# Evaluating the 35°C wet-bulb temperature adaptability threshold for young, healthy subjects (PSU HEAT)

Daniel J. Vecellio[1], S. Tony Wolf[2], Rachel M. Cottle[2], and W. Larry Kenney[2,3]

1. *Center for Healthy Aging, Pennsylvania State University, University Park, PA, 16802*
2. *Department of Kinesiology, Pennsylvania State University, University Park, PA 16802*
3. *Graduate Program in Physiology, Pennsylvania State University, University Park, PA 16802*

ORCID
Vecellio - 0000-0001-9431-0744

**Corresponding Author:**
Daniel J. Vecellio
422 Biobehavioral Health Building
University Park, PA 16802
Email: dj5030@psu.edu

**Running Title:**
Is the 35°C wet-bulb temperature adaptability threshold valid?

**Key Words:**
Climate change; thermoregulation; global warming; human heat stress; environmental limits

## Abstract

A wet-bulb temperature of 35°C has been theorized to be the limit to human adaptability to extreme heat, a growing concern in the face of continued and predicted accelerated climate change. While this theorized threshold is based in physiological principles it has not been tested using empirical data. This study examined the critical wet-bulb temperature ($T_{wb,\ crit}$) at which heat stress becomes uncompensable in young, healthy adults performing tasks at modest metabolic rates mimicking basic activities of daily life. Across six experimentally determined environmental limits, no subject's $T_{wb,\ crit}$ reached the 35°C limit and all means were significantly lower than the theoretical 35°C threshold. Mean $T_{wb,\ crit}$ values were relatively constant across 36-40°C humid environments and averaged 30.55±0.98 °C but progressively decreased (higher deviation from 35°C) in hotter, dry ambient environments. $T_{wb,\ crit}$ was significantly associated with mean skin temperature (and a faster warming rate of the skin) due to larger increases in dry heat gain in the hot-dry environments. As sweat rates did not significantly differ among experimental environments, evaporative cooling was outpaced by dry heat gain in hot-dry conditions, causing larger deviations from the theoretical 35°C adaptability threshold. In summary, a wet-bulb temperature threshold cannot be applied to human adaptability across all climatic conditions and where appropriate (high humidity), that threshold is well below 35°C.

## New and Noteworthy

This study is the first to use empirical physiological observations to examine the well-publicized theoretical 35°C wet-bulb temperature limit for human to extreme environments. We find that uncompensable heat stress in humid environments occurs in young, healthy adults at wet-bulb temperatures significantly lower than 35°C. Additionally, uncompensable heat stress occurs at widely different wet-bulb temperatures as a function of ambient vapor pressure.

## Introduction

In their most recent report, the Intergovernmental Panel on Climate Change stated that global temperatures have increased by ~1°C since the preindustrial era, primarily due to anthropogenic climate change (1). This increase in global mean temperature is accompanied by higher magnitude temperature increases on some regional scales (2), along with increased heatwave frequency, duration, and magnitude (3). While the number of heatwaves is already on the rise, future generations will experience many more extreme temperature events than the present (4). As dry-bulb (air) temperatures ($T_{db}$) increase, there is a thermodynamic basis for concurrent humidity increases via the Clausius-Clayperon relation, as for every 1°C increase in temperature, a parcel of air can hold 7% more water vapor (5). Accordingly, the risk of humid heat stress becomes larger in the face of continued climate change (6). Humid heat stress reduces the body's most efficient way to dissipate heat, i.e., the evaporation of sweat. Hence, the combination of extreme ambient heat and humidity, often quantified using the wet-bulb temperature ($T_{wb}$), prevent human heat loss to the environment and can lead to heat-related illness and even death, especially in vulnerable populations.

Sherwood and Huber (7) were the first climate scientists to propose a $T_{wb}$ adaptability limit for humans to environmental heat stress. Following basic physiological principles, a threshold of $T_{wb}$=35°C was established as the point where consistent exposure would negate the human body's natural cooling processes via both convection and evaporation of sweat and induce hyperthermia. Athough Raymond et al. (8) have reported a few instances of hourly $T_{wb}$ values > 35°C in recent observations, most maximal $T_{wb}$ values on Earth have been in the 30-31°C range. However, climate models have predicted that regions such as the Middle East could experience $T_{wb}$ values that regularly exceed 35°C by the end of the century (9, 10).

Therefore, the aim of this study was to evaluate the theoretical $T_{wb}$ = 35°C survivability threshold with data collected as part of the PSU HEAT (Human Environmental Age Thresholds) project from young, healthy adults. Specifically, we determined critical environmental limits in terms of $T_{wb}$, above which steady state core temperature ($T_c$) cannot be maintained within the confines of a controllable environmental chamber. This analysis involved subjects moving at low metabolic rates to replicate the baseline activities associated with everyday life. We hypothesized that the critical $T_{wb}$ ($T_{wb,crit}$) would be lower than the theoretical limit of 35°C. Secondly, we hypothesized that $T_{wb,crit}$ would be variable depending on combinations of temperature and humidity due to differences in sweat evaporation and heat gain (radiation and convection) in hot-dry versus warm-humid environments.

## Methods and Procedures

Data were collected at Pennsylvania State University with all procedures approved by the Institutional Review Board (IRB). All test subjects gave informed consent during an initial screening visit. Detailed information about testing procedures and measurements are written in detail in Wolf et al. (submitted companion paper). All subjects from Wolf et al. (TBD) were a part of the study detail here. However, individual trials from three of the subjects were removed for this analysis due to missing mean skin temperature ($\overline{T}_{sk}$) data, one each from the 20 mmHg, 36°C, and 40°C experimental protocols. The exclusion of these participants did not affect the statistics of the subject sample or subsequent variable analyses. A brief summary of the testing procedures is provided here. Subject characteristics are presented in **Table 1.**

During experiments, subjects wore a standardized attire consisting of a t-shirt, shorts, socks and sneakers. Female participants also wore sports bras. Subjects free-pedaled a cycle ergometer at a low intensity of ~10W designed to characterize activities of daily living (11). There were six experimental protocols included in this study: three critical water vapor pressure ($P_a$) experiments at 36°C, 38°C, and 40°C ($P_{crit}$) and three critical $T_{db}$ experiments at 12 mmHg, 16 mmHg, and 20 mmHg ($T_{crit}$). After a 30-minute acclimation period, $P_a$ or $T_{db}$ was increased by 1 mmHg or 1°C every five minutes until a clear inflection in $T_c$ was observed, which determined the critical environmental loci of ($T_{db}$, $P_a$). Those loci were then translated to $T_{wb}$ using a psychrometric chart and recorded as $T_{wb,crit}$. Core temperature was measured with gastrointestinal temperature telemetry capsules (VitalSense, Philips Respironics, Bend, OR, USA) that were ingested by subjects 1-2 hours before reporting to the laboratory. $T_{sk}$ was measured continuously (iButton, Whitewater, WI, USA) at the chest, upper arm, inner thigh, and calf. Whole-body $T_{sk}$ was calculated using a weighted-mean ($\overline{T}_{sk}$) of the four measurement sites (12).

### *Calculated variables*

Dry heat gain was calculated at the $T_c$ inflection point based on the clothing ensembles participants wore during the experimental protocols using ASHRAE (13) standards. The intrinsic clothing insulation ($R_{cl}$) was calculated as:

$$R_{cl} = 0.155\ W/m^2(I_{cl})$$

where $I_{cl}$ is the clothing insulation factor set to 0.27 clo based on the participants' standard ensemble. The clothing thermal efficiency ($f_{cl}$) of the ensemble was calculated as:

$$f_{cl} = 1.0 + 0.3(I_{cl})$$

Finally, dry heat gain through convection and radiation ($C + R$) was calculated as a function of the air-skin temperature gradient and defined as:

$$C + R = \frac{T_{db} - \overline{T}_{sk}}{R_{cl} + 1/(f_{cl}h)}$$

where $T_{db}$ and $\overline{T}_{sk}$ are the dry bulb and mean skin temperatures at the time of $T_c$ inflection and $h$ is combined convective and radiative heat transfer coefficients of 4.7 and 3.4 W/($m^2$ °C), respectively.

### *Statistical analyses*

Independent sample t-tests were used to determine differences between mean values among experimental protocols due to their varying sample sizes. To account for multiple comparisons among relative humidity (RH), dry heat gain, and $T_{wb, crit}$ in the 6 experimental protocols (a total of 15 interacting comparisons), significance was accepted at $p = 0.003$. The three $T_{crit}$ and $P_{crit}$ means were also tested against each other for significant differences with significance being accepted at 0.05/3 or $p = 0.017$. One sample t-tests were performed to determine differences between each of the experimentally-determined $T_{wb,crit}$ means and the 35°C theoretical limit for human adaptability to extreme heat ($\alpha = 0.05$). To examine relations among variables, linear least squares regression was performed and $R^2$ and p-values ($\alpha = 0.05$) were reported. All tests were performed using the Python Software Foundation (Python Language Reference, version 3.6). Data are reported as mean ± SD except in Figure 1, which is presented as a box-and-whisker plot with individual data points.

## Results

The physiological characteristics of the study's participants are presented in **Table 1**. Subjects were recruited to be representative of the population in this age group with respect to body size, adiposity, and aerobic fitness. There were no subject sample differences in age, height, weight, Dubois surface area ($A_D$), $A_D$/kg, or $\dot{V}O_{2max}$ among trial conditions (all $p \geq 0.05$).

Mean $T_{crit}$ and $P_{crit}$ values for the protocols are presented in **Table 2**. During $T_{crit}$ experiments, lower clamped $P_a$ values were associated with higher critical $T_{db}$ values and there were statistical differences among the three protocols. However, there was less variance in $P_{crit}$ values among the three clamped $T_{db}$ conditions and no statistical differences were present. All RH values for the six experimental protocols were statistically different from one another except for 36°C vs. 38°C protocols ($p = 0.08$). Taken together, combinations of $T_{db}$, $P_a$, and RH indicate distinct thermal regimes for $T_{wb,crit}$ categorization. Specifically, higher $T_{wb,crit}$ values were associated with warm-humid environments while lower values of $T_{wb,crit}$ were tied to hot-dry environments.

The $T_{wb,crit}$ in each of the three $T_{crit}$ experiments (12 mmHg: 25.75 ± 0.48°C; 16 mmHg: 27.12 ± 0.54°C; 20 mmHg: 27.82 ± 0.71°C) were lower than the $T_{wb,crit}$ in any of the $P_{crit}$ experiments (36°C: 30.34 ± 0.97°C; 38°C: 30.96 ± 0.97°C; 40°C: 30.45 ± 1.06°C) (**Figure 1**). Among $T_{crit}$ experiments, $T_{wb,crit}$ at 12mmHg was lower than that at both 16 mmHg and 20 mmHg (both $p < 0.001$). There was no statistical difference between the $T_{wb,\ crit}$ values for the 16 mmHg and 20 mmHg protocols ($p = 0.046$). There were no differences in $T_{wb,crit}$ among the three $P_{crit}$ experiments (36°C vs. 38°C: $p = 0.24$ ; 36°C vs. 40°C: $p = 0.83$; 38°C vs. 40°C: $p = 0.36$). Importantly, the $T_{wb,crit}$ for all six experimental protocols were significantly different from the reported 35°C $T_{wb}$ theoretical limit for human adaptability to extreme heat (**Figure 1**).

Interactions between $\overline{T}_{sk}$ and $T_{wb,crit}$ are presented in **Figure 2**. Higher $\overline{T}_{sk}$ at the time of $T_c$ inflection was associated with lower $T_{wb,crit}$ values ($R^2 = 0.54$, $p < 0.001$) (**Figure 2a)**. In all cases, $\overline{T}_{sk}$ at the time of $T_c$ inflection was higher than 35°C. $\overline{T}_{sk}$ increased at a faster rate in the hot-dry protocols than in the warm-humid ($R^2 = 0.37$, $p <0.001$) (**Figure 2b**).

Dry heat gain at the $T_c$ inflection point was reflective of ambient environmental conditions, such that $\overline{T}_{sk}$ was higher in hot-dry protocols and lower (approaching zero) in warm-humid protocols (**Table 3**). Dry heat gain across critical environmental conditions were all significantly different from each other except for between the 12 mmHg and 16 mmHg protocols ($p = 0.01$). Conversely, there were no significant differences in whole body sweat rate among the six experimental protocols (**Table 3**).

## Discussion

Our results indicate that the theoretical $T_{wb} = 35°C$ adaptability limit to climate change -- introduced by Sherwood and Huber (7) and used in subsequent papers to determine future regions of livability (9) -- overestimates real-world conditions that lead to uncompensable heat stress in young, healthy adults during minimal physical activity. In controlled experiments, critical wet bulb temperatures ranged from 25 - 28°C in hot-dry environments and 30 - 31°C in warm-humid environments. Sherwood and Huber (7) reasoning was contingent on the assumption of a maximum $T_{sk}$ of 35°C to allow for heat to be moved away from the core of the body which is typically within a half-degree of 37°C. However, our data suggest that $\overline{T}_{sk}$ typically exceeds 35°C after a short duration in ambient thermal environments above 36°C, even at very low metabolic rates, with the effect being more pronounced in hot-dry conditions.

In fact, $\overline{T}_{sk}$ often exceeded $T_c$ by the time of $T_c$ inflection during $T_{crit}$ trials, which according to thermodynamic theory reverses the thermal gradient from the skin toward the core. The higher magnitude and faster rising $\overline{T}_{sk}$ are due to larger increases in dry heat gain in the hot-dry protocols compared to the warm-humid protocols, in conjunction with no difference in sweat rate across the six experimental protocols. With free evaporation occurring in the hot-dry protocols due to the large gradients in vapor pressure between the skin and environment, subject participants did not increase sweating (and thus evaporative) rate to compensate for the relatively higher dry heat gains.

As stated under *Results*, distinct $T_{wb, crit}$ thermal loci were present in the dataset. Higher and more constant $T_{wb, crit}$ values, closer to the 35°C theoretical limit yet still statistically different from it, were found in warm-humid environments while $T_{wb, crit}$ values in hot-dry environments were nearly 10°C lower than the literature-proposed limit. These results indicate that not only is the 35°C theoretical threshold untenable under real-world testing, that ambient environmental control on $T_{wb, crit}$ dictates that one universal wet-bulb temperature cannot be used to quantify human thermal tolerance across the world. Future adaptability and survivability work should incorporate the heterogeneous relations between climate and $T_{wb, crit}$ via a geographic lens to provide a more realistic regional and global risk to continued extreme heat associated with climate change.

The critical environmental limits reported herein document that areas of the planet already experience wet-bulb temperatures associated with uncompensable heat stress on a more regular basis than previously theorized (7, 8). Intervention strategies such as electric fan use and air conditioning allow for survivability in these extreme environments, though they inhibit the ability to acclimatize and/or adapt (14). Still, some caveats apply for their use to combat extreme heat. The World Health Organization has advised against electric fan use at ambient $T_{db}$ above 35°C, subsequently tied to $T_{wb}$ values $< 35$°C, due to increased dehydration and increased convective heat gain (15). However, biophysical modeling has shown that fans can effectively be used at much higher $T_{db}$

values (though $T_{wb}$ values were likely still less than 35°C) given that fans would augment evaporative cooling (16). Laboratory studies have shown the same, especially in young, healthy subjects (17, 18).

The $T_{wb,crit}$ values in this study are applicable to young, healthy individuals meaning that the current risk to more vulnerable populations is even higher than previously thought. Notably, the elderly are at increased risk due to decreased thermoeffector responsiveness to heat stress (19, 20), medication-induced degradation of body cooling capacity (21), and biobehavioral alterations which further inhibit heat tolerance (22). This has been realized in excess deaths amongst the elderly during the 1995 Chicago, USA (23) and 2003 European (24) heatwaves in addition to many others. The importance of continuing to study their interactions with the environment are noted in both clinical (25) and environmental literatures (26). $T_{wb,\ crit}$ values for less heat tolerant populations will likely be lower than the values presented here and more commonly found in not only today's climate, but in future climates as well, and form the scope of the ongoing PSU HEAT Study.

*Limitations*

Although data were collected over the calendar year to account for acclimatizaon effects, all experiments were done in State College, PA which experiences a "warm summer-humid continental" (Dfb) climate according to the Koppen-Geiger climate classification system (27). Acclimatization and adaptation in warmer climates are important to improving the physiological response to extreme heat. Repeatability with subjects living in regions with tropical (class A) or dry (class B) climates which typically experience higher warm-season extreme temperature and humidity values would be useful to verify the critical values found in this study.

The environmental chamber used for this study did not include any considerable source of radiative heat input, neglecting an important source of heat gain for humans in outdoor conditions. Conversely, airflow was also limited in the chamber causing a lack of forced convection to aid in evaporation of sweat, which is the body's main cooling mechanism in extreme heat. In outdoor environments with increased likelihood of forced convection, there is the chance that more sweat could be evaporated and delay the time to $T_c$ inflection, likely allowing for subjects to inflect at higher critical wet-bulb temperatures. It is therefore unclear how additional radiative heat load and forced convection in combination would alter $T_{wb,\ crit}$.

## Perspectives and significance

In this paper, empirical physiological data were used to determine the validity of the theorized human adaptability limit to rising temperatures due to climate change. In all six of the experimental protocols, critical wet-bulb temperatures were significantly lower than the 35°C threshold proposed in the literature (7) and popularized in the lay press. Larger deviations from the 35°C threshold, some as high as 10°C, were found in hot-dry environmental conditions. Subjects in these protocols experienced higher $T_{sk}$, increased dry heat gain, with no statistical difference in sweat rates compared with subjects in the more warm-humid environments, where critical wet bulb temperatures were nearly constant between 30-31°C. Two conclusions are therefore apparent: 1) The theoretical 35°C wet bulb temperature threshold does not hold up under experimental testing and 2) there is likely not one critical threshold that can be set, especially so in lower-humidity environments. Future studies should examine the role of acclimatization on heat tolerance as well as how the impact of these conditions would affect critical wet bulb temperatures in vulnerable populations such as the elderly.

## Acknowledgements

This research was supported by the National Institute on Aging Grant T32 AG049676 to The Pennsylvania State University (DJV) and National Institutes of Health Grant R01 AG067471 (WLK).

## References

1. **Allen M, Dube O, Solecki W, Aragón-Durand F, Cramer W, Humphreys S, Kainuma M, Kala J, Mahowald N, and Mulugetta Y**. Framing and Context in Global Warming of 1.5 C: An IPCC Special Report on the impacts of global warming of 1.5 C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. *Sustainable Development, and Efforts to Eradicate Poverty'(Eds V Masson-Delmotte, P Zhai, HO Pörtner, D Roberts, J Skea, PR Shukla, A Pirani, W Moufouma-Okia, C Péan, R Pidcock, S Connors, JBR Matthews, Y Chen, X Zhou, MI Gomis, E Lonnoy, T Maycock, M Tignor, T Waterfield) pp* 41-91, 2018.
2. **Tamarin-Brodsky T, Hodges K, Hoskins BJ, and Shepherd TG**. Changes in Northern Hemisphere temperature variability shaped by regional warming patterns. *Nature Geoscience* 13: 414-421, 2020.
3. **Perkins-Kirkpatrick SE, and Gibson PB**. Changes in regional heatwave characteristics as a function of increasing global temperature. *Scientific Reports* 7: 12256, 2017.
4. **Thiery W, Lange S, Rogelj J, Schleussner C-F, Gudmundsson L, Seneviratne SI, Andrijevic M, Frieler K, Emanuel K, Geiger T, Bresch DN, Zhao F, Willner SN, Büchner M, Volkholz J, Bauer N, Chang J, Ciais P, Dury M, François L, Grillakis M, Gosling SN,**

**Hanasaki N, Hickler T, Huber V, Ito A, Jägermeyr J, Khabarov N, Koutroulis A, Liu W, Lutz W, Mengel M, Müller C, Ostberg S, Reyer CPO, Stacke T, and Wada Y**. Intergenerational inequities in exposure to climate extremes. *Science* 374: 158-160, 2021.

5. **Trenberth KE, Dai A, Rasmussen RM, and Parsons DB**. The Changing Character of Precipitation. *Bulletin of the American Meteorological Society* 84: 1205-1218, 2003.

6. **Buzan JR, and Huber M**. Moist Heat Stress on a Hotter Earth. *Annual Review of Earth and Planetary Sciences* 48: 623-655, 2020.

7. **Sherwood SC, and Huber M**. An adaptability limit to climate change due to heat stress. *Proceedings of the National Academy of Sciences* 107: 9552-9555, 2010.

8. **Raymond C, Matthews T, and Horton RM**. The emergence of heat and humidity too severe for human tolerance. *Science Advances* 6: eaaw1838, 2020.

9. **Pal JS, and Eltahir EAB**. Future temperature in southwest Asia projected to exceed a threshold for human adaptability. *Nature Climate Change* 6: 197-200, 2016.

10. **Coffel ED, Horton RM, and de Sherbinin A**. Temperature and humidity based projections of a rapid rise in global heat stress exposure during the 21st century. *Environmental Research Letters* 13: 014001, 2017.

11. **AINSWORTH BE, HASKELL WL, WHITT MC, IRWIN ML, SWARTZ AM, STRATH SJ, O'BRIEN WL, BASSETT DR, SCHMITZ KH, EMPLAINCOURT PO, JACOBS DR, and LEON AS**. Compendium of Physical Activities: an update of activity codes and MET intensities. *Medicine & Science in Sports & Exercise* 32: S498-S516, 2000.

12. **Ramanathan NL**. A new weighting system for mean surface temperature of the human body. 19: 531-533, 1964.

13. **ASHRAE**. *2013 ASHRAE handbook: Fundamentals*. Atlanta, GA: American Society of Heating, Refrigerating and Air-Conditioning Engineers, 2013.

14. **Hanna EG, and Tait PW**. Limitations to Thermoregulation and Acclimatization Challenge Human Adaptation to Global Warming. *Int J Environ Res Public Health* 12: 8034-8074, 2015.

15. **Koppe C, Kovats S, Jendritzky G, and Menne B**. *Heat-waves: risks and responses*. Copenhagen: World Health Organization. Regional Office for Europe, 2004.

16. **Morris NB, Chaseling GK, English T, Gruss F, Maideen MFB, Capon A, and Jay O**. Electric fan use for cooling during hot weather: a biophysical modelling study. *The Lancet Planetary Health* 5: e368-e377, 2021.

17. **Morris NB, English T, Hospers L, Capon A, and Jay O**. The Effects of Electric Fan Use Under Differing Resting Heat Index Conditions: A Clinical Trial. *Annals of Internal Medicine* 171: 675-677, 2019.

18. **Ravanelli NM, Hodder SG, Havenith G, and Jay O**. Heart Rate and Body Temperature Responses to Extreme Heat and Humidity With and Without Electric Fans. *JAMA* 313: 724-725, 2015.

19. **Kenney WL, Craighead DH, and Alexander LM**. Heat Waves, Aging, and Human Cardiovascular Health. *Medicine & Science in Sports & Exercise* 46: 1891-1899, 2014.

20. **Schneider A, Rückerl R, Breitner S, Wolf K, and Peters A**. Thermal Control, Weather, and Aging. *Current Environmental Health Reports* 4: 21-29, 2017.

21. **Westaway K, Frank O, Husband A, McClure A, Shute R, Edwards S, Curtis J, and Rowett D**. Medicines can affect thermoregulation and accentuate the risk of dehydration and heat-related illness during hot weather. *Journal of Clinical Pharmacy and Therapeutics* 40: 363-367, 2015.

22. **Terrien J, Perret M, and Aujard F**. Behavioral thermoregulation in mammals: a review. *Frontiers in Bioscience-Landmark* 16: 1428-1444, 2011.

23. **Whitman S, Good G, Donoghue ER, Benbow N, Shou W, and Mou S**. Mortality in Chicago attributed to the July 1995 heat wave. *American Journal of Public Health* 87: 1515-1518, 1997.

24. **Vandentorren S, Bretin P, Zeghnoun A, Mandereau-Bruno L, Croisier A, Cochet C, Ribéron J, Siberan I, Declercq B, and Ledrans M**. August 2003 Heat Wave in France: Risk Factors for Death of Elderly People Living at Home. *European Journal of Public Health* 16: 583-591, 2006.

25. **McDermott-Levy R, and Fick DM**. Advancing Gerontological Nursing Science in Climate Change. *Research in Gerontological Nursing* 13: 6-12, 2020.

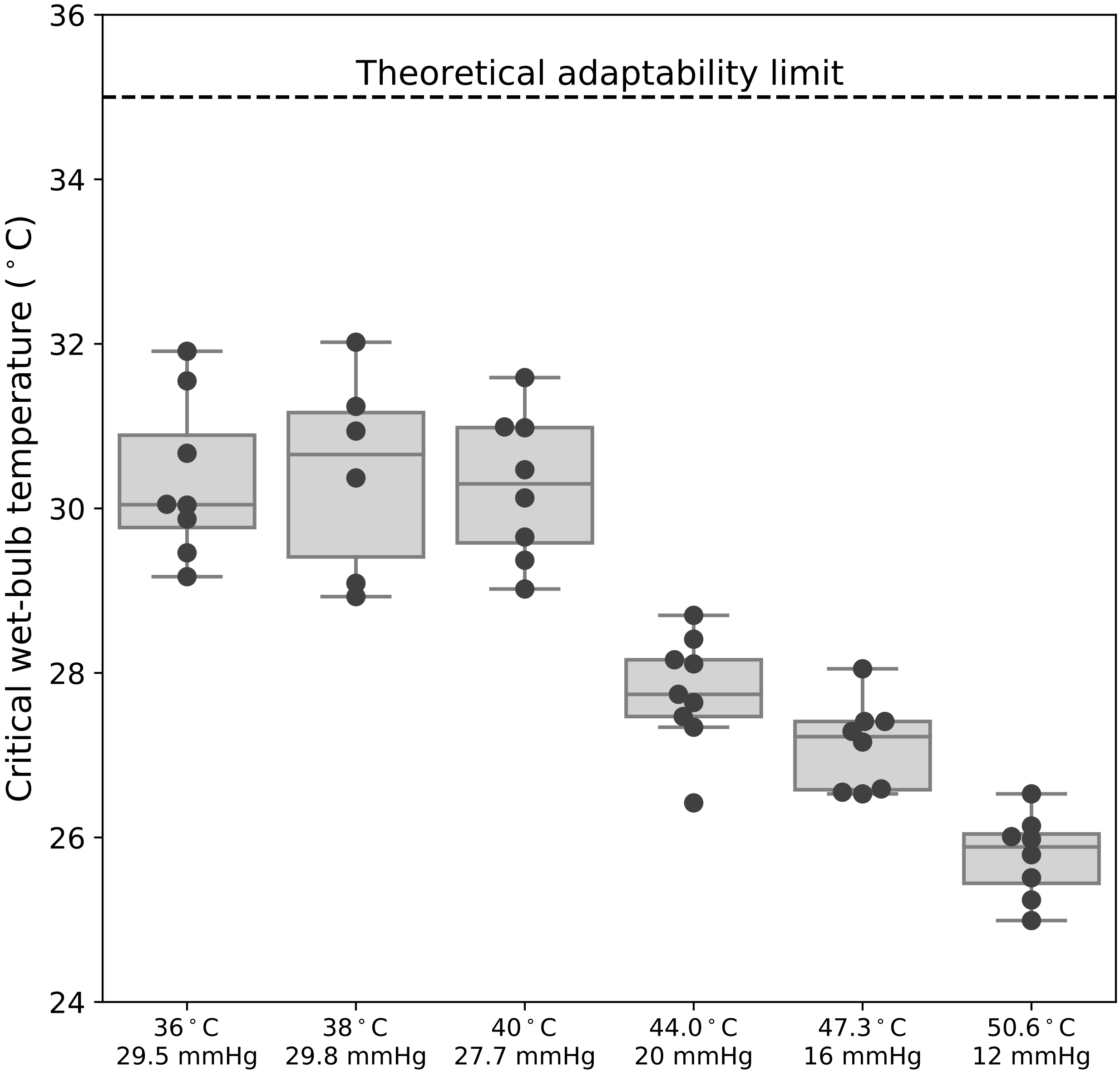
26. **Vecellio DJ, Bardenhagen EK, Lerman B, and Brown RD**. The role of outdoor microclimatic features at long-term care facilities in advancing the health of its residents: An integrative review and future strategies. *Environmental Research* 201: 111583, 2021.

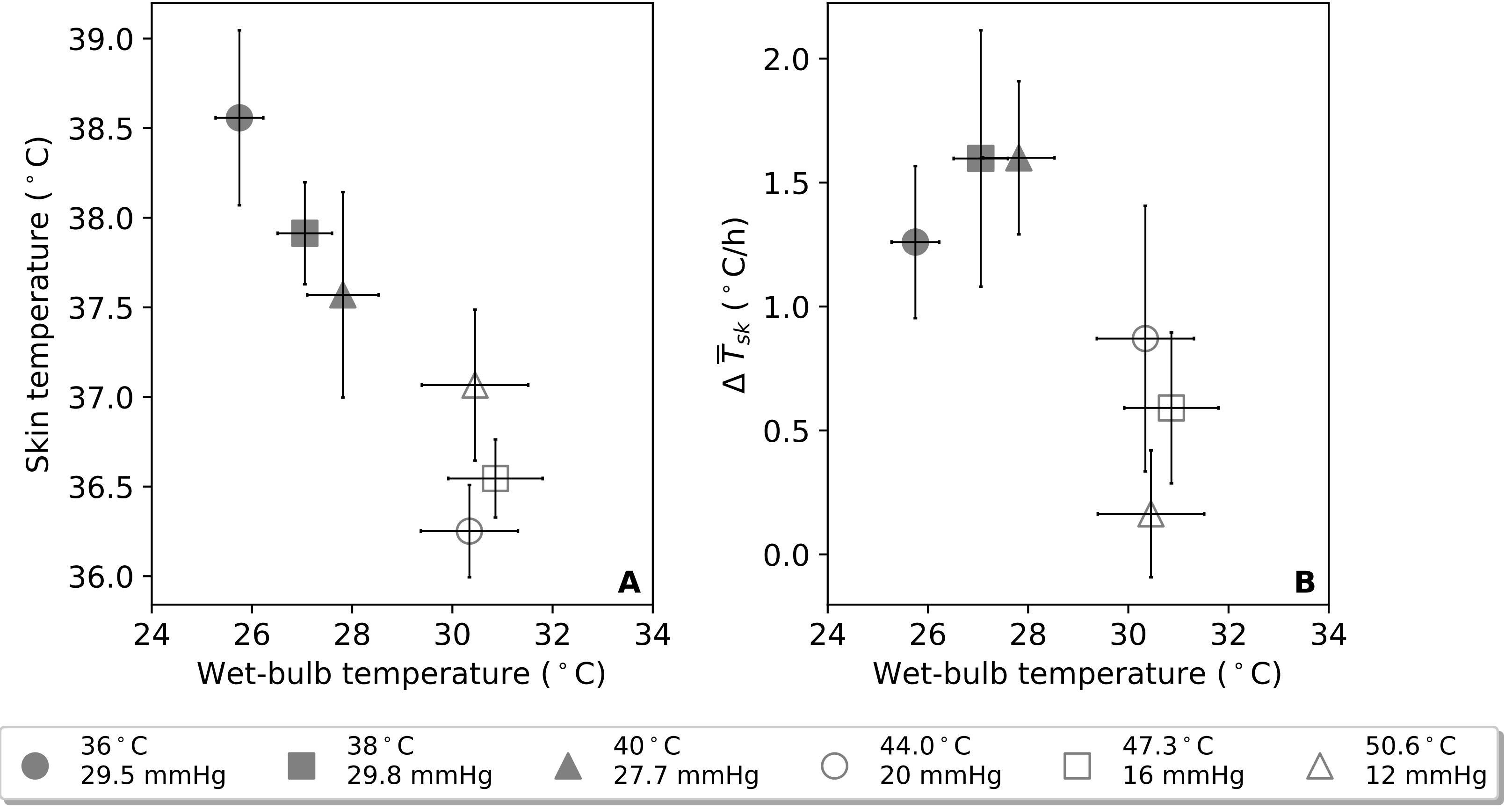
27. **Köppen W**. Die Wärmezonen der Erde, nach der Dauer der heissen, gemässigten und kalten Zeit und nach der Wirkung der Wärme auf die organische Welt betrachtet. *Meteorologische Zeitschrift* 1: 5-226, 1884.

## Figure Captions

**Figure 1.** Critical wet-bulb temperature values for the study's six experimental protocols.

**Figure 2.** Relation between critical wet-bulb temperature and (a) mean skin surface temperature and (b) rate of change in mean skin surface temperature for the six experimental protocols.


Theoretical adaptability limit
Critical wet-bulb temperature (°C)
36
34
32
30
28
26
24
36 °C
29.5 mmHg
38 °C
29.8 mmHg
40 °C
27.7 mmHg
44.0 °C
20 mmHg
47.3 °C
16 mmHg
50.6 °C
12 mmHg



Skin temperature ( °C)
39.0
38.5
38.0
37.5
37.0
36.5
36.0
24
26
28
30
32
34
Wet-bulb temperature ( °C)
A
$\Delta\,\overline{T}_{sk}$ ( °C/h)
2.0
1.5
1.0
0.5
0.0
24
26
28
30
32
34
Wet-bulb temperature ( °C)
B
● 36 °C 29.5 mmHg
■ 38 °C 29.8 mmHg
▲ 40 °C 27.7 mmHg
○ 44.0 °C 20 mmHg
□ 47.3 °C 16 mmHg
△ 50.6 °C 12 mmHg

**Table 1.** Experimental subject characteristics. (24 subjects; 11 male/13 female)

| **Characteristic** | **Mean ± SD** | **Range** |
|---|---|---|
| **Age (yr)** | 24 ± 4 | 18 - 34 |
| **Height (m)** | 1.73 ± 0.1 | 1.57 – 1.98 |
| **Weight ($kg{\cdot}m^{-2}$)** | 71 ± 12 | 52 - 98 |
| **$A_D$ ($m^2$)** | 1.84 ± 0.20 | 1.50 – 2.31 |
| **$A_D{\cdot}kg^{-1}$ ($m^2{\cdot}kg^{-1}$)** | 0.026 ± 0.002 | 0.022 – 0.029 |
| **$\dot{V}O_{2max}$ ($ml{\cdot}kg^{-1}{\cdot}min^{-1}$)** | 49 ± 12 | 30 - 79 |

**Table 2.** Critical environmental limits for the study's six experimental protocols. Values are presented as mean ± standard deviation. Mean $T_{crit}$ values all are statistically different from one another while no statistical differences are present amongst the mean $P_{crit}$ values. *Differences existed between all mean RH values except for between the 36°C and 38°C experimental protocols ($p = 0.08$).

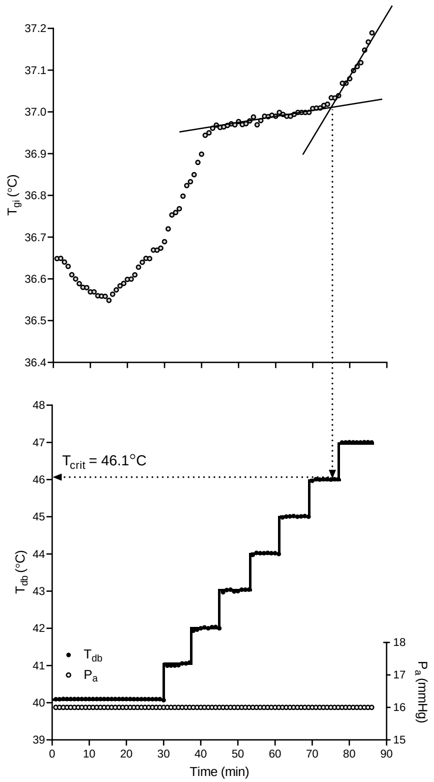
| ***Protocol:*** | ***36°C*** | ***38°C*** | ***40°C*** | ***20 mmHg*** | ***16 mmHg*** | ***12 mmHg*** |
|---|---|---|---|---|---|---|
| *# of participants* | 8 (3M/5F) | 8 (5M/3F) | 8 (3M/5F) | 8 (6M/2F) | 9 (4M/5F) | 9 (4M/5F) |
| $T_{crit}$ *(°C)* | | | | 44.04 ± 0.23 | 47.48 ± 2.02 | 50.57 ± 1.65 |
| $P_{crit}$ *(mmHg)* | 29.54 ± 2.37 | 30.03 ± 2.40 | 27.74 ± 2.52 | | | |
| *RH (%)* | 66.25 ± 5.72* | 60.83 ± 5.40* | 50.24 ± 4.58 | 28.81 ± 2.70 | 20.14 ± 1.56 | 12.70 ± 1.50 |

**Table 3.** Summary table of dry heat gain (via convection and radiation) and sweat rate for the study's six experimental protocols. Values are presented as mean ± standard deviation. *Differences existed between all mean dry heat gain values except for between the 12 mmHg and 16 mmHg experimental protocols (p = 0.01). There was no statistical difference in mean sweat rates across conditions.

| | ***36°C*** | ***38°C*** | ***40°C*** | ***44.0°C*** | ***47.3°C*** | ***50.6°C*** |
|---|---|---|---|---|---|---|
| | ***29.5 mm Hg*** | ***29.8 mm Hg*** | ***27.7 mm Hg*** | ***20 mmHg*** | ***16 mmHg*** | ***12 mmHg*** |
| *Dry heat gain (W $m^{-2}$)* | -1.51 ± 3.00 | 8.34 ± 1.72 | 18.60 ± 2.78 | 41.46 ± 9.67 | 61.38 ± 10.91* | 76.95 ± 11.43* |
| *Sweat rate (g $m^{-2}$ $h^{-1}$)* | 97.61 ± 65.33 | 183.14 ± 113.42 | 159.87 ± 63.91 | 111.98 ± 35.59 | 142.98 ± 66.20 | 171.82 ± 98.25 |

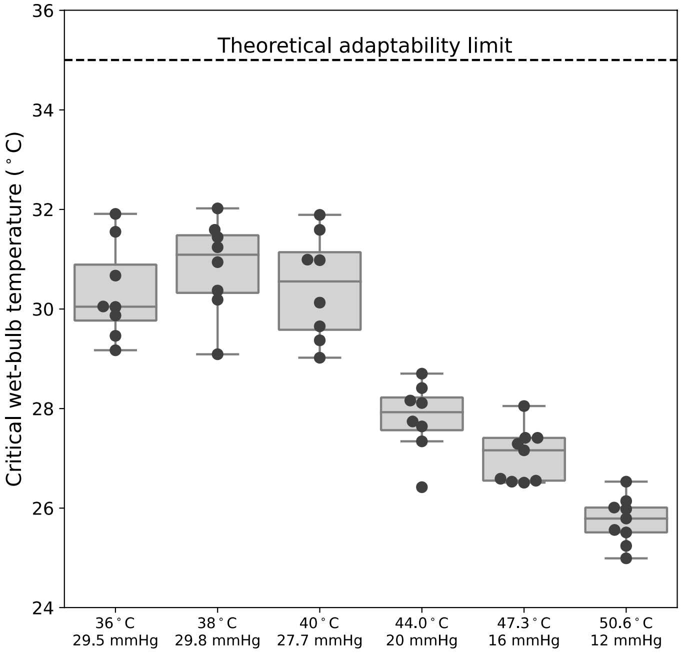
# Evaluating the 35°C wet-bulb temperature adaptability threshold for young, healthy subjects (PSU HEAT)

## METHODS



Representative tracing of chamber and subject data.

## OUTCOME



Critical wet-bulb temperature values for the study’s six experimental protocols.

**CONCLUSION: Critical wet-bulb temperatures in both hot-dry and warm-humid environments all are significantly less than the literature’s theorized 35°C threshold for human adaptability to extreme heat.**