It's Not the Humidity, It's the Heat!

Don't blame 'corn sweat' for sweltering summer conditions in the Midwest

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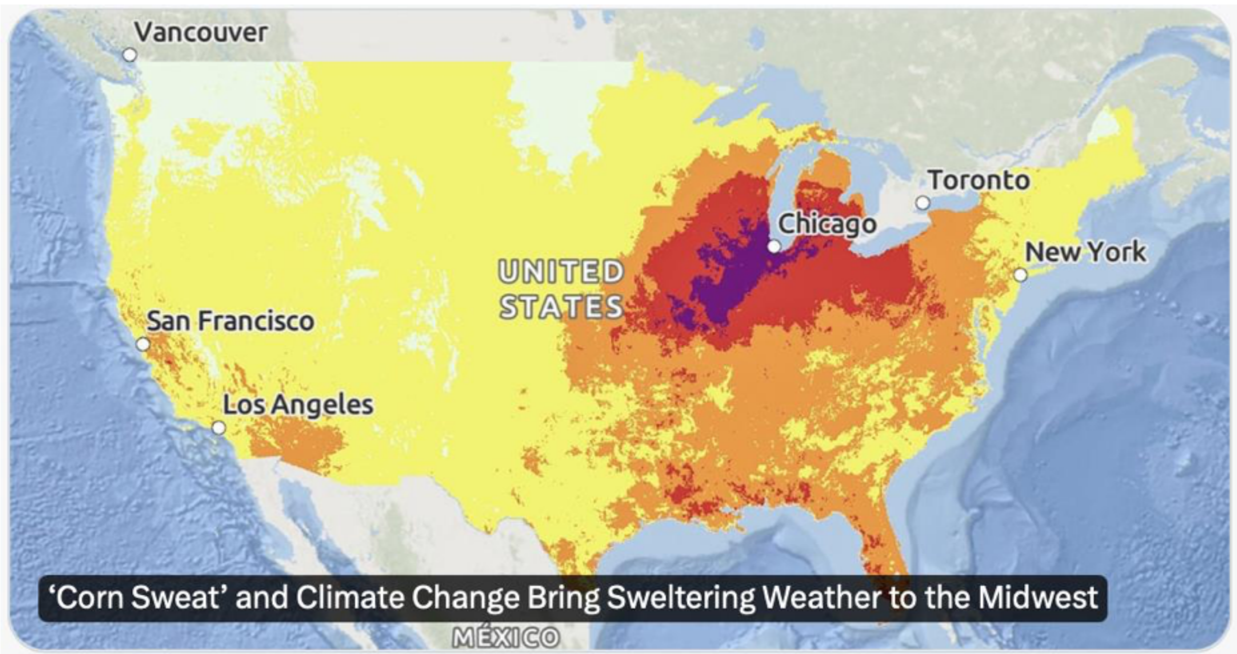
Something named 'corn sweat' was big in the news this summer, allegedly contributing to the sweltering conditions in the Midwest. But the allegation is 100% flawed, as it completely ignores the beneficial (from a comfort perspective) effect of evaporative cooling. Yes, thick forests would have more of such a cooling effect, but that won't happen anytime soon, and corn cools more than the other crops or alternative rural land-uses possible across the Midwest. It was very disappointing to see such 'junk science' even show up in *Scientific American*! It was after I saw this prestigious publication join in the nonsense that I launched a brief effort to set the record straight.

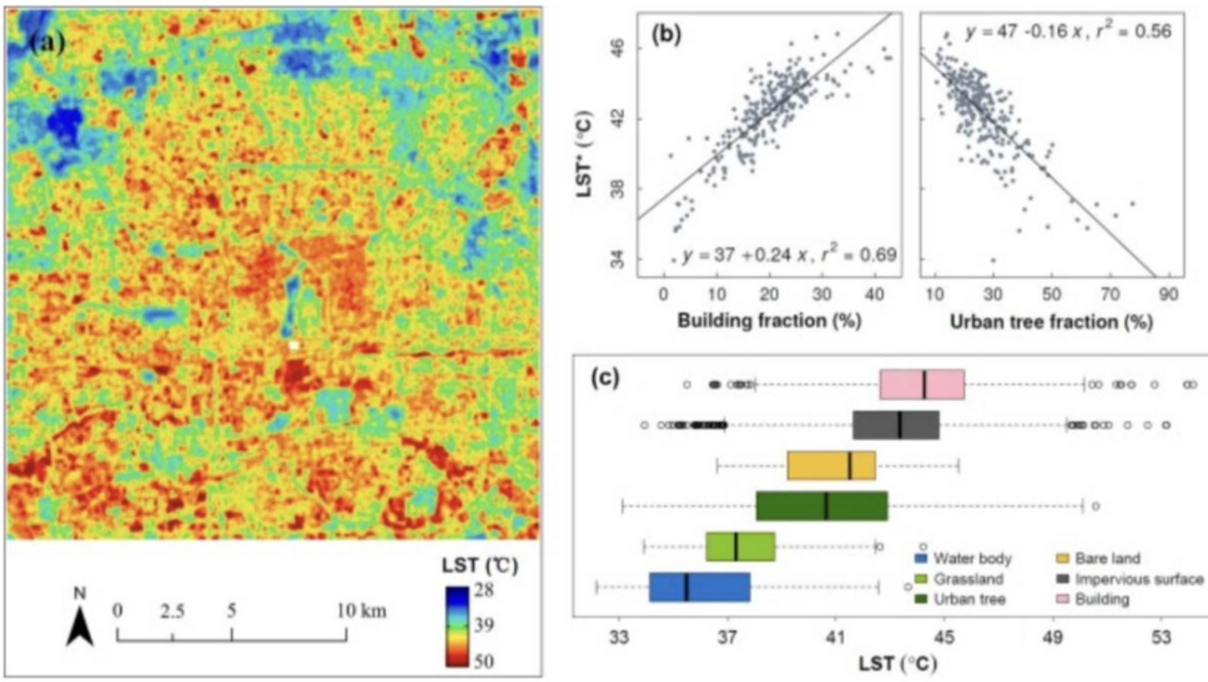


From scientificamerican.com

Debunking the idea that 'corn sweat' is making the Midwest more uncomfortable is just Thermodynamics 101. I realize not many folks took or remember that class. At Stanford, it was used to weed out wannabe pre-med's, but I took several classes in the topic there and at the University of Washington on my way to B.S. and Ph.D. degrees in Chemical Engineering.[1] Evaporative cooling is fundamental to many processes used by chemical engineers. The molecular phenomenon involved in such cooling is relatively simple to understand, based on the first Law of Thermodynamics: conservation of energy. As liquid molecules escape a fluid to enter a gaseous phase, they suddenly acquire a tremendous increase in velocity. This gain in kinetic energy must come from somewhere, and the liquid experiences a commensurate loss in thermal energy – i.e. it's temperature falls.

[1] More recently, I've found inspiration to "stay sharp" on this topic by joining a monthly Feynman Lectures Zoom discussion group. Our session last night was actually on this very topic! See Chapter 45, Volume 1.

Now the incremental amount of temperature loss associated with the evaporation of a single molecule of water is vanishing small, but once we start talking about the amount of water evaporating from an acre of actively growing corn (perhaps 4000 gallons per acre per day or even more), then that becomes a lot of measurable cooling. And it turns out that this cooling has a MUCH greater impact on the comfort level of our Midwestern cities than the relatively small contribution that this moisture contributes to overall humidity levels. More details are given below on those calculations (it turns out they're complicated), but first, let's consider this graphic recently published in a peer-reviewed scientific journal (Zhao et al., 2020).



At the upper left is a "heat map" of Beijing. As is normally the case in such maps, blue is cool and red is hot. Unsurprisingly to anyone who has walked around such a city, the hottest parts are near buildings and the coolest areas are water bodies, with grasslands and urban trees not far behind. We can immediately see why urban planners are seeking to add greenspaces to cities as a way to help with climate adaptation, thereby making them more comfortable in the face of increasing heat and humidity. Does any of this profoundly obvious evidence square with the idea that corn is somehow making Midwest cities less comfortable? Or course not! The opposite is true. But why?

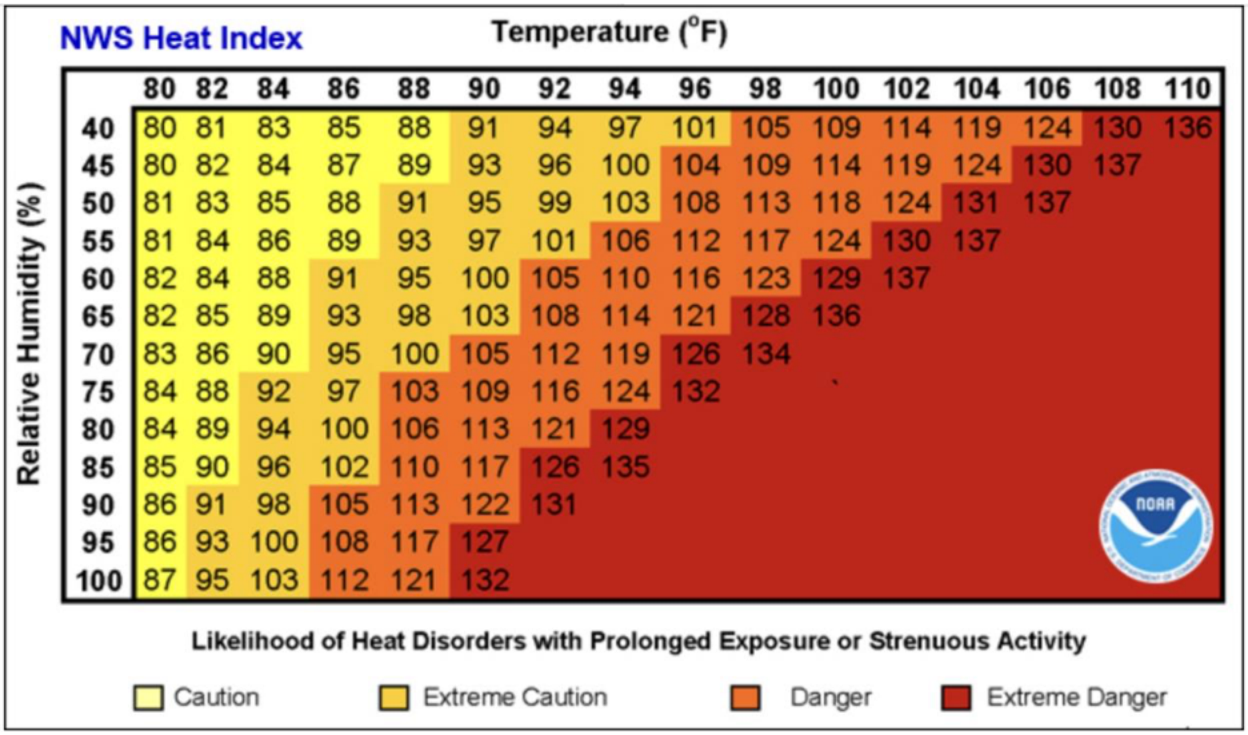
In order to quantify this, we now need to do some calculations on corn and delve into the topic of the Heat Index: how the presence of humidity can give air a so-called "real feel" temperature that is hotter than what is measured by a standard thermometer). There is a ton of detailed literature on this, but in order to keep things as simple as possible, let's adopt the approach used by the US NOAA National Weather Service (NWS). They use the following equation[2] to calculate the Heat Index (see next page):

[2] US NOAA National Weather Service, https://www.wpc.ncep.noaa.gov/html/heatindex_equation.shtml.

$$HI = -42.379 + 2.04901523*T + 10.14333127*RH - .22475541*T*RH - .00683783*T*T - .05481717*RH*RH + .00122874*T*T*RH + .00085282*T*RH*RH - .00000199*T*T*RH*RH$$

> where **T** is temperature in °F and **RH** is relative humidity in percent. **HI** is the heat index expressed as an apparent temperature (°F).

Given that most folks would work up a sweat[3] trying use this equation, the NWS has published the following helpful chart.



NWS Heat Index — Temperature (°F)

Relative Humidity (%)	80	82	84	86	88	90	92	94	96	98	100	102	104	106	108	110
40	80	81	83	85	88	91	94	97	101	105	109	114	119	124	130	136
45	80	82	84	87	89	93	96	100	104	109	114	119	124	130	137	
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Likelihood of Heat Disorders with Prolonged Exposure or Strenuous Activity

Caution — Extreme Caution — Danger — Extreme Danger

So now we finally get to the heart of the matter. How does the presence of transpiring corn on the landscape cause cities to move around on this chart? Does such cooling lower temperatures so much that the increase in relative humidity is insufficient to increase the Heat Index above what it would have been without the corn? Let's do the math and find out.

But first, we need to simplify things, because the actual scenario is incredibly complicated to work out with 100% precision. Let us imagine (see next page) that we have adjacent counties of the same size, one completely urban and the other completely rural – and let us further imagine that the rural county is planted with corn from end to end and that the city/county (perhaps St. Louis?) had ignorant urban planners[4] and there is no actively transpiring greenspace within its boundaries. We imagine both counties to be squares (see Table 1 for the assumed sizes) and that the height of

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[3] Pun intended

[4] This isn't actually true for St. Louis City, thankfully. It has some large parks (esp. Forest Park and Tower Grove Park), as well as the expansive grounds of the Missouri Botanical Garden.

the boxes is not at all to scale, perhaps only 10 m in height, where all of the excess humidity from the corn is forced to remain. That's what we engineers call a "worst case assumption."

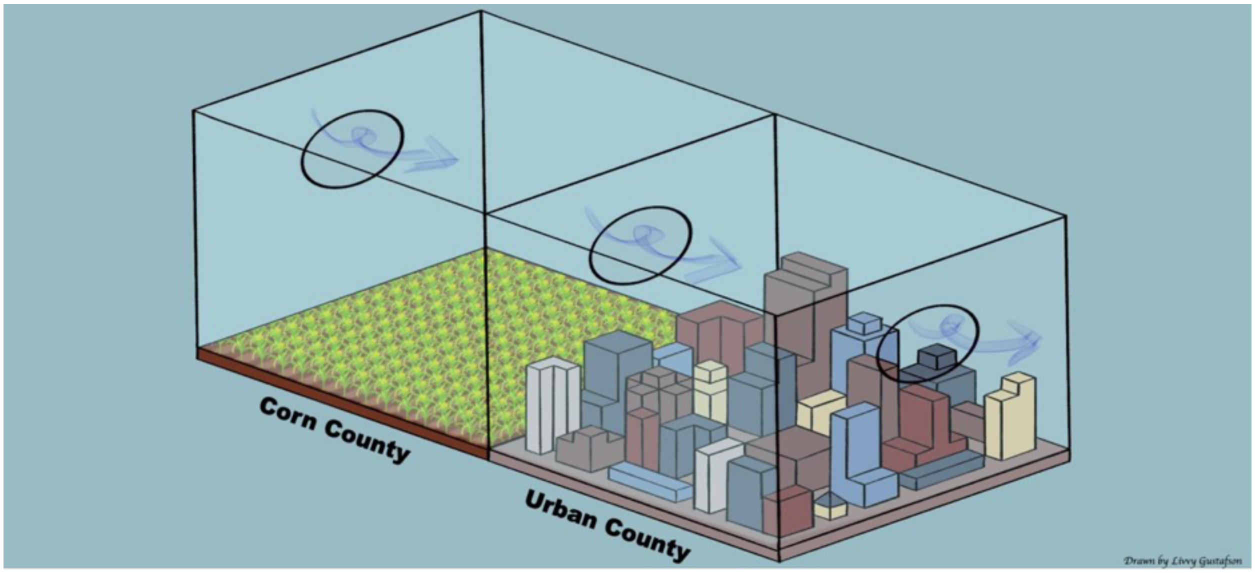
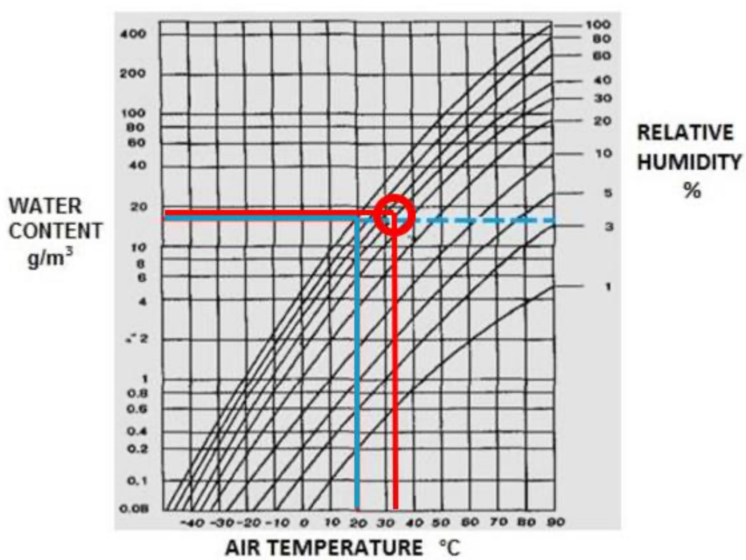


Table 1, which contains all of the numbers and formulas we will use here, is taken directly from a simple Excel worksheet that I'd be happy to share. The first thing we'll estimate is the amount of excess humidity created by the corn. We'll start by assuming that there is no wind, such that all the evaporated moisture hovers in place above the corn county. For the rate of evaporative water loss, we'll use a number even higher than quoted in the news articles: 10,000 gallons per acre per day. It's not just a matter of unit conversion to get this into an atmospheric concentration, because the density of moist air is a strong function of the both temperature and relative humidity, as shown in the chart at the right. So we need to assume some nominal atmospheric starting conditions in order to begin. Let's say it's a sunny, warm, and fairly humid day, 90°F with 50% relative humidity. According to the chart at the right (focus on the red markings, please ignore the blue!), this corresponds to a nominal water content of around 18 g/m^3, as listed in Table 1 (albeit with different units). There is a helpful online tool[5] that calculates the overall density of the air (i.e., by including the other gases, which are mostly nitrogen and oxygen). That tool gives us the overall air density listed in Table 1: 1.145531 kg/m^3.



[5] https://www.omnicalculator.com/physics/air-density

Table 1. Summary of Assumptions and Calculations

IL state area	57,915	sq mi	
Number of IL counties	102		
IL county size	567.79	sq miles	IL average
IL width	23.83	miles	assume a square
	38.35	km	
Mixing Height	0.01	km	
Max ET	10,000	gal/acre/day	
	9.4	mm/day	Reality check
	37.85	m^3/acre/day	
County H_2O (liquid)	13,755,735	kg/day	
H_2O Vap Density (increase)	0.0009354	kg/m^3	
Air Density (90°F, 50% RH)	1.145531	kg/m^3	Omni Calculator
Nominal H_2O content	0.018	kg/m^3	From chart on page 4 at (90°F, 50% RH)
Percent Increase in RH	5.20%		as a percentage of 50%(!)
Final RH	52.60%		
Evaporative Cooling	80,000,000	BTU/acre/day	
Above ground biomass	10	tons/acre	
Soil depth being cooled	1.00	m	
Mass of soil being cooled	5,858	tons/acre	
Mass of air being cooled	0.01	tons/acre	
Cooling of Soil+Corn+Air	6.82	°F	assumes heat capacity of liquid water
Temperature (°F)	**Relative Humidity (RH, %)**	**Heat Index (°F)**	
90	50	94.6	Nominal
83.2	52.6	84.6	Max cooling effect in the corn county
86.6	51.3	89.2	After complete mixing of adjacent counties

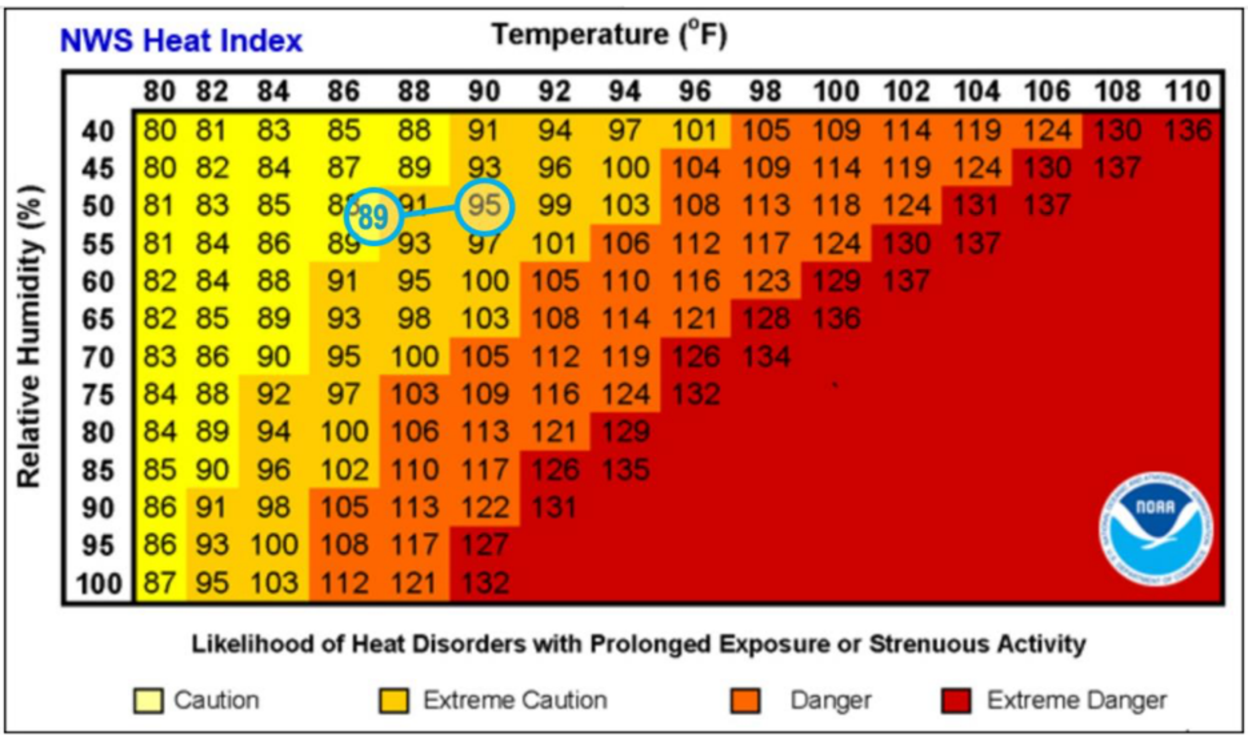
Given all of these numbers it is now possible to directly calculate the increase in relative humidity that is associated with the 10,000 gallons evaporating per day. As indicated in Table 1, the new relative humidity is indeed higher, but only by a little bit – it is now 52.6%. But the tougher thing to calculate is how much the corn-soil-air system in the corn county has cooled.

For this, we must convert the energy loss associated with evaporating all that water (roughly 8000 BTU per gallon) into a temperature drop for the substance being cooled. But what is the object that is actually being cooled? That’s not so simple. There are multiple empirical observations in the literature saying that the drop is likely to be in the range 5-10°F above the corn canopy, under the kind of “worst case” evaporation rate assumption that we have made. As shown in Table 1, most of the mass that is actually being cooled is the soil. The above-ground biomass and air are therefore relatively less important, so what matters is how deep the soil profile is cooled. In order to make the numbers work out close to empirical observations, we are forced to assume (as indicated in Table 1) a soil depth of 1 m (which seems quite high). Regardless, it gives us a reasonable number to work with.

So, as shown at the bottom of Table 1, we simply plug the new temperature and relative humidity into the NWS equation to calculate the experienced Heat Index. Instead of the 94.6°F associated with nominal conditions (90°F, 50% RH), the Heat Index has fallen by 10°F – to 84.6°F. But all of this is just for the corn county, because we made the drastic assumption that there was no wind and therefore no mixing of the corn county's air with the air above the city. The simplest way to relax this assumption is to simply allow complete mixing of the atmospheres above each county, which results in a final Heat Index of 89.2°F – a drop of more than 5°F for the urban county. As shown below, this moves the city from "Extreme Caution" down to the "Caution" category.

We can repeat this analysis for different initial conditions and tweak some of the methodology (e.g., recalculate air densities in an iterative manner, etc.), but this simple analysis gives the answer we expected from our real life experience: the presence of corn (or any actively transpiring vegetation) in the surrounding landscape helps to make things more comfortable in the city – the exact opposite of the allegation in the *Scientific American* article. In fact, the more evapotranspiration that takes place, the greater the beneficial effect on Heat Index. So the overall annualized benefit from corn is greater than other common row crops (like soybeans), although it is true that soybeans generally transpire more than corn during the later portions of the summer.

Note: I've reached out to *Scientific American* urging them to publish a retraction. No response yet, but please stay tuned.


NWS Heat Index

Temperature (°F)

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