Fast and Accurate Calculation of Wet-bulb Temperature for Humid-Heat Extremes

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Motivation

Humid-heat research often requires wet-bulb temperature (T_w) to be calculated from dry-bulb temperature (T), pressure (p), and a humidity metric, such as relative humidity (RH), however, some commonly used calculation methods produce substantial errors. For example, T_w errors can reach >1°C for the Stull (2011) method, which overestimates T_w for high T and low RH. The use of various T_w methods with differing accuracies across the humid-heat research community limits our ability to accurately identify past and future change in humid-heat extremes.

Aims

1) Develop a highly accurate, fast method for calculating T_w ➡ NEWT,
2) Compare the accuracy of different T_w methods, and,
3) Make Python code for the new T_w method widely available.

1. A new, better wet-bulb temperature method

Due to a lack of long-term, T_w observations, the Stull (2011), MetPy (May et al. 2022), and Davies-Jones (2008, henceforth DJ08) adiabatic methods are commonly used to approximate T_w when examining humid-heat extremes. Here, we introduce a new adiabatic T_w method, the Noniterative Evaluation of Wet-bulb Temperature (NEWT). We find that maximum T_w error magnitudes using NEWT (~0.01°C) are smaller than those for Stull, MetPy, and DJ08 (~1.3°C, 0.4°C, and 0.05°C, respectively, Fig. 1). Thus, NEWT and DJ08 are both suitable for extreme humid-heat research, whereas we strongly advise against Stull due to the large errors.

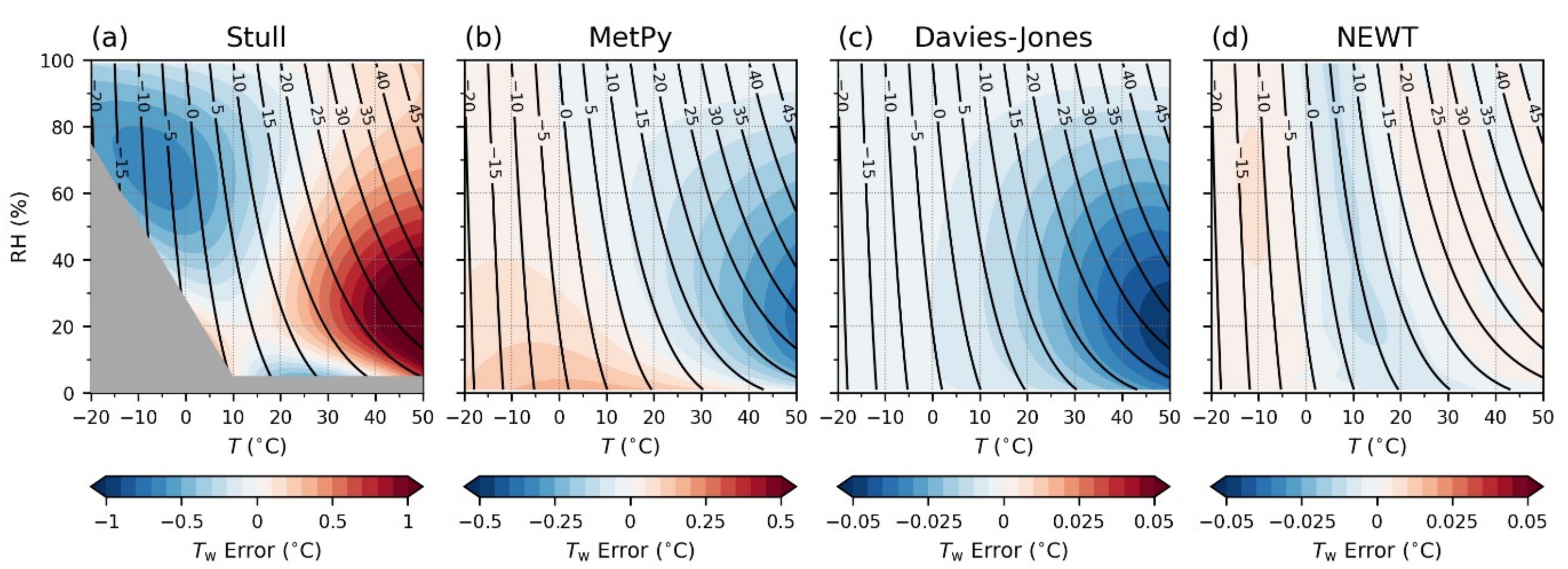


*Fig 1: **Errors in T_w, relative to an "exact" diagrammatic solution, using the (a) Stull, (b) MetPy, (c) DJ08, and (d) NEWT methods.** Values are calculated at a pressure of 1,000 hPa and plotted as a function of T and RH. Contours show T_w (in °C) from the diagrammatic solution. Results for the Stull method are masked where the method is considered invalid. Note the different colour scale for each panel.*

References

Buzan, J.R., Oleson, K. and Huber, M., 2015. Implementation and comparison of a suite of heat stress metrics within the Community Land Model version 4.5. *Geoscientific Model Development*, *8*(2), pp.151-170.

Davies-Jones, R. (2008). An efficient and accurate method for computing the wet-bulb temperature along pseudoadiabats. *Monthly Weather Review*, *136*(7), 2764–2785.

May, R.M., Goebbert, K.H., Thielen, J.E., Leeman, J.R., Camron, M.D., Bruick, Z., Bruning, E.C., Manser, R.P., Arms, S.C. and Marsh, P.T., 2022. MetPy: A meteorological Python library for data analysis and visualization. *BAMS*, *103*(10), pp.E2273-E2284.

Stull, R. (2011). Wet-bulb temperature from relative humidity and air temperature. *Journal of Applied Meteorology and Climatology*, *50*(11), 2267–2269.

2. Wet-bulb temperature from observational data

Fig. 2 shows the distribution of observational data for an example station using Bureau of Meteorology 3-hourly station data. High T_w (>25°C) occasionally coincide with relatively large errors for Stull (>1°C, Fig. 2a) and MetPy (<-0.25°C, Fig. 2b), thus, these methods substantially over/underestimate potentially dangerous humid-heat events.

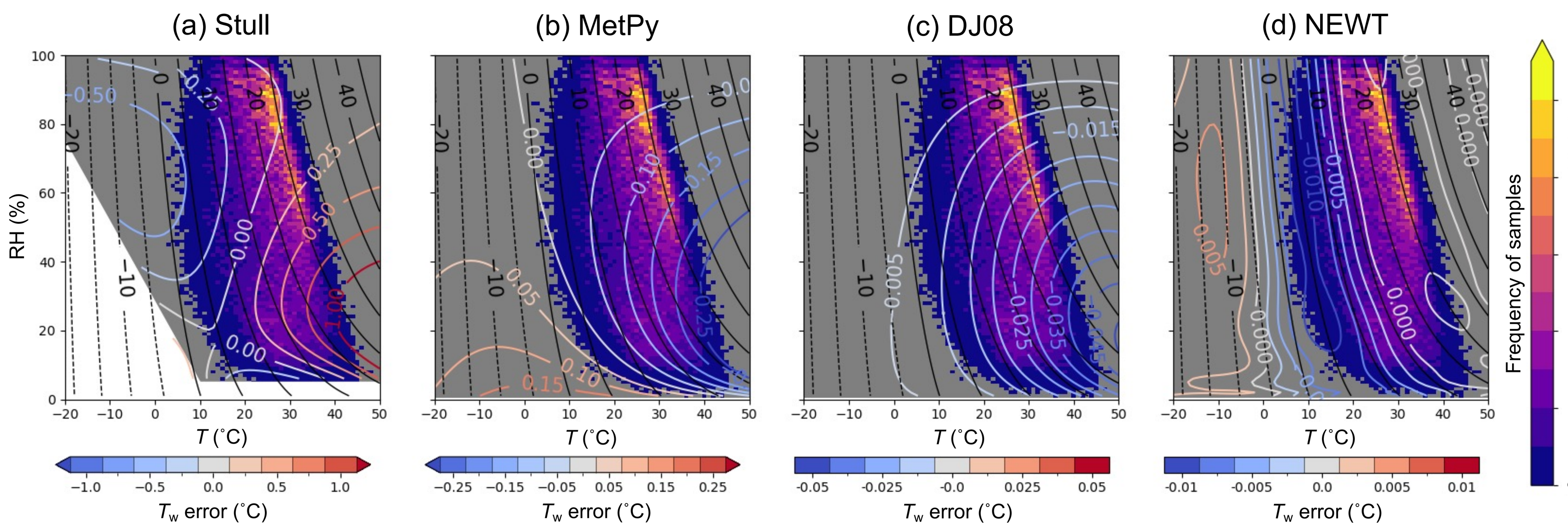


*Fig 2: **Distribution of T_w for an example observation station in northern Australia.** Pixel colour shows the frequency of each T-RH combination. Coloured contours show T_w error for the (a) Stull, (b) MetPy, (c) DJ08, and (d) NEWT methods. Black contour lines show exact T_w for the corresponding T-RH combination. Note the different colour scale for each panel.*

3. NEWT Python code available *NOW!*

The NEWT method has been implemented as part of "atmos", a comprehensive Python library for atmospheric thermodynamics. The code also includes an improved method for calculating the isobaric wet-bulb temperature. Note, however, that the library is still under development and has yet to be rigorously tested or documented. https://github.com/robwarrenwx/atmos

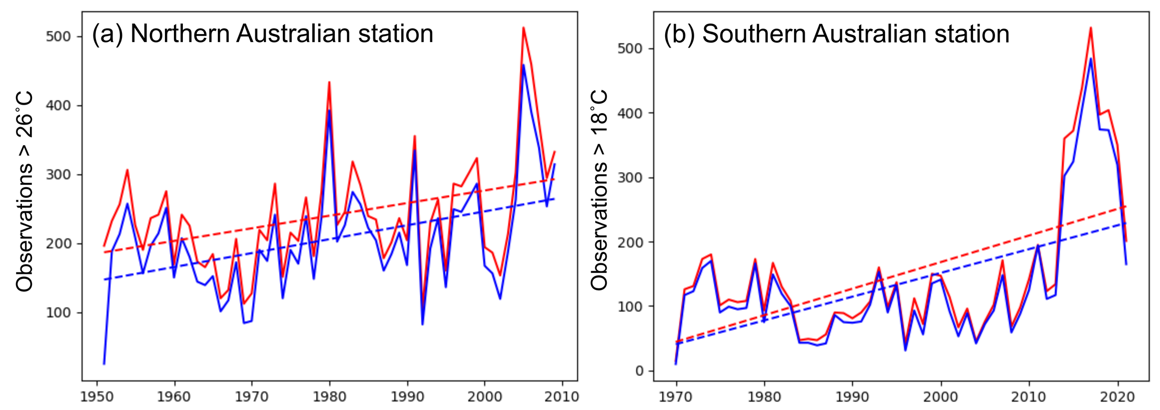
The NEWT method is more accurate and faster than other common wet-bulb temperature calculation methods

Key takeaways

- We have developed a new, highly accurate method for calculating adiabatic wet-bulb temperature, NEWT.
- Both NEWT and the DJ08 method are suitable for extreme humid-heat research, but we strongly advise against the use of the Stull (2011) method due to large errors.
- We recommend researchers revisit past analyses using the DJ08 method due to bugs in several open-source implementations.

4. T_w threshold exceedances for Stull and NEWT

Fig. 3 shows the number of T_w observations above a high threshold for the least accurate method, Stull, and the most accurate method, NEWT. Stull overestimates the number of high T_w observations at both stations and overestimates the trend at the southern station (Fig. 3b), but underestimates the trend at the northern station (Fig. 3a).



	North Aust. (a)		South Aust. (b)	
	Stull	NEWT	Stull	NEWT
Trend (decade⁻¹)	18.3	20.2	41.2	36.9
Change	69.2	78.7	208.9	184.9
Maximum	512	458	532	484

*Fig 3: **Number of 3-hourly T_w observations above (a) 26°C and (b) 18°C,** for the Stull (red) and NEWT (blue) methods, for (a) one northern, and (b) one southern Australian observation station.*

5. Bugs in existing wet-bulb implementations

While testing NEWT against other T_w methods, we identified three bugs in a widely used DJ08 implementation, adapted from HumanIndexMod, a Fortran library designed for use with the Community Land Model (Buzan et al. 2015). Figs. 4 and 5 show the impact of the bugs on T_w accuracy. When using specific humidity (q) as the input moisture variable, the errors from the three bugs largely cancel (Fig. 5b). Conversely, when using RH as the input moisture variable, errors exceed 0.5°C for T >~40°C (Fig. 5d). Bugs 1 and 2 are addressed in some open-source scripts through additional iterations, but this can prevent the cancellation of errors for q. A corrected and Numba-accelerated implementation of the DJ08 method has recently been made available by Colin Raymond (https://github.com/cr2630git/wetbulb_dj08_spedup).

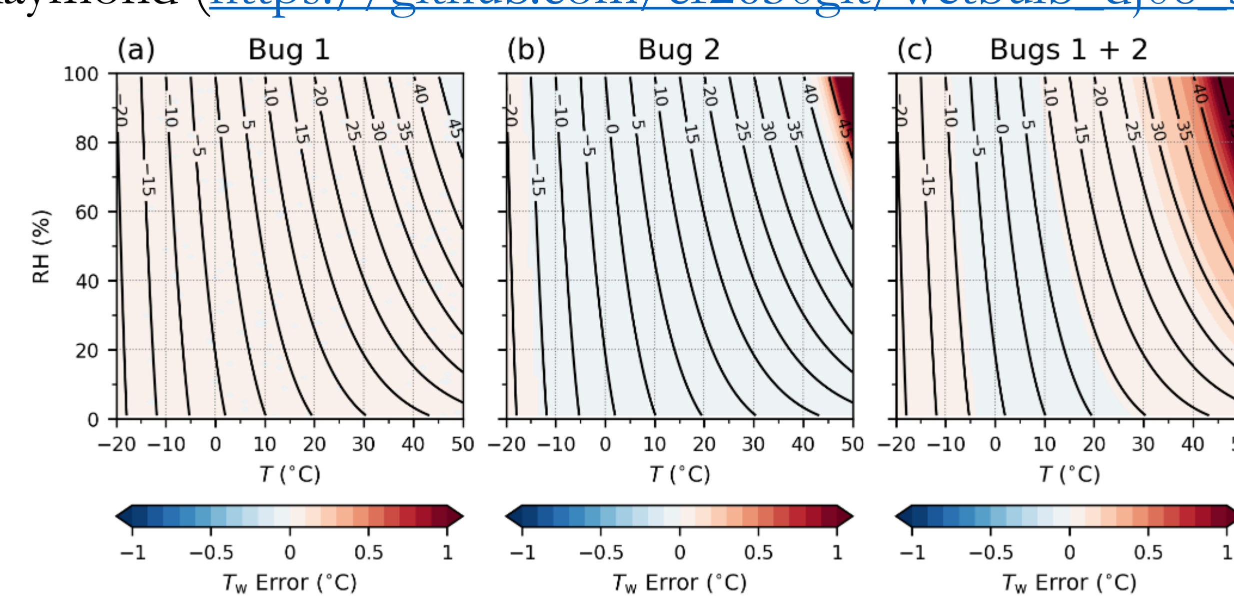


*Fig 4: **T_w errors due to Bugs 1 and 2.** Errors caused by a) Bug 1, b) Bug 2, and c) Bugs 1 and 2 combined, plotted as a function of T and RH. Values are calculated at a pressure of 1,000 hPa. Contours show T_w (in °C) from a corrected implementation of DJ08.*

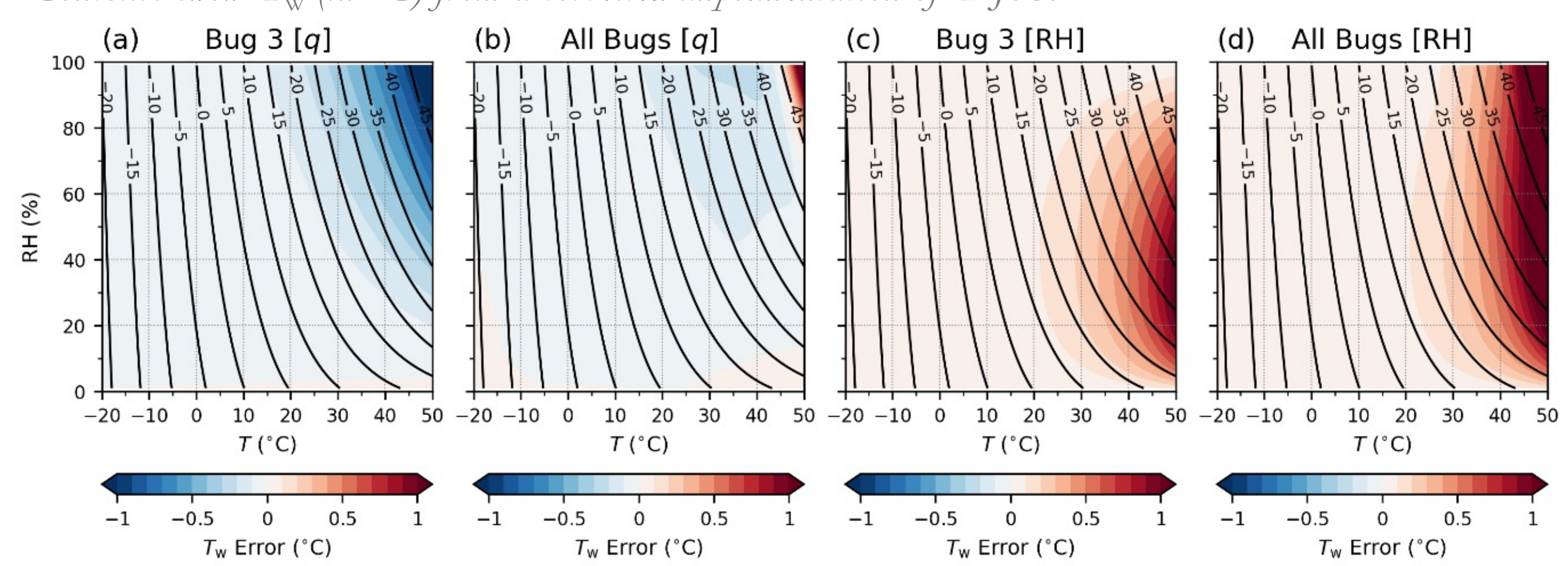


*Fig 5: **T_w errors due to Bug 3 and all bugs.** As in Fig. 1 but showing errors caused by a,c) Bug 3 and b,d) all three bugs with a,b) specific humidity (q), and c,d) RH as the input moisture variable.*