U.S. Heatwave Analysis

Exploring Different Parameters to Classify Extreme Heat Events

Literature Review

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Abstract

The purpose of this literature review is to explore some of the different classifications, decisions, and parameters that factor into the definition of heat waves. The study aims to better comprehend the bigger picture of how heatwaves are defined in different scientific, socioeconomic, and geographic scopes. The importance of this understanding is so that people have a better understanding of the origins, the expectation, and the intensity of extreme heat events in a plethora of situations and can therefore be better informed in a warming world where climate change is inevitable.

Acknowledgements

Many thanks to the National Oceanic and Atmospheric Administration (NOAA) for hosting my internship during the Summer of 2016 and giving me the opportunity as an Ernest F. Hollings Scholar to be involved with their many missions, specifically their goal of “Climate Adaptation and Mitigation”. I am grateful for the opportunity to specifically work in the Oceanic and Atmospheric Research Line Office (OAR) within NOAA, the Climate Program Office (CPO) within OAR, and the Research Programs Division (RPD) within CPO to explore the entire system of extreme weather events -- from initial problem to societal outcome and climate effects. Through working with the wonderful people at NOAA, I have not only been able to obtain knowledge about extreme heat events but also gain invaluable insight on the importance of this climate work and connectivity of this information with the public. Special thanks to my mentors Hunter Jones and Juli Trtanj for involving me with the National Integrated Heat Health Information System (NIHHIS) project and acquainting me with the integrated information systems approach to extreme weather events.

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Introduction

While there no universal definition of a heat wave, research shows that extreme heat events characterized by high temperatures accompanied by humidity and intense durations have been linked to high mortality rates and notable impacts on regional economies and ecosystems (Meel et. al, 2004). In the future, these extreme heat events are expected to worsen as the intensity, frequency, and duration of heat waves increases (Meel et. al, 2004).

Importance of Understanding Heat Waves

It is important to understand heat waves because they are a part of a bigger meteorological feedback loop that affects many other extreme weather events such as drought and wildfires. In the case where humidity is not accompanied, the absence of water exacerbates the heat wave, as there is no surface water to act as an evaporative cooler ("Heat Waves and Wildfires" 2016). This causes wilted crops, lack of water supply, and other destroyed ecosystems that human societies and economies require. Heat waves also promote heat exhaustion on the human body, which bring symptoms such as headaches, fainting, hyperthermia, and heat stroke. While extreme heat only causes an average of 688 deaths per year in the US according to the Centers for Disease Control and Prevention (Harmon, 2010), heat-related illnesses such as organ damage results in more deaths than any other natural disaster (EPA 2014). Heat waves are destructive to the environment and human body both directly and indirectly; thus, it is meaningful to further our knowledge about them.

Current Understanding of Heat Waves

While heat is the leading cause of weather-related deaths in the United States, most of those deaths are avoidable through intervention and outreach (EPA 2014). The number of abnormally hot summers in the last decade have increased in frequency in the 48 contiguous states and the number of heat-related deaths are expected to increase because of this (EPA 2014). Vulnerable populations such as the elderly, young children, and people with cardiovascular and respiratory illnesses (EPA 2014). Research shows that deaths related to extremely cold weather events may decrease or stay the same as the climate warms, but these are likely to be substantially less than the number of deaths expected from increase in heat-related deaths (EPA 2014).

Expected Heat Wave Patterns for the Future

While Earth has gone through phases of warming and cooling through various ice ages without the aid of humanity, our current global warming situation is warming much more rapidly than past global warming events. When Earth moved out of ice ages over the past few million years, it took approximately 5,000 years for the temperature to increase 4 to 7 degrees Celsius (NASA Earth Observatory). However, in the past century alone, our global temperature has risen 0.7 degrees Celsius, indicating a rate that is at least 20 times faster than what Earth is used to seeing (NASA Earth Observatory). This rate of change is very unusual. Figure 1 from Mann et al., 2008 shows the projected global temperature change (NASA Earth Observatory).

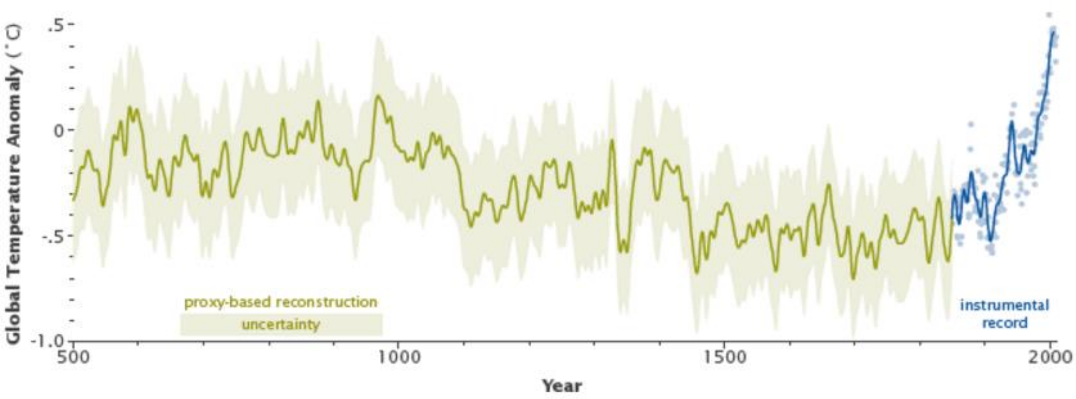


Figure 1. The green line depicts temperature histories from paleoclimate data and the blue line indicates present day warmer temperature increases.

In a paper published in Environmental Research Letters, future scenarios where humans continue to rely heavily on fossil fuels (IPCC scenario RCP8.5) and where humans transition away from fossil fuels (IPCC scenario RCP2.6) were compared (Nuccitelli, 2013). In both cases, the land area experiencing extreme heat will quadruple by 2040 due to greenhouse gases already emitted thus far (Nuccitelli, 2013). However, in the RCP2.6 scenario, extreme heat tends to stabilize after 2040 where in the RCP8.5 scenario, these high temperatures become the new norm (Nuccitelli, 2013).

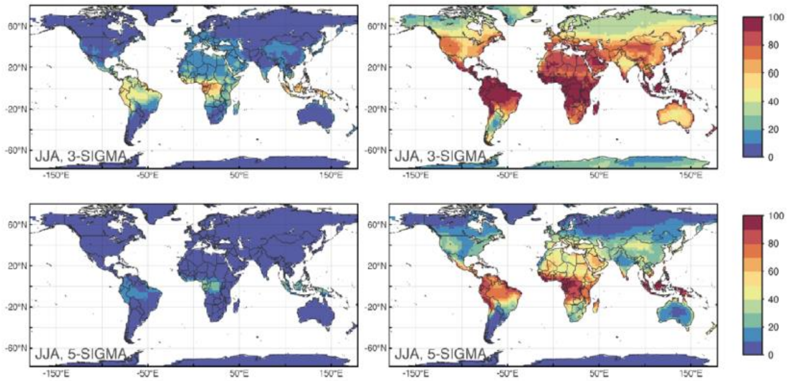


Figure 2. “Multi-model mean of the percentage of boreal summer months in the time period 2071-2099 with temperatures beyond 3-sigma (top) and 5-sigma (bottom) under low emissions scenario RCP2.6 (left) and high emissions RCP8.5 (right)” (Nuccitelli, 2013).

Classification Schemes in Different Parts of the World

Europe

Table 1 shows various European countries’ level, trigger indicator, threshold trigger, and lead time for heatwave classification (Lowe et al., 2011). Some countries have simple classification schemes while others have more elaborate classification schemes.

Country	**Level**	**Trigger Indicator**	**Threshold trigger**	**Lead time**
Belgium	National	Tmax, Tmin	3 day mean Tmax >= 30 degrees Celsius	**3 days**
France	National & Regional Plans	Tmax, Tmin, HSI*	3 days mean of Tmax > regionally dependent thresholds and 3 days mean of Tmin > regionally dependent thresholds HSI risk: 27 degrees Celsius High risk: 32 degrees Celsius Danger: 41 degrees Celsius	5 day forecast, 24 hour alert
Germany	National with warnings on county level	PT*, Tmin	Severe heat stress: PT >= 32 degrees Celsius (exact threshold depends on weather situation of last 30 days	48 hour

			but does not exceed 34 degrees Celsius) Extreme heat stress: PT >= 38 degrees Celsius Warnings if thresholds are exceeded for 2 consecutive days and Tmin (night between) > 16-18 degrees Celsius	
Hungary	National with local monitoring	Tavg	3 day Tavg > 26.6 degrees Celsius	10 day forecast, 3 day heatwave alert
Italy	National and local	Tapp max*	3 days Tapp max thresholds (increasing monthly) range: 25.5 °C to 37.5 °C for 10–20% excess mortality & for >20% excess mortality range: 27.5 °C to 39.5 °C. Airmass models: Excess mortality in 65+ population (%): Dry Tropical (DT): 7% to 20% Moist Tropical plus (MT+): 15% to 46% Moist Tropical (MT): 4% to 8.6%	Up to 72 hours in advance in 27 cities
The Former Yugoslav Republic of Macedonia	National with 6 regional thresholds	Tmax	Specifies Tmax specific monthly trigger threshold for each of the 4 phases for 13 cities in 6 regions from May to Sept	2 day forecast; 24 hr alert
Netherlands	National	Tmax	5+ days above 27 °C	At least 24 hours
Portugal	National with regional thresholds	Tmax, Tmin, regional Tmax, ICARUS index*, HSI, data considered	6 day Tmax >5 °C higher than Tmax mean of 1961–1990 period; Yellow alert: Icarus 0.01 to 0.99, or 1 day observed Tmax + 2 days forecasted Tmax May-Sept ≥ 32 °C and <35 °C; Tmax all regions; ≥35 °C to <38 °C July-Sept Alentejo only, or Tmin: May-Sept ≤24 °C & <26 °C (all	Daily 3 day forecast

			regions) 2 days Tmin observed & > 2 days Tmin expected. Red alert is triggered if the indices > yellow alert.	
Romania	National	Tmax	Alert: Tmax 35–38 °C; Maximum response: Tmax 35–40 °C	48 hours
Spain	National with thresholds for each province	Tmax, Tmin	Tmax and Tmin (simultaneously) >95% of the past series (sic, 'historical series') for the next 5 days Some exceptions for some regions (*i.e.*, coastal northern region	5 days The level is assigned depending on the number of forecasted days exceeding the threshold Level 0: 0/5 Level 1: 1–2/5 Level 2: 3–4/5 Level 3: 5/5
UK	National with regional thresholds	Tmin, Tmax	Level 2 alert: 60% chance of trigger; Temp ≥ 30 °C by day & 15 °C overnight for 2 days and night b/n (range of regional Temps specified). Level 3 alert: heatwave conditions met in 1 or more regions.	Level 2: 2–3 days Level 3: 1 day of threshold conditions met and next day forecast meets threshold
Switzerland	National with 3 regional plans	HI	NOAA's Heat Index threshold: 90 as a max daily value—which equals an air temperature of 32 °C at a humidity of 40%.	The next day

*HSI = heat stress index - intensity and duration of heatwave, air humidity, air pollution), PT = perceived temperature, Tapp max = maximum temperature apparent (air mass, humidity), ICARUS index = predicts effects of heatwaves on mortality, HI = NOAA's heat index threshold

Table 1. European countries' level, trigger indicator, threshold trigger, and lead time for heatwave classification.

The elderly and low socioeconomic populations are especially at risk for heat stress and stroke. The French action plan provides brochures tailored to each vulnerable population (athletes through sports groups and centers and children through schools, for example) because they are more effective than blanket statements (Lowe 2011). Additionally, the elderly and those of lower socioeconomic rank are typically much more illiterate than the general population. Research has shown that a combination of both text and visuals is more effective in getting the point across as opposed to one or the other (Lowe 2011).

North America

In Canada, a heat wave is an event where the Tmax is 32 degrees Celsius (89 degrees Fahrenheit) or greater for three or more days (Canadian Geographic Enterprises, 2016).

Australia

The Bureau of Meteorology claims that a heatwave is “three days or more of high maximum and minimum temperatures that is unusual for that location” (Australian Government). Heatwave intensity is a function of the maximum and minimum temperature over a three-day period and also factors in the climatological norm of the specific location as well as the variability of the temperature over the last thirty days (Commonwealth of Australia).

In Adelaide, Australia, a heatwave is five consecutive days at or above 35 degrees Celsius or three consecutive days at or over 40 degrees Celsius. This definition only applies to Adelaide because climatic norms differ across the state (Australian Government, 2010).

While Australia is considered a “hot” country, a heatwave service still needs to be in place because like the US, extreme heat causes the most weather-related deaths in its country. During the 2009 Victorian bushfires, 173 people died in the bushfires and 374 people died in the heatwave preceding the bushfires (Commonwealth of Australia, 2010).

Asia

In China, the China Meteorological Administration has a three-tier colored system for heat waves. Figure 3 shows each of these levels where the first level (depicted in yellow) is issued when the Tmax is more than 35 degrees Celsius for 2 consecutive days, the second level (depicted in orange) is issued when the Tmax is more than 37 degrees Celsius in 24 hours, and the third level (depicted in red) is issued when the Tmax is more than 40 degrees Celsius in 24 hours (China Meteorological Administration, 2011).

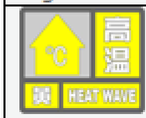
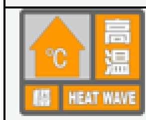
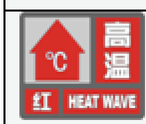
Signal	Meaning	Preventive Measures
	The maximum temperature is more than 35 Celsius degreeper day for 2 consecutive days.	1. Government and related sectors should do preparation work for sunstroke prevention; 2. Reschedule strenuous activities to early morning or evening 3. Provide the guidance of sunstroke prevention to old, weak or young people. 4. Take extra precautions if you work or spend time outside.
	The maximum temperature is more than 37 Celsius degree in 24 hours.	1. Government and related sectors should implement the support measures for sunstroke prevention ; 2. Avoid outdoor activities during heat period. Shorten the continuous working hours if you work outside. 3. Provide the guidance of sunstroke prevention to old, weak or young people and take necessary measures. 4. Related departments should prevent from fire which caused by high electricity consumption, and other too large electrical load.
	The maximum temperature is more than 40 Celsius degree in 24 hours.	1. Government and related sectors should take the emergency measures for sunstroke prevention ; 2. Stop outdoor operation. (In addition to the special industry) 3. Provide the protective measures to old, weak or young people. 4. Related departments should precautions against fire especially.

Figure 3. Heat wave classification scheme in China by the China Meteorological Administration

In Japan, early warning information on extreme weather is issued every Monday and Thursday at 14:30 JST when high probability (30% or more) of very high or very low mean temperature is expected in the next 7 days. This warning is issued 5 to 8 days in advance of the extreme event (Japan Meteorological Agency).

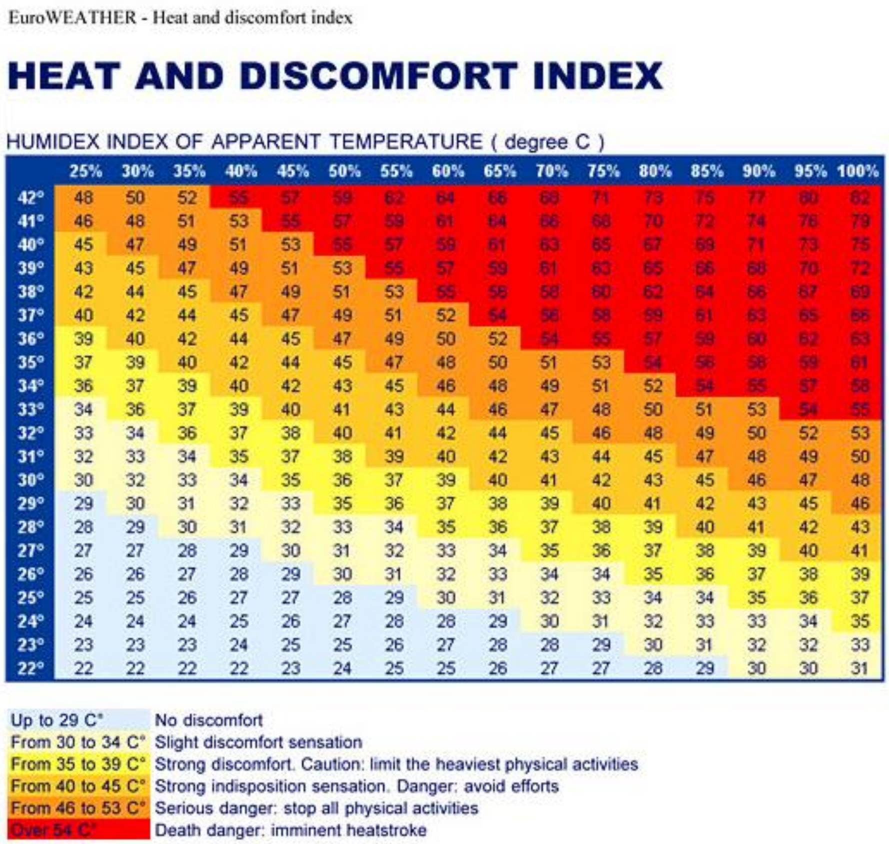
Africa

The South African Weather Service defines a heat wave as three consecutive days where the Tmax is at least five degrees higher than the Tavg of the hottest month. South Africa uses Heat

Index and discomfort index to classify heat waves. Figure 4 displays the Heat Index chart. The Discomfort Index is calculated by:

$$\text{Discomfort Index} = (2 \times T) + (RH/100 \times T) + 24$$

Where T is the air temperature in degrees Celsius and RH is the percentage relative humidity.



	25%	30%	35%	40%	45%	50%	55%	60%	65%	70%	75%	80%	85%	90%	95%	100%
42°	48	50	52	55	57	59	62	64	66	68	71	73	75	77	80	82
41°	46	48	51	53	55	57	59	61	64	66	68	70	72	74	76	79
40°	45	47	49	51	53	55	57	59	61	63	65	67	69	71	73	75
39°	43	45	47	49	51	53	55	57	59	61	63	65	66	68	70	72
38°	42	44	45	47	49	51	53	55	56	58	60	62	64	66	67	69
37°	40	42	44	45	47	49	51	52	54	56	58	59	61	63	65	66
36°	39	40	42	44	45	47	49	50	52	54	55	57	59	60	62	63
35°	37	39	40	42	44	45	47	48	50	51	53	54	56	58	59	61
34°	36	37	39	40	42	43	45	46	48	49	51	52	54	55	57	58
33°	34	36	37	39	40	41	43	44	46	47	48	50	51	53	54	55
32°	33	34	36	37	38	40	41	42	44	45	46	48	49	50	52	53
31°	32	33	34	35	37	38	39	40	42	43	44	45	47	48	49	50
30°	30	32	33	34	35	36	37	39	40	41	42	43	45	46	47	48
29°	29	30	31	32	33	35	36	37	38	39	40	41	42	43	45	46
28°	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43
27°	27	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41
26°	26	26	27	28	29	30	31	32	33	34	34	35	36	37	38	39
25°	25	25	26	27	27	28	29	30	31	32	33	34	34	35	36	37
24°	24	24	24	25	26	27	28	28	29	30	31	32	33	33	34	35
23°	23	23	23	24	25	25	26	27	28	28	29	30	31	32	32	33
22°	22	22	22	22	23	24	25	25	26	27	27	28	29	30	30	31

Up to 29 C°	No discomfort
From 30 to 34 C°	Slight discomfort sensation
From 35 to 39 C°	Strong discomfort. Caution: limit the heaviest physical activities
From 40 to 45 C°	Strong indisposition sensation. Danger: avoid efforts
From 46 to 53 C°	Serious danger: stop all physical activities
Over 54 C°	Death danger: imminent heatstroke

Figure 4. Heat Index is calculated based on humidity and air temperature

Cape Town in South Africa has a Mediterranean-like climate, characterized by cool, wet winters and hot, dry summers. Similar regions are all situated near large bodies of water, which allows the region to have moderate temperatures and relatively small temperature range throughout the seasons because the water provides a cooling effect.

Classification Schemes in Different Parts of the US

NWS issues excessive heat warnings, excessive heat watches, heat advisories, and excessive heat outlooks based on NOAA's heat index, which takes into account temperature and humidity for apparent temperature. However, whether or not heat advisories are issued can vary on local NWS offices based on local conditions.

Excessive Heat Warning issued within 12 hours of the onset of the following criteria:

- Heat index of at least 105 degrees Fahrenheit for more than 3 hours per day for 2 consecutive days
- Heat index more than 115 degrees Fahrenheit for any period of time

Excessive Heat Watches are issued when there is projected to be an excessive heat event in the next 24 to 72 hours. These are issued when there is an increased risk of a heat wave but time of occurrence is unknown.

Heat Advisories are issued within 12 hours of an extremely dangerous heat event.

- 100 degrees Fahrenheit or higher for the next 2 days

Excessive Heat Outlooks are issued when there is a potential for excessive heat in the next 3-7 days.

Southeast

According to NC State University, a heatwaves are "prolonged periods of hot weather, with temperatures at least 9 degrees Fahrenheit greater than the average daily maximum (NC State, 2013). Heat waves are particularly important to understand in this region because agriculture is very prevalent and an accompanying drought will destroy crops and livestock.

In Florida, a heat wave is an extended period of time of uncomfortably hot and unusually humid weather lasting at least a day but conventionally lasting a few days to a few weeks (Florida Division of Emergency Management).

South

Midwestern states tend to classify heatwaves as a duration of two or more days where the temperature is greater than the average temperature for a given location (Midwestern Regional Climate Center, 2016).

Classification Schemes based on Different Heat Metrics

Meteorological Metrics

Temperature metrics including Tmin, Tmax, Tavg, apparent temperature, and heat index (temperature and humidity) are common metrics in determining heat waves (Smith et al., 2012). Other factors such as absolute threshold (Tmax greater than a certain value, for example) versus relative threshold (the 95th percentile) are considerations when classifying extreme heat events (Smith et al., 2012). Furthermore, looking at the duration of the heat wave (one day versus many consecutive days) also plays a role (Smith et al., 2012).

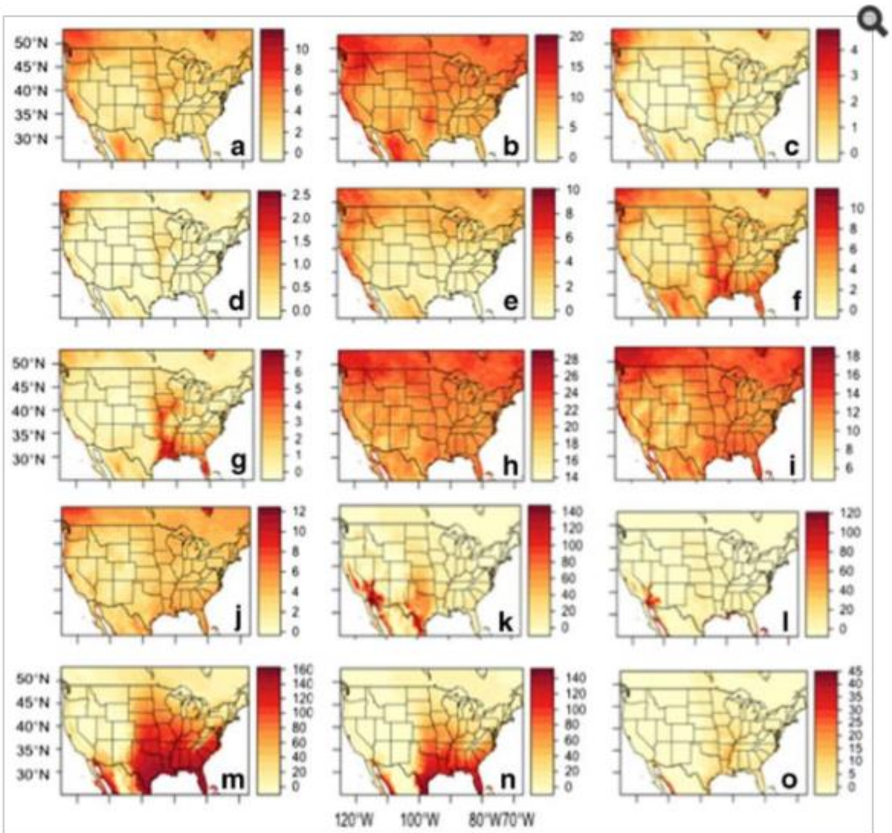
Health Metrics

Health researchers, in contrast, are more interested in the aspects and factors that link directly to human well being in extreme heat events (Smith et al., 2012). These are typically region-specific factors that are linked to morbidity and mortality for vulnerable populations (Smith et al., 2012). These make it possible to customize heatwave definitions for specific geographic locations and are interworked with meteorological metrics to make better decisions about when a heatwave alert needs to go out, based on how it the health indices match up with the heat indices.

Bias

Given the diversity of heat wave experts from meteorologists to health researchers, there usually results in some confusion on climate trends or change based on the different definitions of heat waves given by different stakeholders.

Choosing one metric over the other usually leads to some bias. For example, indices heavily reliant on Tmax will usually outline areas in regions with a hot, dry climate while indices heavily reliant on Tmin will outline areas that are more humid (Smith et al., 2012). It is valuable to define and measure heat waves based on different criteria, but is important to consider the context that they are delivered to avoid jumping to conclusions. Figure 5 shows a study done by Smith et al. in 2012 where 15 different heatwave definitions are plotted to show the annual average number of heatwave days depending on different meteorological metrics. The number of heatwave days for any given region vary depending on the definition.



1979–2011, annual average number of heat wave days. Note the varying scales. Results for HI01–HI15 are shown by **a–o**, respectively

Figure 5. 15 Annual average number of heatwave days based on 15 different heatwave definitions. Data drawn from 1979-2011.

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