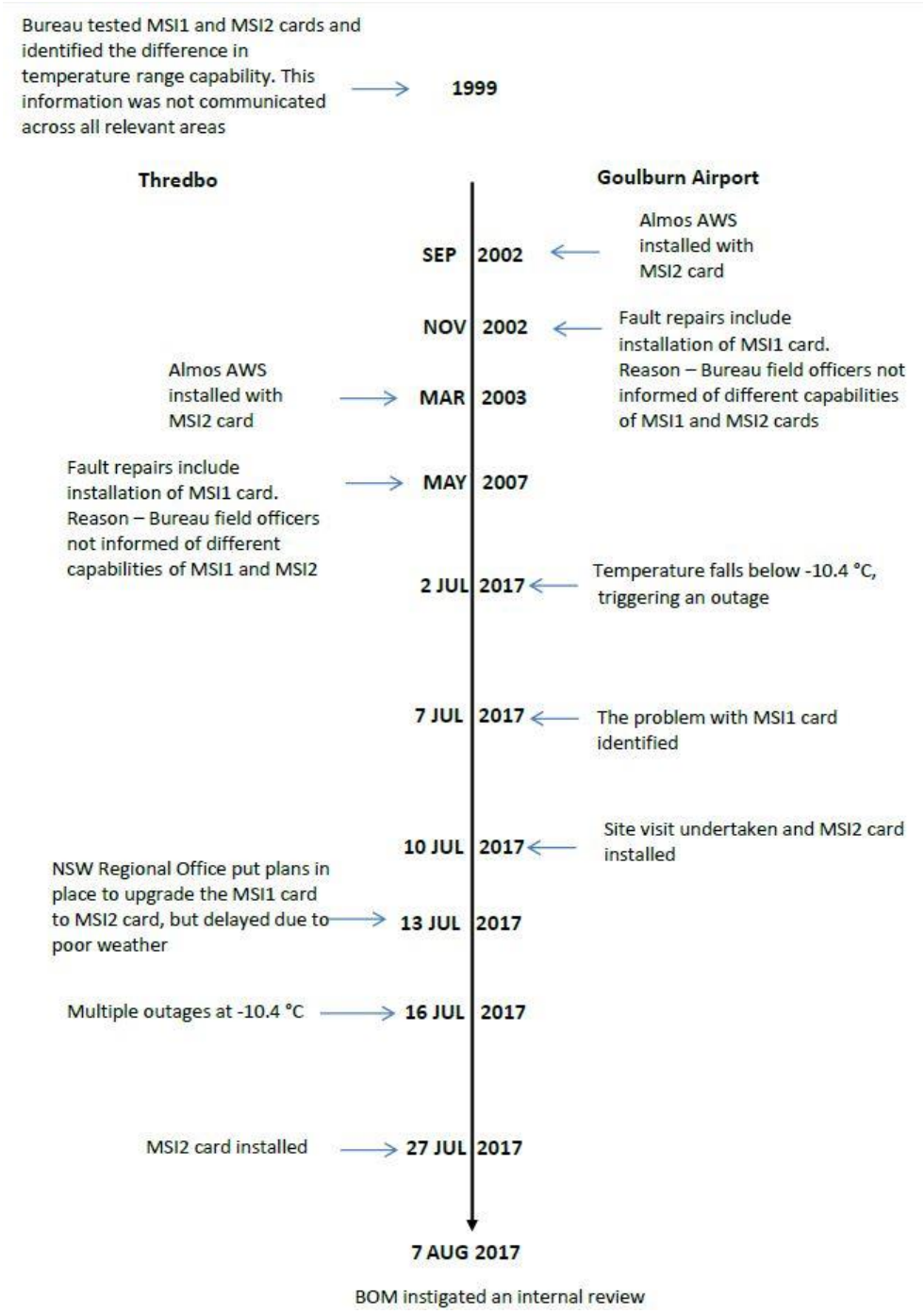
Given the frequency, length, and proximity of the outages, the true minimum temperature for 16 July cannot be conclusively determined. The daily minimum temperature at a neighbouring site with similar climatology (Perisher Valley AWS) recorded a value of –12.1°C on the same day. Consequently, as per standard procedures, the relevant climate web page recorded no value for the daily minimum temperature at Thredbo AWS for 16 July.

Bureau field officers replaced the MSI1 card with the MSI2 at the Thredbo AWS on 27 July, which was the earliest safe opportunity to do so, given the weather conditions at the site.

Since the replacement of the card, temperatures below –10.4°C have been captured and recorded from the Thredbo AWS, which has returned to routine operations.

A timeline of events is provided at Figure 4.

Figure 4: Event timeline for the sensor interface cards (MSI1 and MSI2) at Thredbo and Goulburn Airport AWS



Appendix B: Tables Referred to in the Report

Table 1: Tiers of AWS and their schedule of activities

AWS Tier	Activities schedule (for budgeting and planning)
ACORN-SAT AWS	1 inspection per year, 1 maintenance visit per year, return to service as required
Aviation or defence AWS	1 inspection per year, 1 maintenance visit per year, 1 return to service visit per year
Non-aviation/defence AWS, non-ACORN-SAT AWS	1 inspection/maintenance visit (scheduled or return to service) per year
Offshore AWS	1 combined inspection and maintenance per year, pre-cyclone season where relevant
Externally funded AWS	Visits as documented in relevant contract with client

Table 2: ADAM AWS temperature data ingestion rules

AWS Location	Range type	AWS data ingestion threshold before 12 July 2017	Temporary ingest threshold (during review)
Standard	Minimum temperature	–10°C	–30°C
Standard	Maximum temperature	+50° C	+70 °C
Alpine	Minimum temperature	–18°C	–40°C
Alpine	Maximum temperature	+38° C	+60 °C

Table 3: Key components of data flow

Component of Data Flow	Description
AWS	The Bureau's extensive AWS network covers mainland Australia, key islands, and Antarctic sites. Currently, 563 AWS stations record surface temperature across Australia.
AWS Telmet	The Telmet AWS is one of the two main types of AWS used to measure surface temperature. The Telmet stations provide one-minute data in named value pair format. The Telmet AWS have rules for the valid temperature range, and valid sample for one-minute observations.
AWS Almos	The Almos AWS is one of the two main types of AWS used to measure surface temperature. The Almos stations typically provide data in one-minute data format. At remote locations, an Almos AWS can also provide 30 minute data in METARAWS format, and three-hourly data in met data format. The Almos AWS have rules for the valid temperature range, valid sample for one-minute observations, and missing data rules. There are two types of Almos AWS, the MSI1 model has a valid temperature range of –10°C to +55^{0}C; the MSI2 model has a valid temperature range of –25°C to +55°C.
CMSS	Central Messaging Switching System
Real-time database	The Bureau's real-time database retains AWS data for 10 days. Before moving to the new Oracle Exadata environment in June 2017, the database had a full table backup each night. This data was stored on the Bureau's centralised deep storage system, Storage and Archive Manager. With the migration to the Oracle Exadata Environment, data backups use a vendor solution, a zero data loss recovery appliance. This system keeps track of changes in the database daily. The real-time database accepts data as is, and does not apply any boundary checks or other data rules.
ASOS	ASOS receives one-minute data from AWS via the Central

	Meteorological Messaging System, and generates daily statistic and message formats, such meteorological data format messages, Surface Synoptic Observation, and aviation messages. The system has two types of user interface for monitoring, and manual corrections or commentary (WebEFB and WebConsole). The ASOS system shares the same outage rule as the Almos AWS, and has several data rules to build, schedule, and trigger messages. ASOS also include network monitoring, system performance, and alerting tools.
AIFS	AIFS is a complete interactive weather forecasting system, comprising data collection, message switching, forecast preparation, and product delivery. AIFS is a regional system, and runs on local infrastructure. The AIFS decoder does several syntax checks to ensure that the incoming data has the correct format. AIFS validation does several data checks, such as dry bulb temperature being greater or equal to dew point temperature, and maximum temperature being greater or equal to the daily minimum temperature. The AIF system has a regional product archive.
AIFS Automatic Product Generation	The Automatic Product Generation runs on the AIFS servers in each Australian state and territory. It provides the latest coastal, state, and capital city weather observations to the Bureau's external website. It is made up of a complicated series of configuration files, processing scripts, intermediate files, database access routines, dynamic calculations, and formatting procedures. It produces about 1,200 products, including the latest weather observations for areas and sites, and the observations shown on the Bureau's homepage.
AIFS database	The AIFS database holds data on guidance and observations, forecasts, products, client despatch rules, data backups, and archiving information.
ADAM database	ADAM is the Bureau's master data repository for climate and related data. The database uses the latest manufactured system to ensure performance, reliability, and robustness.

ADAM applications	For the purposes of the data flow, the main ADAM applications are ADAM Ingest and ADAM AWS Archive. ADAM Ingest moves data from the Bureau's real-time database into the ADAM database. This system uses temperature thresholds based on location type, and has data ingestion order rules. The ADAM archive service take data from the Central Meteorological Messaging System stores it in the Bureau's centralised deep storage system, Storage and Archive Manager.
ADAM quality management system	The ADAM quality management system is a quality control system designed to flag potential errors in observational data before it is archived, as part of the official climate record. This system complies with WMO standards. Several quality control tests are applied to the database. The system has a graphical user interface to allow data recovery, quality flagging, and quality investigation.
Climate Data Online	Climate Data Online provides statistics, recent weather observations, and climate data from the Australian Data Archive for Meteorology. It provides the replication rules for the website climate database (eADAM), and for data on various websites, including daily weather observations, and daily minimum temperatures. It uses a rule-based approach to populate webpages based on quality flags.
Services and Information Management System	The Services and Information Management System is the master data management tool for subscription and product management. It contains product and distribution rules and information.
Storage and Archive Manager	The Storage and Archive Manager is the main deep storage archive system for the Bureau.

Table 4: Graphical user interface tools for the AWS review data flow

GUI Tool	Description
Comms GUI	COMMS GUI is part of the AIFS application. It alerts staff to 'message syntax' and 'parameter out of range errors', and can be used to edit data messages for distribution to downstream systems in near real time.
Met Console	The Met Console is a monitoring interface collocated at limited sites with an Almos AWS.
Quality management system GUI	The quality management system GUI is the standard interface for QC operators to quality control daily and hourly surface data (including data recovery) for climate data in ADAM.
Web Console	The Web Console enables manual monitoring and modification. It is used to send messages at Bureau observer locations. It is the updated version of Met Console.
WebEFB	Web Electronic Field Book (WebEFB) allows for manual data modification. It is used regenerate AWS messages in near real time.

Table 5: Main data formats for the data flow

Data Format Name	Description
Meteorological Data Format	The Meteorological Data Format data is used for high-precision observation sent every three hours, and in the 9am daily message, which also includes daily summary information. This format is also referred to as DFXX.
Meteorological Aerodrome Report	Meteorological Terminal Aviation Routine Weather Reports or Meteorological Aerodrome Report are generally produced every 30 minutes for each site. Related data formats include aviation special weather report, and internal formats such as METARAWS and SPECIAWS.
Named Value Pair	The named value pair is a Bureau data format used by the Telmet AWS for one-minute data. It is the basis for other message formats in ASOS, including Meteorological Data Format, Meteorological Aerodrome Reports, and Surface Synoptic Observation.
One-Minute Data	The one-minute data format is an older Bureau format used by the Almos AWS. It is the basis other message formats in ASOS, including Meteorological Data Format, Meteorological Aerodrome Reports, and Surface Synoptic Observation.
Surface Synoptic Observation	The Surface Synoptic Observation is a WMO format for the transmission of surface observation data. Generally, these are produced every hour or three hours. This includes international distribution via the Global Telecommunication System. This format is also referred to as AAXX.

Table 6: Quality management system automated tests for maximum temperatures[23]

QMS test name	What test does	How suspects are triggered
Climate test	Checks whether consistent with upper or lower climate range.	Generic test reports suspects if the following condition is met: (a) The element is outside of the upper or lower climate range.
Three-hourly test	Checks whether daily observation is consistent with three-hourly observation.	Generic test reports suspects by comparing daily data to three-hourly observation if the following conditions are met: (a) The difference between the reported maximum (or minimum) air temperature and the highest (or lowest) three-hourly air temperature is outside of lower and upper thresholds. (b) For maximum air temperature, a three-hourly observation was received between 13:55 and 15:05 local time. (c) For minimum air temperature, a three-hourly observation was received between 04:55 and 06:05 local time. (d) For maximum wind gust, the comparison is to three-hourly wind speeds for the previous 24 hours (00:00:00 to 23:59:59).
Maximum and minimum test	Checks the difference between the daily minimum and daily maximum.	Test reports suspects if the following condition is met: (a) The maximum air temperature minus the minimum air temperature is less than 0 or greater than a climate threshold.

[23] See QMS test specification, version 3.3.0.

Spatial test	Checks whether consistent when compared with neighbouring sites, using Barnes spatial analysis.	Generic test reports suspects when comparing observations to neighbouring sites if the following conditions are met: (a) The target value is outside the lower or upper Barnes spatial analysis thresholds. (b) The target observed period is one day. (c) There is a low number of neighbouring sites within a defined radius.
Flatline test	Checks whether consecutive observations are the same.	Generic test reports suspects over a defined number of consecutive observations if the following condition is met: (a) An element value is the same.
Period gap test	Checks whether period is consistent with the previous observation.	Generic test reports suspects if the following condition is met: (a) The element period value does not match the expected gap to the previous record.
Large period test	Checks whether period is beyond an upper threshold.	Generic test reports suspects if the following condition is met: (a) The element has a period of less than one day, or greater than an upper threshold.
diff.MaxAirTempDiffTest	Checks whether consistent with METAR_SPECI air temperatures.	Test reports suspects when the following conditions are met: (a) Any METAR_SPECI observed air temperature minus the reported maximum air temperature is greater than 1^0C. (b) Neither have quality flags set between 6 and 9.

Table 7: Quality management system automated tests for minimum temperatures

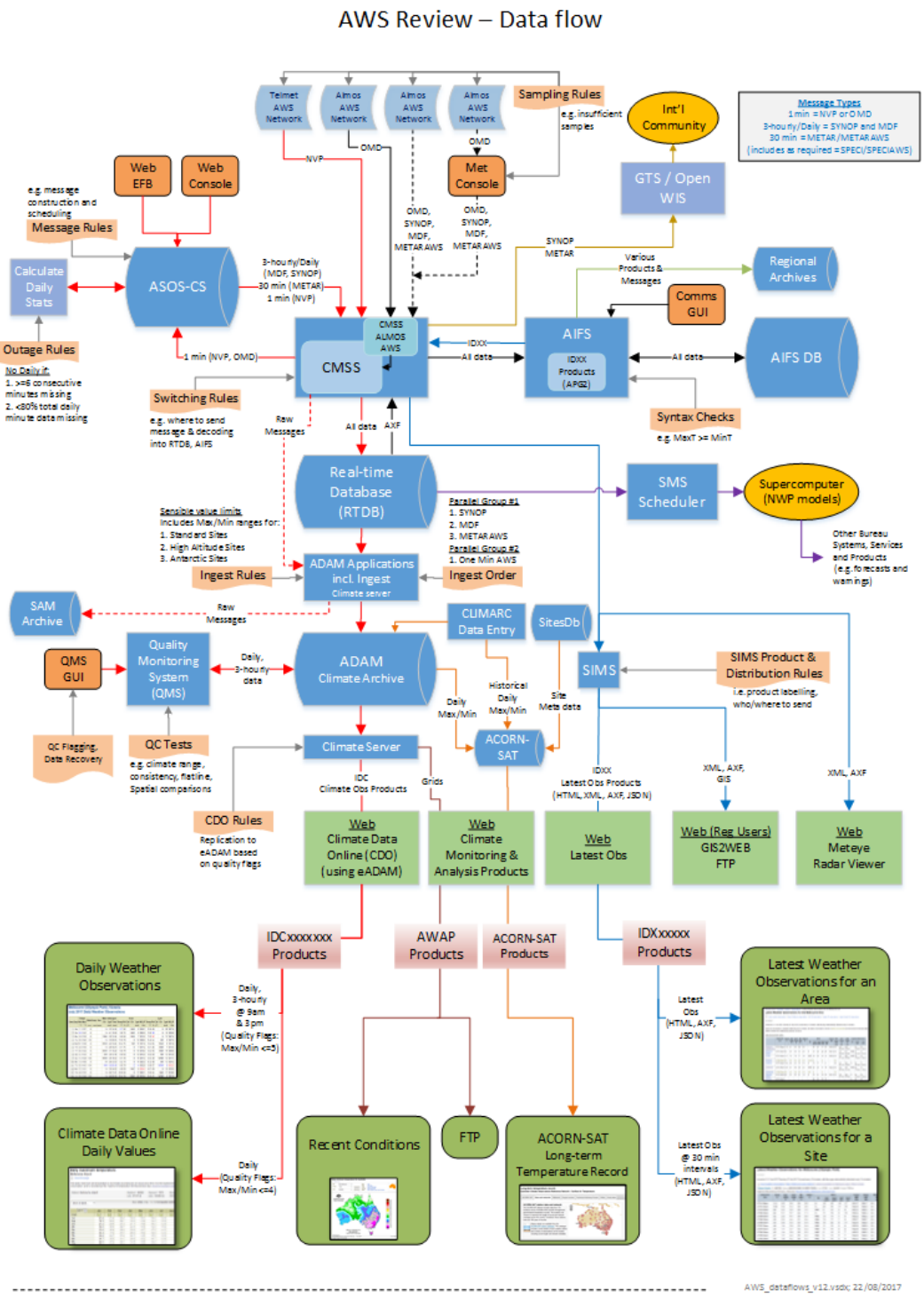
QMS test name	What test does	How suspects are triggered
Climate test	Checks whether consistent with upper or lower climate range.	Generic test reports suspects if the following condition is met: (a) The element is outside of the upper or lower climate range.
Three-hourly test	Checks whether daily observation is consistent with three-hourly observation.	Generic test reports suspects by comparing daily data to three-hourly observation if the following conditions are met: (a) The difference between the reported maximum (or minimum) air temperature and the highest (or lowest) three-hourly air temperature is outside of lower and upper thresholds. (b) for maximum air temperature, a three-hourly observation was received between 13:55 and 15:05 local time. (c) For minimum air temperature, a three-hourly observation was received between 04:55 and 06:05 local time. (d) For maximum wind gust, the comparison is to three-hourly wind speeds for the previous 24 hours (00:00:00 to 23:59:59).
Maximum and minimum test	Checks the difference between the daily minimum and daily maximum.	Test reports suspects if the following condition is met: (a) The maximum air temperature minus the minimum air temperature is less than 0 or greater than a climate threshold.
Spatial test	Checks whether consistent when compared with neighbouring sites, using Barnes spatial	Generic test reports suspects when comparing observations to neighbouring sites if the following conditions are met: (a) The target value is outside the lower or upper Barnes spatial analysis

	analysis.	thresholds. (b) The target observed period is one day. (c) There is a low number of neighbouring sites within a defined radius.
Flat line test	Checks whether consecutive observations are the same.	Generic test reports suspects over a defined number of consecutive observations if the following condition is met: (a) An element value is the same.
Period gap test	Checks whether period is consistent with the previous observation.	Generic test reports suspects if the following condition is met: (a) The element period value does not match the expected gap to the previous record.
Large period test	Checks whether period is beyond an upper threshold.	Generic test reports suspects if the following condition is met: (a) The element has a period of less than one day, or greater than an upper threshold.
diff.MinAirTempDiffTest	Checks whether consistent with METAR_SPECI air temperatures	Test reports suspects when the following conditions are met: (a) Any METAR_SPECI observed air temperature minus the reported minimum air temperature is greater than 1^0C (b) Neither have quality flags set between 6 and 9.

Table 8: List of quality flags used in the quality control process

Descriptor	Code
As read	00
Derived	01
Corrected	02
Estimated, high certainty	03
Estimated, medium certainty	04
Estimated, gross	05
Suspect, read	06
Suspect, derived	07
Suspect, estimate	08
Wrong	09
Inconsistent	20

Appendix C: Data Flows



Appendix D -The Review Panel

Dr Mark Ballico (National Measurement Institute)

Mark led the National Measurement Institute (NMI) Temperature Standards Group for nearly 20 years, establishing and maintaining Australia's primary standards for temperature and developing numerous automated calibration facilities and data-analysis systems and established the National Association of Testing Authorities (NATA) accreditation for these laboratories. Mark led the development of NMI's yearly Temperature Measurement course, which supports the calibration labs and key precision users in the thermometry community. Mark was chair of NATA's technical advisory committee for heat and temperature for several terms, representing Australia at the Bureau International de Poids et Mesures (BIPM) over that period. Mark also chaired the Asia Pacific Metrology Forum's Technical Committee for Temperature, the premier region body for Temperature Standards for several terms. Mark chaired the BIPM's consultative committee for temperatures working group on key comparisons, establishing and overseeing a framework for the review of key comparisons in that field. Mark has an extensive publication record covering the development of primary standards and calibration systems for temperature, and the statistical analysis of calibration data.

Mr Bruce Hartley (New Zealand MetService)

Bruce Hartley is a versatile, experienced and accomplished Lead Systems Engineer. His work experience spans 23 years with three years' experience as a Lead Engineer. He has an outstanding record of achievement in areas as diverse as concept, design, implementation and operation (for internal and Client projects), Consultancy, and Local Government planning.

Bruce is a senior engineer with wide ranging experience in the design, implementation, maintenance and management of data acquisition systems in New Zealand, Australia, the Pacific and England. He has extensive experience covering most aspects of data acquisition and telecommunications. His expertise covers: Meteorological systems for the NZ mainland and islands, the Pacific Islands, and England; Aviation systems for NZ and Australia; Road systems for NZ. Bruce has been managing projects for most of his career and his managerial experience allied to his wide ranging technical skills and experience give him the versatility to handle any challenge effectively.

Dr Rod White (Measurement Standards Laboratory of New Zealand)

Dr Rod White is one of the world's most highly regarded temperature measurement experts whose research has led breakthroughs in several areas of thermometry. He is best known for *Traceable Temperatures*, a widely used text on practical temperature measurement and calibration. He is also the author of more than 100 peer-reviewed papers, has contributed several chapters to texts, and contributed

several sections on temperature measurement for encyclopaedia. Dr White represents New Zealand on the Bureau International de Poids et Mesures (BIPM) Consultative Committee on Thermometry (CCT), and is an active member of seven of its tasks groups. He is currently the chairman of the task group on Guides in Thermometry, and for 12 years was the chair of the working group on Uncertainty in Temperature Measurement. He is also on the editorial boards for the two most influential journals in the field, and has edited a major conference proceedings and a recent collection of papers on measurements of Boltzmann's constant. He has won two NZ Royal Society medals for his work, and in 2010 was awarded a Doctorate of Science from the University of Waikato for his contributions to Temperature Metrology.

Mr Neil Plummer (Bureau of Meteorology)

Neil Plummer has been General Manager of Community Forecasts with the Bureau of Meteorology since July 2017 after being the Bureau's head of Climate Information Services for more than six years. He started his career in weather forecasting in 1986 before shifting into climate monitoring and prediction, climate change and data management. He then led the Bureau's National Climate Centre in 2002. In 2008 he shifted into the world of hydrology as Manager Extended Hydrological Prediction. Neil has held positions on various World Meteorological Organization (WMO) expert teams and management committees and has been a collaborating author with the Intergovernmental Panel on Climate Change (IPCC). He currently chairs the Bureau's board for the 'Climate and Ocean Support Program in the Pacific'. Neil has Masters degrees in both Business Administration and Science, a Bachelor of Science, a Graduate Diploma in Computing and a Diploma in Meteorology.

Dr Anthony Rea (Bureau of Meteorology)

Dr Anthony Rea is the General Manager of the Bureau's Data Program and Chief Data Officer. Previously, he was Head of the Bureau of Meteorology's Observing Strategy and Operations Branch for four years. He joined the Bureau in 2000 after starting his career as a land surveyor and working in offshore exploration, construction and hydrography. He has a PhD in meteorological remote sensing and a Masters in Public Administration. In the Bureau, Dr Rea has responsibility for policy and governance in relation to data, end-to-end quality for all data and planning of the Bureau's data gathering capabilities. He also takes a leading role in observations within the World Meteorological Organisation and chairs its Open Program Area Group on Integrated Observing Systems.

Appendix E: Abbreviations

AAD	Australian Antarctic Division
ACORN-SAT	Australian Climate Observations Reference Network – Surface Air Temperature
ADAM	Australian Data Archive for Meteorology
AIFS	Australian Integrated Forecasting System
ASOS-CS	Automated Surface Observation System-Central System
AWS	Automatic Weather Station
CMMS	Central Meteorological Messaging System
CMSS	Central Message Switching System
DAS	Data Acquisition System
ISO	International Organization for Standardization
QA	Quality Assurance
QC	Quality Control
WMO	World Meteorological Organization
RIC	Regional Instrument Centre
WebEFB	Web Electronic Field Book

Appendix F: Glossary of Terms

ADAM	The archive where Australia's long term climate data is stored
Almos	An Automatic Weather Station model introduced to Australia in 1993
Ambient temperature	The temperature of the surrounding environment
Australian Integrated Forecasting System	The system which generates the latest weather products
AIFS consistency checker	The system which alerts staff in capital city airports of inconsistencies between stations' observations that need investigating
Calibration laboratories	Bureau's laboratories which verify and calibrate the AWS systems and sensors
Central Messaging Switching System (CMSS)	The system which handles and relays messages and data from observing systems and other Bureau systems.
Climate Data Online	The online platform which provides public access to various statistics, recent weather observations, and climate data from ADAM
Climate products	Bureau products relating to longer term weather observations over years or decades.
Daily statistics	Summaries of daily weather values at a location such as maximum and minimum temperature, rainfall, humidity and wind. The meteorological day is from 9am to 9am.
Daily temperature extremes	Maximum and minimum temperature values at a location measured from 9am to 9am.
Data Acquisition System	The system that interprets the sensor signals, and converts them to quantities with appropriate units within the AWS
Data Governance	Overall management of the availability, usability, integrity, and security of the data employed
External bulletins	Messages transmitted to users, such as aviation, defence, and other meteorological centres
Homogenisation	Removal of non-climatic changes such as relocations or changes in instrumentation from the observed climate data
In-situ calibration check	A physical check by a technician where a field system (such as an AWS) is compared to a reference instrument.
Network monitoring tool	The system which provides a web interface and monitoring capability, and alerts staff of possible sensor anomalies, and of data from an AWS that might have been

	processed incorrectly by downstream systems
NextGen AWS	AWS with 3G and satellite communications
Numerical weather prediction	Predicting the weather based on current weather conditions using mathematical models of the atmosphere and oceans.
One-minute data application	The software which monitors real time AWS data. It displays the current minute only, and alerts staff of abnormal system behaviour
One-minute maximum air temperature	The maximum valid one-second temperature value recorded in a minute interval
One-minute minimum air temperature	The minimum valid one-second temperature value recorded in a the minute interval.
Quality Assurance	The process of managing the quality of data
Quality Control	The process used to verify the quality of the data
Quality flags	Measurement of confidence in the accuracy of data
Rain gauge	An instrument used by meteorologists and hydrologists to gather and measure the amount of liquid precipitation over a set period of time.
Real-time database	Bureau's database for storing real-time weather information for use in models and forecasts .
Services and Information Management System	The master data management tool for subscription and product management. It contains product and distribution rules and information.
SitesDB	Bureau's station metadata repository
Stevenson screen	A standard shelter for meteorological instruments, particularly wet and dry bulb thermometers used to record humidity and air temperature
Storage and Archive Manager	The Bureau's tape-based data storage sytem.
Surface Synoptic Observation	A meteorological observation taken at a Bureau station, either manually or automatically, and used in global and regional weather analysis.

Telmet 320	Model of automatic weather station introduced in 2007
Web Console	The system which enables manual monitoring and modification of meteorological messages. It is used to send messages at Bureau observer locations. It is the updated version of Met Console.
Web Electronic Field Book	The system which sends messages on behalf of manual observer locations or is used to generate AWS messages where sufficient data exists (for example, where an outage is unlikely to affect the daily maximum, minimum, or cumulative rainfall)
Wind mast	A 10 metre free-standing tower or a removed mast, which carries measuring instruments for wind (an anemometer).