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A Comment on T_{min} at Goulburn and at Thredbo Top Station

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Problems with measurement of air temperatures below -10.4°C at the Bureau of Meteorology's Goulburn and Thredbo Top Station automatic weather stations have been reviewed to evaluate the effect on the data records from those sites. A nine-minute gap in the T_{min} record at Goulburn on just one day, 2 July 2017, is assessed to have no effect on that data record, as the likely actual minimum temperature was estimated to be essentially unchanged at -10.4°C +0.0/-0.1°C.

To assess the effect on the Thredbo data of six days within the last decade in which T_{min} was inadvertently limited to -10.4°C a hypothetical data record was constructed in which any day after May 2007 (seventeen in total) with T_{min} below -9.9°C had that value replaced by -13°C, heavily overcompensating for the data logger limitation. Three different tests were carried out comparing the original data record with the overcompensated record. All tests pointed to the conclusion that the small number of limitations has had no material impact on the Thredbo record. Another conclusion from the analysis was that the frequency of occurrence of cool days at Thredbo, including days below -10.4°C, has fallen compared with the late 1960s due to the general warming of Australia since then.

1. Introduction

In July 2017 following input from the public and its own internal quality assurance processes the Bureau of Meteorology identified a problem with measurement of very low air temperatures at two stations in its meteorological station network, Goulburn (#070330; 34.81S, 149.73E) and Thredbo Top Station (#071032; 36.49S, 148.29E). A Review Panel of three international experts plus two Bureau officers was formed immediately to review the integrity of the Bureau's automatic weather station (AWS) network. The Review Panel Report was published on 7 September 2017 (BoM, 2017a). The Review Panel concluded that the problem originated in replacement data logger cards installed at Goulburn late in 2002 and Thredbo in May 2007. The replacement cards did not record air temperature below -10.4°C, leading to one day at Goulburn and six days at Thredbo where this limitation on minimum temperature, T_{min}, occurred since 2002 and 2007 respectively. The logger cards at both sites were replaced by the end of July 2017 to reinstate measurements below -10.4°C.

The Review Panel's summary findings included the following statements: "*The panel found that the Bureau's data quality 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.*

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.

Importantly, the Panel was definitive in its view that this very small number of extreme days with -10.4°C limitation to T_{min} at Goulburn and Thredbo have had no effect at all on the national climate record for air temperature, the Australian Climate Observations Record Network - Surface Air Temperature (ACORN-SAT), which does not involve those sites:

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"*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*".

Thus the integrity of the national climate record is unaffected. Quality is high, as has been documented by the Bureau's Technical Advisory Forum set up in January 2015. That Forum's third and final report was also published in September 2017 (BoM, 2017b), providing a separate, detailed, expert confirmation of the quality of the Bureau's approach to curation, quality assurance and maintenance of vast amounts of meteorological data it generates in real-time across the nation. The Goulburn and Thredbo T_{min} issue is separate from the Forum's work, but sits within the context of the Forum's three year assessment that the Bureau's approach to data quality, as encapsulated by ACORN-SAT, is world-standard.

While that context is important, the purpose of this short note does not concern ACORN-SAT. The purpose is not to revisit either of those two recent review reports (BoM 2017a,b), which stand alone and are definitive for their own purposes. The purpose here is far more prosaic given that of the Bureau's 695 AWSs across the nation, only two have exhibited the -10.4°C T_{min} measurement limitation (BoM, 2017a), and even then very rarely - at Goulburn on just one day, for nine minutes, and at Thredbo on just six days spread over more than a decade. The purpose here is simply to provide for the historical record an analysis of those extremely rare events in terms of any effects on those two meteorological station records.

2. Goulburn

The effect of the -10.4°C T_{min} limitation at Goulburn is simple to analyse, since the single occurrence on two July 2017 was so short-lived. The Review Panel report (BoM, 2017a) in its Figure 2, reproduced partially here in Figure 1, displays the one minute data containing the nine minute gap commencing at 06:18 Eastern Standard Time caused by the data logger limitation.

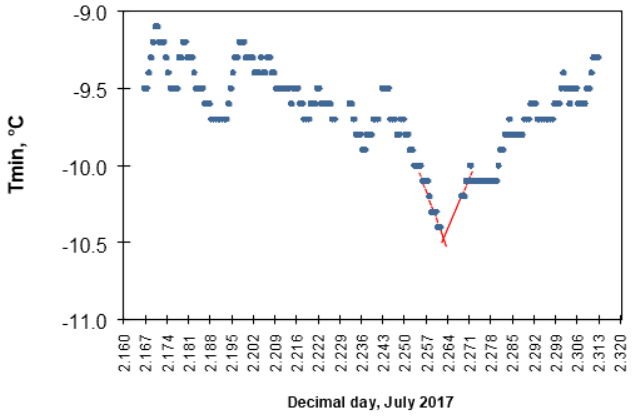

Figure 1. One minute T_{min} values from Goulburn Airport AWS on 2 July 2017 for the period 03:50 to 07:40 Eastern Standard Time. The arrow points to the nine minute gap in the data record commencing at 06:18; the x-axis scale interval is ten minutes.

A qualitative estimate of actual T_{min} is possible by projecting straight lines into the gap from a ten minute period either side of the gap in the record. This suggests that -10.4°C measured at 06:17 is a reasonable estimate for the actual T_{min} reached, although a value 0.1°C lower also may be plausible. The conclusion for Goulburn is that the most likely value of T_{min} on 2 July 2017 is -10.4°C +0.0/-0.1°C. The effect of that nine minute outage is therefore zero, or effectively so at the data resolution of 0.1°C. This qualitative evaluation suggests that the Goulburn record is not compromised by the nine minute outage.

3. Thredbo

The case of Thredbo Top Station is more complicated than the single nine minute outage at Goulburn. Outage at -10.4°C at Thredbo on 16 July 2017 occurred not once but seven times as the temperature oscillated above and below the lower

measurement limit of -10.4°C during the period 01:47 to 07:23 Eastern Standard Time (BoM, 2017a, Appendix A, Case Study 2, Figure 3). Thus a simple estimation of likely actual T_{min} is not possible as for Goulburn.

Moreover, unlike the single 2017 incident at Goulburn the Review Panel found that in the decade from May 2007 up to July 2017 five other incidents of data logger limitation to -10.4°C had occurred (BoM, 2017a). So the analysis of the Thredbo case uses the full data record from November 1966 and approaches the evaluation in three separate ways.

3.1 T_{min} Extreme Replacement Test

First, for the period post-May 2007 when the AWS datalogger with a lower limit of -10.4°C was in place, a new, hypothetical dataset was created in which any T_{min} of less than -9.9°C was replaced by a value of -13°C. That value was chosen as a very extreme minimum value rarely encountered at Thredbo: since 1966 only 94 days have T_{min} of -10°C or less, and of these only six days were cooler than -13°C. Moreover, no day cooler than -13°C has occurred at all in the last 23 years.

Recomputing monthly mean air T and monthly mean T_{min} for the Thredbo station with this value in place heavily overcompensates for the datalogger error, to provide an extreme estimate of its effect on the Thredbo record. Table 1 provides the data for the relevant months since May 2007: only fifteen days in fourteen of 175 months had T_{min} less than -9.9°C. One day in August 2014 and one day in July 2017 also had no value of T_{min} in the Bureau record. It was simply assumed that a limitation to -10.4°C had occurred and these two days were added to the evaluation, which thus was finalised as having the six identified days of data logger limitation overcompensated for by seventeen days having T_{min} arbitrarily lowered to -13°C.

	T_{mean}	$T_{mean-13}$	Δ	number	T_{min}	T_{min-13}	Δ	number
Jun-07	-2.22	-2.28	-0.07	1	-4.74	-4.85	-0.11	1
Jul-07	-3.16	-3.25	-0.09	2	-5.65	-5.82	-0.18	2
Jul-08	-2.93	-2.98	-0.05	1	-5.36	-5.45	-0.09	1
Aug-08	-3.58	-3.63	-0.05	1	-6.09	-6.18	-0.10	1
Jul-09	-3.04	-3.09	-0.05	1	-4.94	-5.03	-0.10	1
Sep-09	0.97	0.92	-0.04	1	-1.92	-2.01	-0.09	1
Aug-10	-3.51	-3.55	-0.04	1	-5.83	-5.91	-0.08	1
Sep-13	2.84	2.80	-0.04	1	-0.19	-0.28	-0.09	1
Aug-14	-1.62	-1.70	-0.08	2	-5.13	-5.29	-0.17	2
Jun-15	0.74	0.69	-0.05	1	-2.93	-3.02	-0.09	1
Jul-15	-2.79	-2.83	-0.04	1	-5.40	-5.48	-0.08	1
Aug-15	-2.26	-2.30	-0.04	1	-4.57	-4.66	-0.08	1
Aug-16	-1.83	-1.87	-0.04	1	-4.37	-4.46	-0.08	1
Jul-17	-2.74	-2.82	-0.08	2	-4.88	-5.05	-0.17	2
-13.0°C		**Mean**	**-0.055**	**17**		**Mean**	**-0.108**	**17**
-12.1°C		Mean	-0.037			Mean	-0.072	
-11.0°C		Mean	-0.015			Mean	-0.029	

Table 1 Mean and minimum monthly air temperatures, T_{mean} and T_{min} (°C), for any month since May 2007 in which one or more days (see the number column) had a T_{min} value below -9.9°C, compared with the mean and minimum monthly values recalculated with any value below -9.9°C replaced by -13°C ($T_{mean-13}$, T_{min-13}). Δ is the difference between these two monthly values. The bottom lines show the effect of using -12.1 or -11.0°C instead of -13°C.

It is evident from Table 1 that the monthly mean T in this extreme test is affected on average by just over five one hundredths of a degree, with monthly minimum T on average affected by just over a tenth of a degree. These values shown in Table 1 drop to -0.037°C and -0.072°C respectively if instead of -13°C the replacement value in this test is set to -12.1°C that the Review Panel noted was observed at the Bureau's Perisher Station on 16 July 2017, a value still unusually extreme based on the shape of the Thredbo T_{min} time evolution on 16 July provided in The Review Panel's Figure 3. The effects calculated are very small, and must be significantly larger than the actual effects given the use of the very conservative

extreme value of -13°C or the still unusually low value of -12.1°C as replacement values. The perturbations are halved again if a more plausible replacement value of -11°C is used, to very low difference values of -0.015°C and -0.029°C.

It is worth reiterating that the replacement test also overcompensates too many times, since in this test seventeen values were replaced whereas the Review Panel notes that the logger failure occurred at Thredbo only six times: "*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*" (BoM, 2017a, page 51). Thus the replacement of 17 T_{min} values below -9.9°C with -13°C will cause a low bias in eleven values that were between -9.9°C and the logger cut-off of -10.4°C.

To conclude: even with the extreme overcompensation inherent in the very conservative test undertaken here, the effects of this test on daily, monthly and annual average temperatures in only nine years out of fifty (as listed in Table 1) are close to imperceptible. As an example, the most affected year in Table 1 is 2015 which has three entries. The annual average minimum temperature calculated from the monthly averages is reduced by only 0.02°C when the three months involved have the affected T_{min} values replaced by -13°C. Thus there is no change to the annual mean at the reporting resolution of 0.1°C. It can be concluded without qualification that while undesirable and requiring correction, the datalogger limitation of T_{min} to -10.4°C at Thredbo has not introduced any material distortion into this station's air T record.

3.2 T_{min} Trend Test

To underscore this conclusion a second test of how these few data limitations affect the Thredbo long-term T record was carried out by fitting trend lines to the monthly average T dataset from November 1966 to July 2017. This was done for the original dataset containing any logger-limited T_{min} values and for the revised, hypothetical dataset with the small number of months (Table 1) with T_{min} values <-9.9°C having those values replaced by -13°C. However this is not a climate reference station and there are several significant gaps in the overall long-term record. Thus the numerical value of the trends may not be representative. Nevertheless the fractional change in trend from the -13°C replacement experiment in comparison with trend in the original dataset is a useful exploration of the level of bias introduced by the the inadvertent data logger limitations to -10.4°C. The fractional change is tiny, -0.89%, the slope dropping from 0.2590 to 0.2567°C per decade. That is well within the statistical uncertainty of the trend estimates and does not distort any interpretation of the Thredbo record in a material way. Additionally, it is worth reiterating the point made by the Review Panel, that the Thredbo record itself does not contribute to Australia's mean climatological record because it is not a climate reference station (BoM, 2017a). Therefore both in terms of absolute values (Section 3.1 above) and in terms of the trend test the evidence is that the logger limitation to T_{min} at Thredbo has been so infrequent and small as to have no material impact on that station's long-term temperature records.

3.3 T_{min} Frequency Distribution Test

Given the observation in Section 3.1 that T_{min} values at Thredbo below -13°C have not been observed for more than 23 years it is of interest to add to the analyses in the previous sections by assessing whether extremely cold conditions at Thredbo have diminished in frequency as Australia has warmed over the last half century. Ayers (2016) concluded that: "*Using three different methods of trend estimation applied to five temperature anomaly time series, the anthropogenic contribution to warming of the Australian region since 1950 is determined to have occurred at a rate of 0.12 ± 0.02K per decade, which translates to a total anthropogenic warming contribution of 0.78 ± 0.13K over the period 1950 to 2015*".

This question was addressed using daily T_{min} data from May to September each year for the five years 1967, 1968, 1969, 1971 and 1972, and comparing the frequency distribution from those data with that from the equivalent T_{min} data for 2010, 2011, 2012, 2015 and 2016. A second late-1960s vs 2010s comparison was made for the hypothetical test data from Section 3.1 in which T_{min} less than -9.9°C in the latter five years had that value replaced by -13°C. The non-contiguous lists of years reflect the need to use only years with complete data records from May to September. Even so, for each of the years 1969, 1971 and 1972 one day's data was missing. Each was filled with a T_{min} value interpolated from the adjacent days. None of the interpolated values was close to -10.4°C (-7.8, -1.4 and -4.2°C interpolated for 1969, 1971 and 1972): their inclusion or not makes no difference to the analysis below. Figure 2 displays the resultant T_{min} frequency distributions.

It is evident from Figure 2 that over the more than forty years spanned by the data there has been a secular increase in T_{min} that causes the whole frequency distribution to shift to warmer temperatures in the 2010s compared with the late 1960s. That is reasonable. It is consistent with and explicable as a manifestation of the warming of Australia, mostly attributable

to anthropogenic greenhouse gas forcing (Ayers, 2016). It cannot be an artifact of the data logger limitation to -10.4°C, as it occurs at all temperatures. Figure 2 shows a decrease in the number of days below the mode of the T_{min} distribution from the 1960s that transfers directly into an increase in the frequency of occurrence of all T_{min} values above that mode in the 2010s (the dashed purple "change" line in Figure 2).

The mean T_{min} value for the May-September in the two five year periods increases from -4.1°C in the 1960s to -3.3°C in the 2010s, and remains unchanged in the test case with -13°C extremes, again emphasising the lack of materiality that the few logger outages have had on the overall record. The implication is clear: as Australia warms, the number of cool days at Thredbo, including extremely cold days, will continue to decline. The decline in frequency of very cold days is not an artefact, is consistent across the T_{min} range and not confined to very infrequent extreme values at or below -10.4°C. This change has been well documented more broadly in Australia's State of the Climate reports (see BoM, 2016).

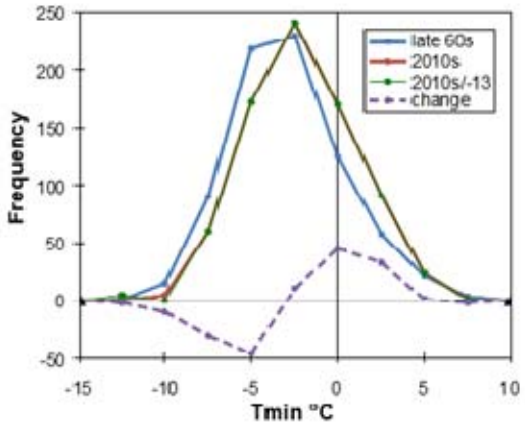

Figure 2 Frequency distributions for daily T_{min} from Thredbo for five years from the 2010s vs five years from the late 1960s. The purple line shows the change in frequency distribution over that period: a consistent, secular increase in T_{min} occurs across the T interval spanned by the distributions. The thin green line is the -13°C test case distribution.

A final comment concerning Figure 2 is that it confirms the -13°C test case to be an over-compensation for the datalogger limitation to -10.4°C, since it distorts the 2010s distribution shape in a manner that is not physically reasonable (the green curve at -12.5°C is higher, not lower than at -10°C as it is for the other curves in that region).

4. Conclusions

The effect on air temperature data at Goulburn and Thredbo Top Station of inadvertent data logger limitation at minimum temperatures of -10.4°C has been investigated. A single logger outage of nine minutes at Goulburn on 2 July 2017 was deemed to have no impact on that data record, as the likely actual minimum was estimated to be -10.4°C +0.0/-0.1°C.

The occurrence of the logger limitation at Thredbo on six days within the last ten years was investigated by creating a hypothetical dataset in which seventeen days with T_{min} values less than -9.9°C had that value replaced by -13°C, heavily overcompensating for the datalogger error in the number of occurrences and in temperature: no temperature less than -13°C has been measured at Thredbo for twenty-three years. Three tests in which the hypothetical, overcompensated temperature dataset was compared with the existing Thredbo temperature record demonstrated that logger error on just six days at Thredbo since 2007 has no perceptible effect on the data record at that station. An additional finding was that the frequency of cool days at Thredbo has decreased at all temperatures across the T_{min} temperature range from the late 1960s to the present, consistent with the well understood warming of Australia over that period attributable to anthropogenic greenhouse gas increase.

5. References

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