Climate Insights

High quality, robust, defensible, actionable, climate physical assessment and risk ranking platform

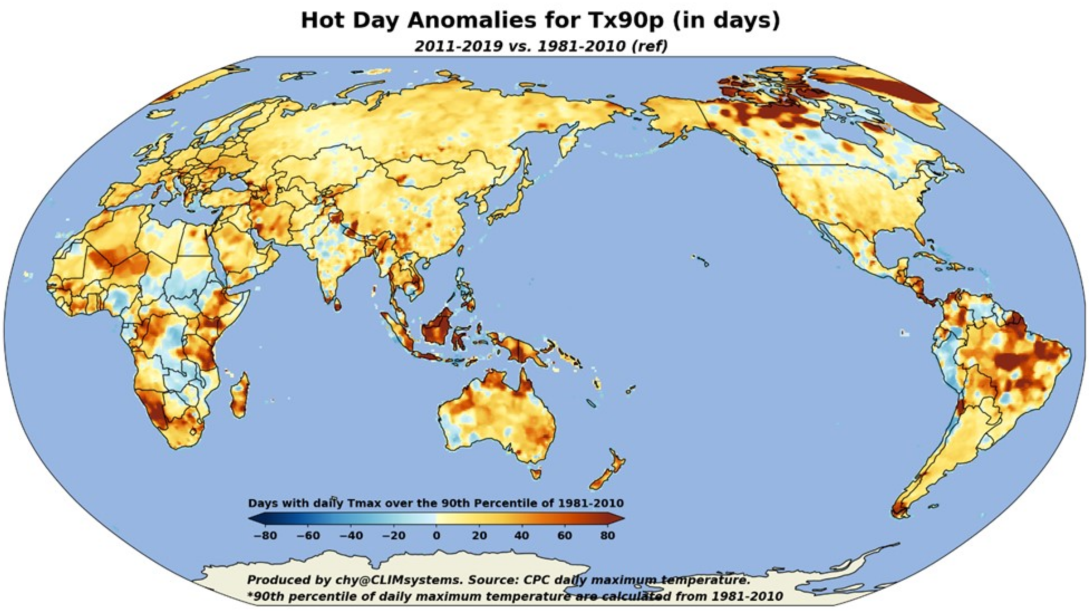
Extreme Temperatures: Hot and Cold Days and Nights and Heat Waves

Introduction

A critical question for climate mitigation and adaptation is to understand when and where the signal of changes to climate extremes have persistently emerged or will emerge from the background noise of climate variability. In fact, we already found observational evidence that such persistent changes to temperature extremes have already occurred over large parts of the Earth (e.g., *Fig.11 - Fig.14).*

Climate Insights focus on four extreme temperature indices, defined by the Expert Team on Climate Change Detection and Indices ("ETCCDI"): the percentages of hot nights (TN90p), hot days (TX90p), cold nights (TN10p) and cold days (TX10p) per year. However, a little bit of adjustment is made that *all percentages are transformed into absolute days*. Another two indices of warm spell duration index (WSDI) and cold spell duration index (CSDI) are also provided as a supplement to TX90p and TN10P, respectively.

Hot days are defined as the number of days over a time period where daily maximum temperature is above the 90th percentile of daily maximum temperatures of a five day window centred on each calendar day of a given 30 year climate reference period (1981-2010). This index corresponds to TX90p. However, the latter is used to describe the frequency of hot days (%). Details are described in Zhang et al. (2005). This climate index is a measure of daytime heat, with high values corresponding to hot conditions. An increase of this index with time means that the chance of hotter conditions will increase.



Hot day changes in latest 9 years compared with the baseline period of 1981-2010

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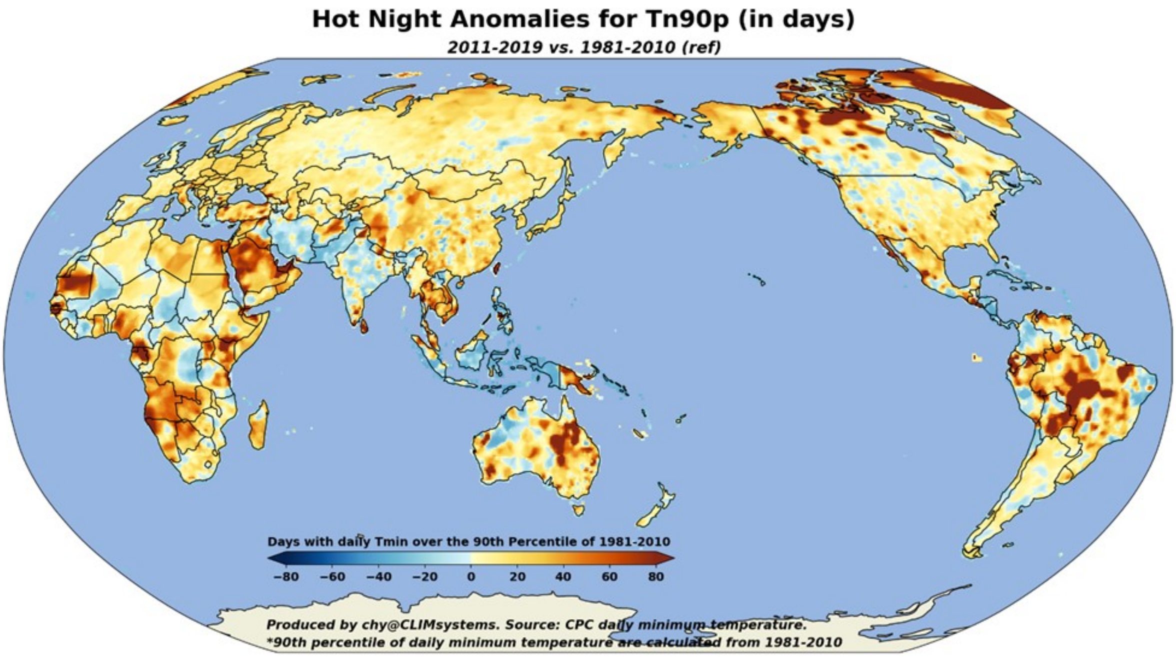

Hot night changes in latest 9 years compared with the baseline period of 1981-2010

Cold nights are defined as the number of days over a time period where daily minimum temperature is below the 10th percentile of daily minimum temperatures of a five day window centred on each calendar day of a given 30 year climate reference period (1981-2010). This index corresponds to TN10p. Details are described in Zhang et al. (2005).

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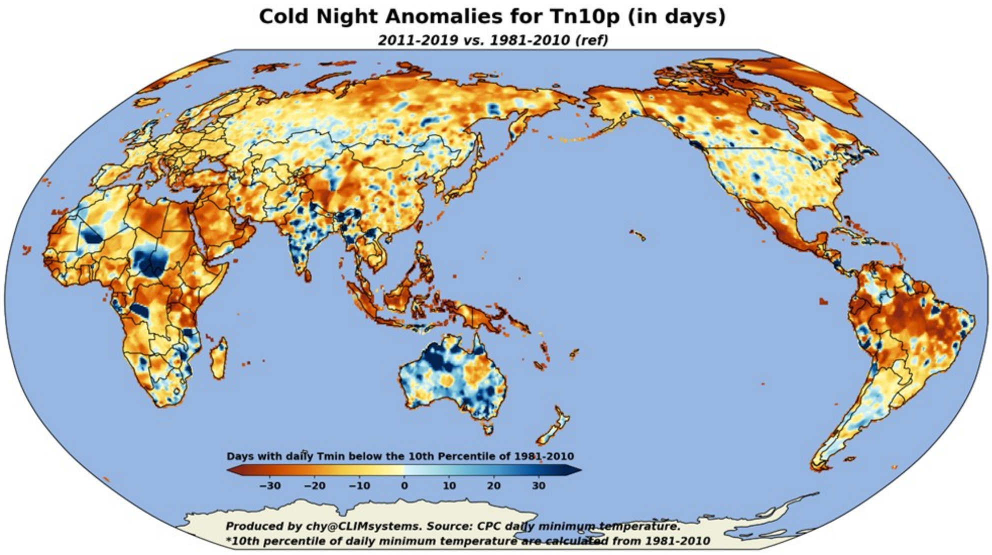

Cold night changes in latest 9 years compared with the baseline period of 1981-2010

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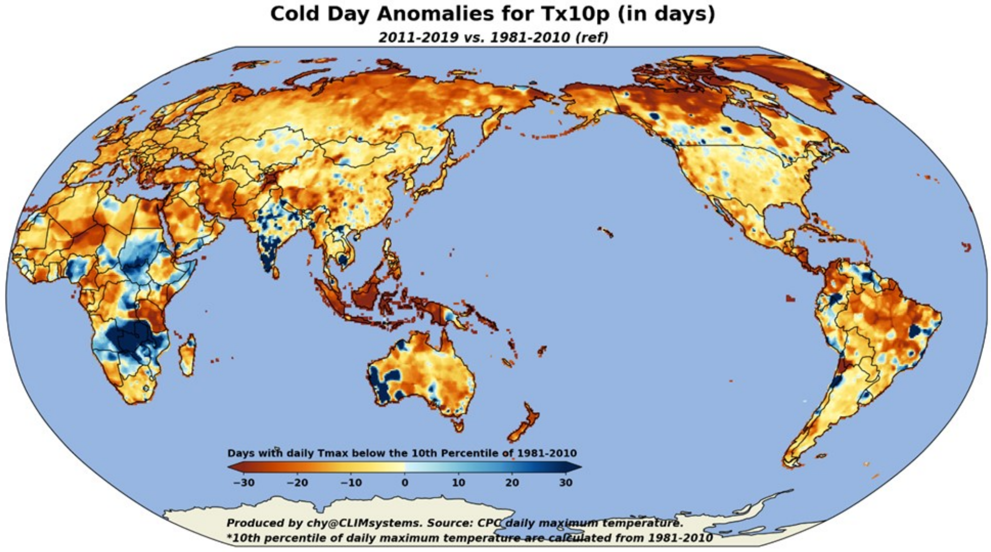
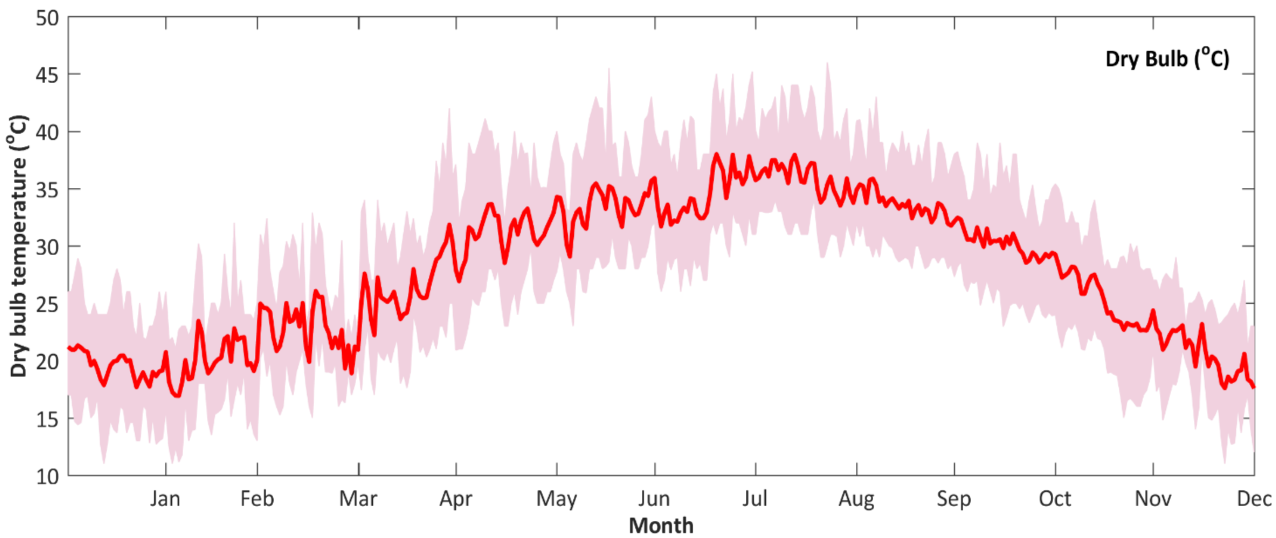


Cold day changes in latest 9 years compared with the baseline period of 1981-2010

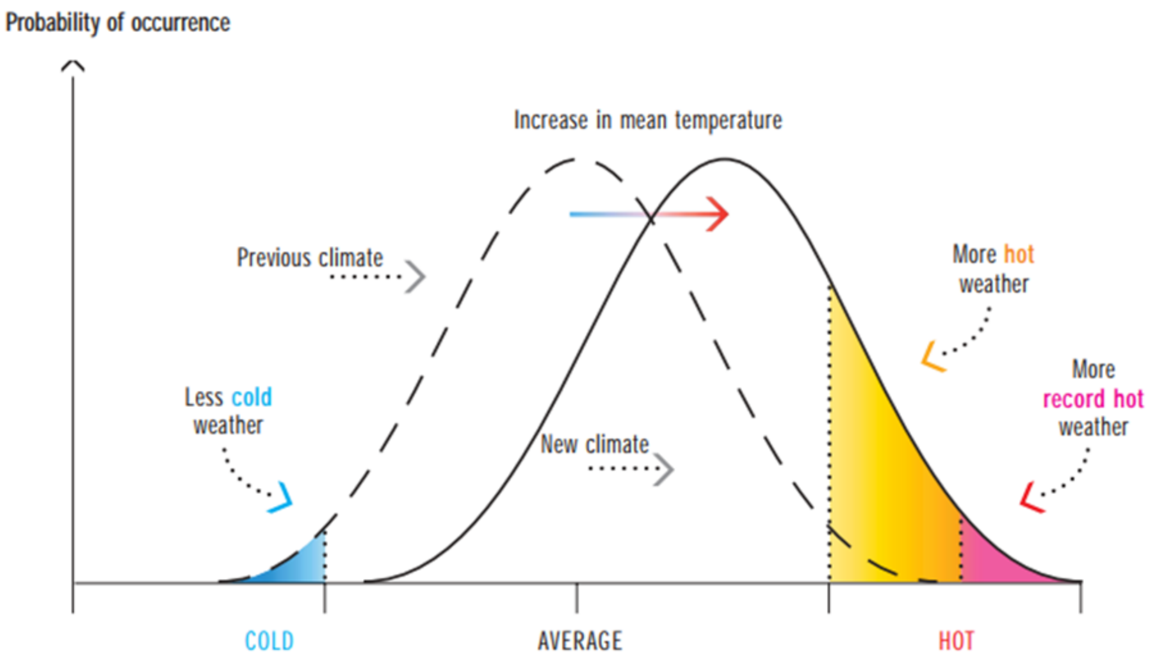
The definitions of these four indices are quite straightforward. However, each of them requires a corresponding daily climatology (i.e., 366 days in total) at a specific percentile (illustrated in *Fig.15*) such as 90% for TX90p and TN90p while 10% for TN10p and TX10p, which is different from other indices using static thresholds such as growing degree day using 4°C as a global threshold for planting (GDD4). At the same time, it makes the calculation procedure more complicated and time-consuming. They are percentile-based indices and offer a robust way to analyse temperature extremes across different climatic zones.



Daily temperature climatology with a 10- 90% percentile bound, red line for the median

Due to using the 10th or 90th percentiles as thresholds, the hot/cold days/nights should be about 36.5 days on average for the baseline period (1981-2010), during which the corresponding daily percentile climatology is calculated. However, the hot days/nights could increase, while cold nights/days would decrease, with climate change, even if the statistical distribution of such events remains the same, a shift in the mean will entail a nonlinear response in the frequency of extreme events.

Extreme Temperatures: Hot and Cold Days and Nights and Heat Waves



Changes in the probability of extreme temperature events (after Houghton et al., 2001)

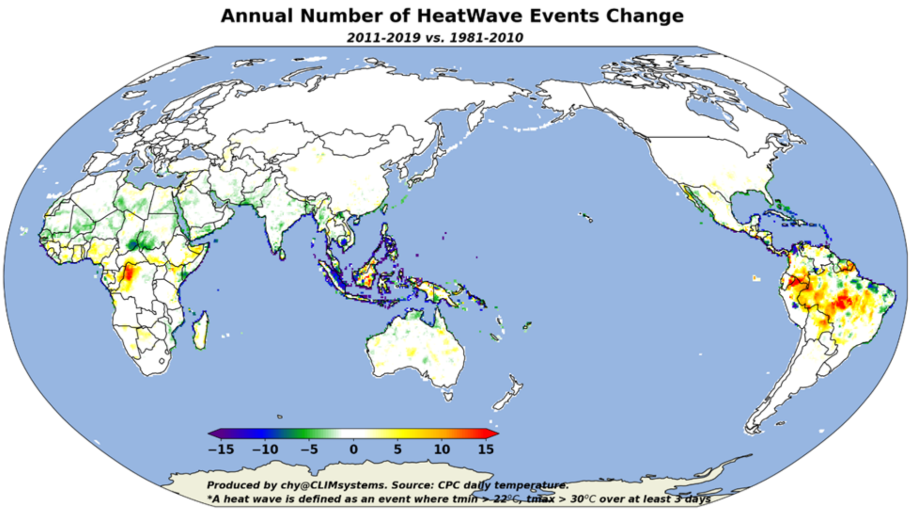
Heat Waves

As a result of human-induced changes in climate, global mean surface air temperature shows a rising trend over the last 100 years (Intergovernmental Panel on Climate Change, 2013). This has led to a world-wide increase in frequency, intensity and duration of extreme heat events or heatwaves (Perkins et al., 2012) (noting these terms are often used interchangeably). Some of the most notable events are the heat waves of 2003 and 2005 in western Europe (Schär et al., 2004), 2010 in Russia (Barriopedro et al., 2011), and 2011 and 2012 in Texas and the Midwest of the USA (Hoerling et al., 2013).

The Intergovernmental Panel on Climate Change 5th Assessment Report (*AR5*) indicates an increase in frequency, length and intensity of heatwaves will be 'very likely over most land areas' well into the future (Intergovernmental Panel on Climate Change, 2013, p.135). Heatwaves are a pervasive natural hazard. Generally, they should be periods of unusually hot and dry or hot and humid weather that have a subtle onset and cessation, a duration of at least two–three days, usually with a discernible impact on human and natural systems.

Extreme Temperatures: Hot and Cold Days and Nights and Heat Waves

There is no universally accepted definition of heatwave. To determine a set of applicable heat wave definitions and methods, a wide range of heat wave and extreme temperature indices already defined in the scientific literature have been carried out within Climate Insights. In general, these methods could be put into *two groups*. The first one is to apply absolute or fixed temperature thresholds to define heatwaves (e.g., *Fig.17*). For example, Health Canada professionals used the thresholds of 22° and 25°C for night temperatures and 30° and 35°C for day temperatures following a temperature–mortality analysis to define heatwaves with a duration at least three days. These absolute temperature thresholds characterise the occurrence of hot weather events that can result in adverse health outcomes for Canadian communities (Casati et al., 2013). However, the thresholds would be 27.22 °C for daily minimum temperature, 39.44 °C for daily maximum temperature, while the heatwave duration period at least two days in Robinson (2001).



Heatwave frequency changes (times/year) in latest 9 years compared with the baseline period of 1981-2010

The second group applies daily percentile climatology from a reference period (e.g., 1981-2010) as thresholds. For example, the threshold is the calendar day 90th percentile of Tmax, based on a 5-day window (i.e., CTX90pct). That is, there is a different percentile value for each day of the year (thereby accounting for the seasonal cycle), where the window is centered on the day in question. Using a moving window accounts for temporal dependence while producing a reasonable sample size to calculate a realistic percentile value. The thresholds are calculated for each time period and grid box separately. The threshold also could be the calendar day 90th percentile of Tmin (CTN90pct), as described for Tmax. These two thresholds are already applied to *identify* hot days (TX90p) and hot nights (TN90p) by Climate Insights. *As a heat wave is considered to be an event of at least three consecutive days (Collins et al., 2000; Pezza et al., 2012), single (1 day) threshold exceedances defined by ETCCDI indices (such as TX90p and TN90p) are not used here to define heatwaves.*

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Extreme Temperatures: Hot and Cold Days and Nights and Heat Waves

Some researches employed only one threshold to identify heatwaves. For instance, the maximum temperature (T_{max}) heatwave definition is applied in Perkins and Alexander (2013) and Perkins and Gibson (2017). That is, daily Tmax must exceed the calendar-day 90th percentile for at least three consecutive days for a heatwave to be declared. In addition, Nairn et al. (2009) applied the 95th percentile of daily mean temperature (T_{mean}) for the time period in question as the thresholds to define the Excess Heat Factor (EHF), one of the heatwave components in their research. On the other hand, some researches applied both CTN90pct and CTN90pct thresholds to defined heatwaves.

In Climate Insights, we adopt the idea from the second group, namely using percentile thresholds to define heatwaves, as this kind of method is more robust and applicable across different climatic zones than the first group of methods that uses fixed thresholds. A given temperature that defines what is extreme heat, heatwaves are relative to a location's climate: the same meteorological conditions can constitute a heatwave in one place but not in another (e.g., *Fig.17*). Moreover, it is thought that day and night-time conditions are equally important for understanding the health effects of heatwaves, which may range from heat rash to heat cramps, heat exhaustion, heatstroke, and death. At the individual level, poor thermoregulation, or the inability to balance heat gains to, and heat losses from, the body are responsible for heat-related health outcomes. As a result, CTN90pct and CTN90pct thresholds are both applied to defined heatwaves. That is, daily T_{max} and T_{min} must simultaneously exceed the calendar-day 90th percentile (CTN90pct and CTN90pct) for at least three consecutive days for a heatwave to be declared.

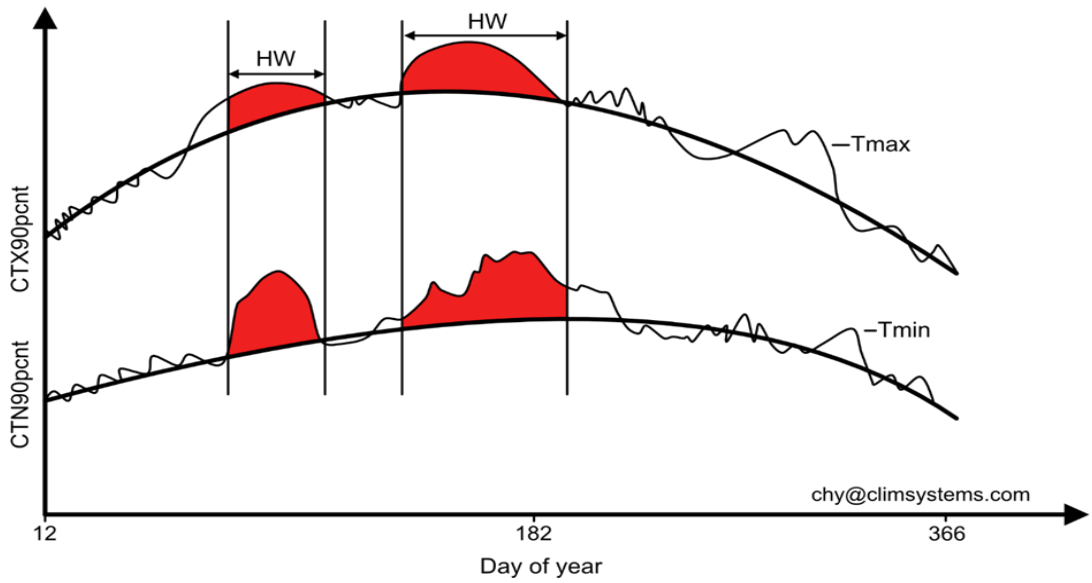
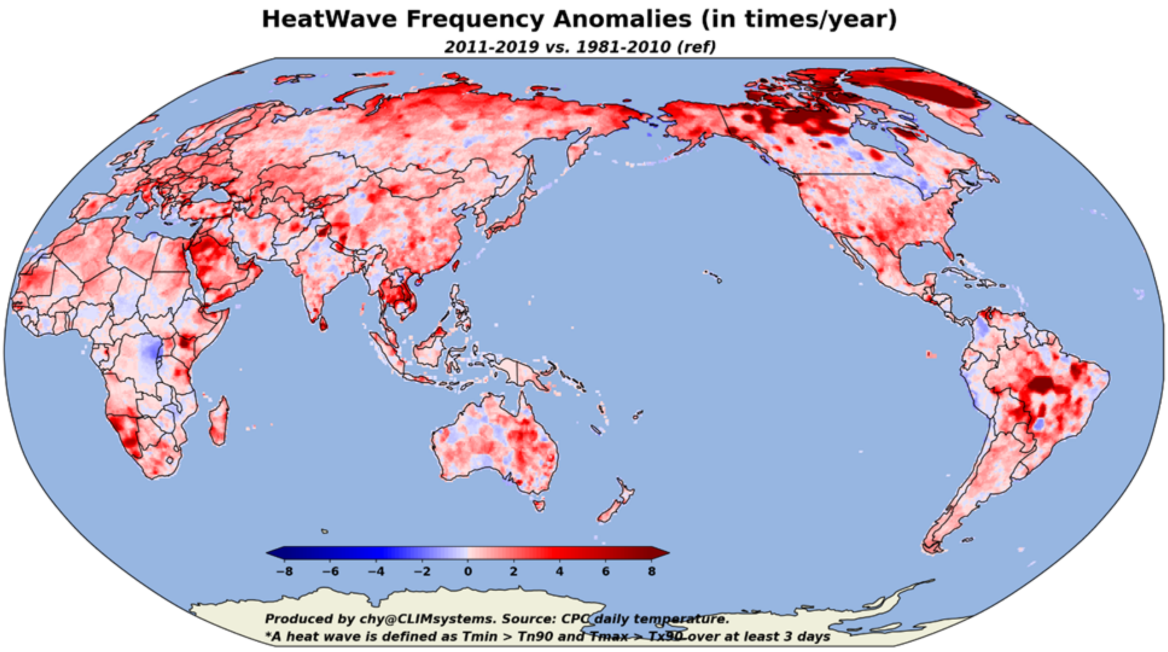


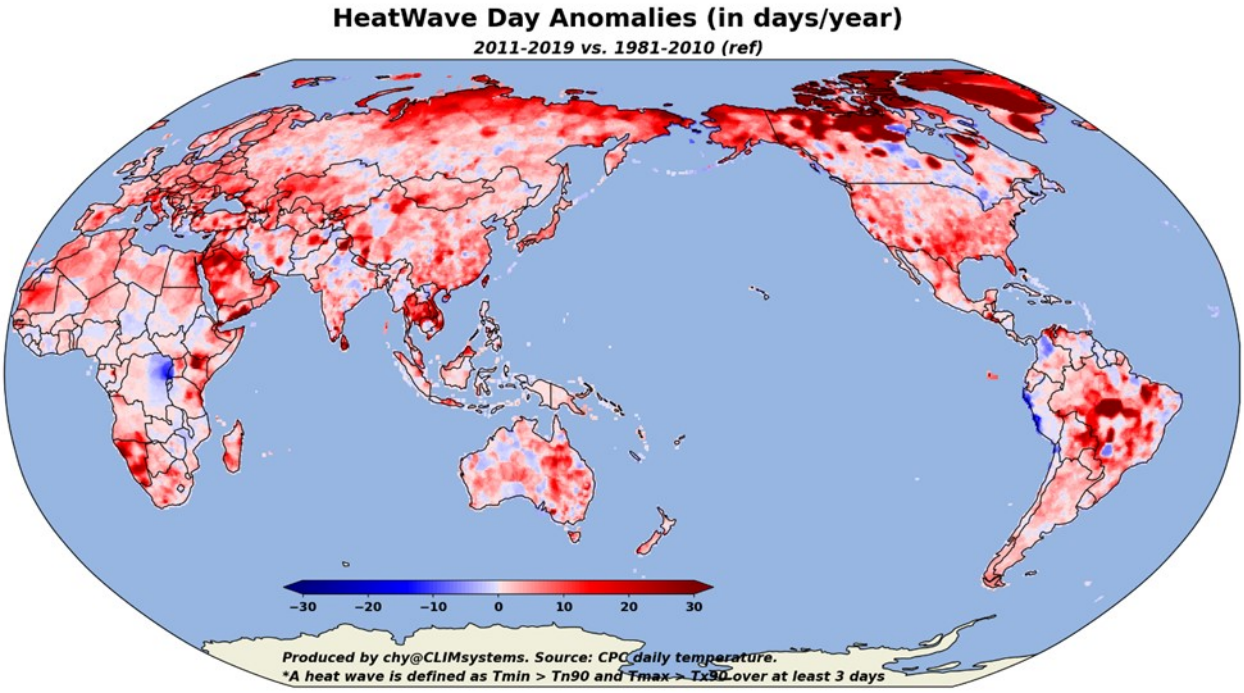
Illustration of defining heatwaves in Climate Insights. A heatwave is an event that daily T_{max} and T_{min} must ***simultaneously*** *exceed the calendar-day 90th percentile (CTN90pct and CTN90pct) for at least three consecutive days*

Annual heatwave *frequency* (HWF, times/year) and heatwave total *days or length (HWD, days/year)* are presented in Climate Insights (e.g., *Fig.19 and Fig.20*). It is recommended that these two layers are used together. Due to climate change, a decrease in the heatwave frequency might occur concurrently with an increase in the length. That is, heatwave days could become more consecutive in the future. Or end-users can calculate the mean heatwave duration as the following equation, and then apply it in practice.

$$Mean\ heatwave\ duration = \frac{Heatwave\ length}{Heatwave\ frequency} = \frac{HWD}{HWF}$$



Extreme Temperatures: Hot and Cold Days and Nights and Heat Waves



Heatwave length changes (days/year) in latest 9 years compared with the baseline period of 1981-2010

Heat Index – Danger and Extreme Danger Days

It is well-known that the body retains more heat when the weather is hot and humid than it does during a drier but equally warm day. As a response to excessive heat in the surrounding environment, our bodies perspire to enhance cooling. Evaporation works best when the air is dry. In moist, saturated air, perspiration cannot evaporate as readily. The combination of excess heat and moisture will cause discomfort i.e. the higher the humidity, the greater the discomfort.

Relative humidity is the amount of moisture that the air contains compared to how much it could hold at a given temperature. A figure of 100 per cent would mean that the air has become saturated. At this point, mist, fog, dew and precipitation are likely. Relative humidity is normally at its maximum when the temperature is at its lowest point of the day, usually at dawn or in the evening. Even though the absolute humidity may remain the same throughout the day, the changing temperature causes the ratio to fluctuate.

The heat index (HI) is an index that combines air temperature and relative humidity, in shaded areas, to posit a human-perceived equivalent temperature, as how hot it would feel if the humidity were some other value in the shade. The result is also known as the "felt air temperature", "apparent temperature", "real feel" or "feels like". For example, when the temperature is 32 °C (90 °F) with 70% relative humidity, the heat index is 41 °C (106 °F). Because it considers the two most important factors that affect comfort, it can be a better measure of how stifling the air feels than either temperature or humidity alone.

The calculation follows the formula outlined by Rothfusz (1990), which is a multi-variable least-squares regression of the values obtained from Steadman (1979). Additional conditional corrections are applied to match what the USA National Weather Service operationally uses (Anderson et al., 2013). The algorithm flowchart is presented in the following image (*Fig.8*), which is extracted from the USA NWS online HI calculator (NWS, 2011). The PGF(v3) data is used to calculate the global heat index in Climate Insights. However, it is a global daily dataset. Therefore, we cannot calculate the Heat Index as the NOAA National Weather Service operationally does, where the calculations are based on sub-daily or hourly data. In this project, the daily maximum temperature (Tmax) is applied, instead of mean temperature (T) to calculate Heat Index. It presumes that the heat stress should occur with a maximum temperature more often than with a daily mean one.

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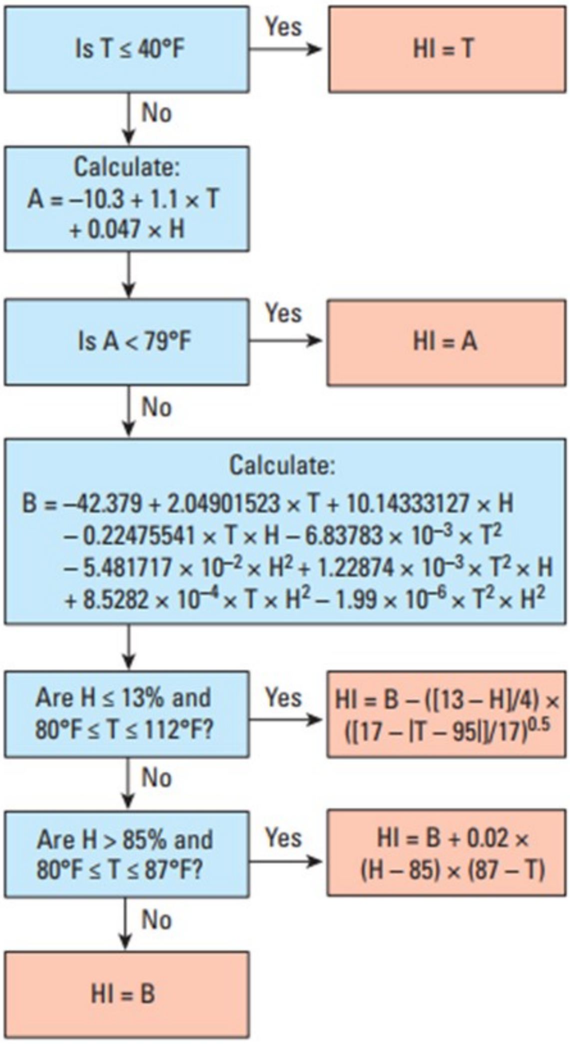


Algorithm used by Climate Insights to determine heat index based on air temperature in degrees Fahrenheit (T) and relative humidity in percent (H)

if we consider the statistics for the past 30 years of weather-related fatalities all over the world, fatalities due to heat is the highest, followed by hurricane and flood. Summer temperatures especially in the Middle East can reach as high as 50 degrees Celsius (122 degrees Fahrenheit), making heat related illness (such as heat exhaustion, heat stress and heat stroke) a profoundly serious concern. Heat stroke can be fatal in many cases because it happens so quickly - there is not much time to react. And not only that, to determine the actual heat that a person feels, you need also to consider the relative humidity - not just the temperature reading.

Extreme Temperatures: Hot and Cold Days and Nights and Heat Waves

In Climate Insight, the global heat index dataset followed the generalized classification standard (*Fig.9* and *Table 5*). Two key thresholds are applied – one for defining ***a danger day*** with HI > 41°C and the other for ***an extreme danger day*** with HI > 54°C. The annual days of each of these two categories are statistically summarized and ported into the platform of Climate Insights.

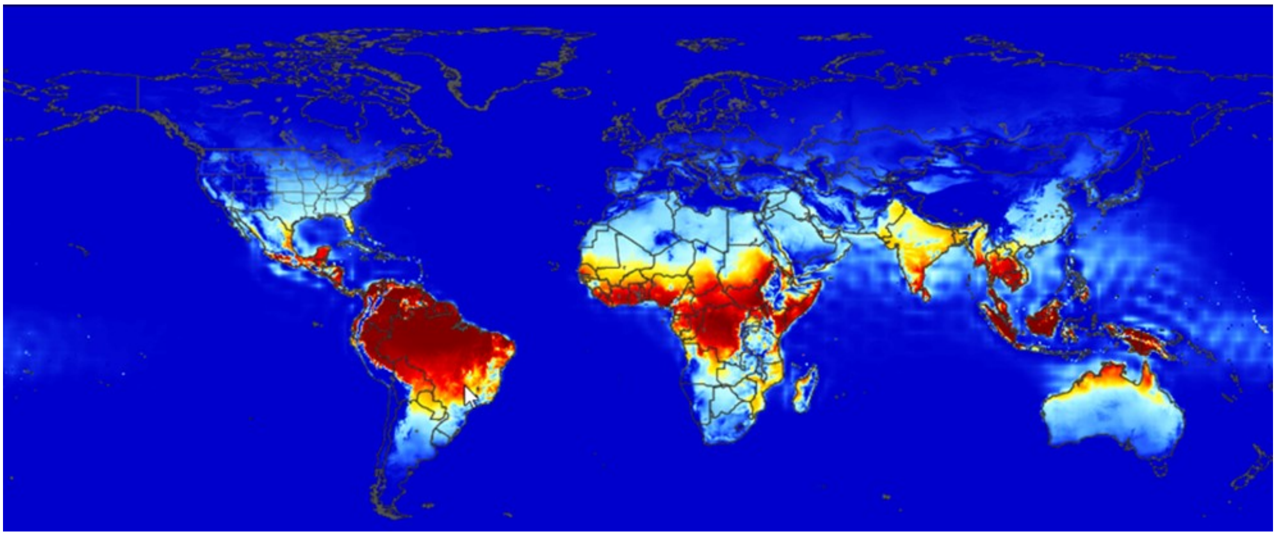
NOAA national weather service: heat index

Temperature / Relative humidity	80 °F (27 °C)	82 °F (28 °C)	84 °F (29 °C)	86 °F (30 °C)	88 °F (31 °C)	90 °F (32 °C)	92 °F (33 °C)	94 °F (34 °C)	96 °F (36 °C)	98 °F (37 °C)	100 °F (38 °C)	102 °F (39 °C)	104 °F (40 °C)	106 °F (41 °C)	108 °F (42 °C)	110 °F (43 °C)
40%	80 °F (27 °C)	81 °F (27 °C)	83 °F (28 °C)	85 °F (29 °C)	88 °F (31 °C)	91 °F (33 °C)	94 °F (34 °C)	97 °F (36 °C)	101 °F (38 °C)	105 °F (41 °C)	109 °F (43 °C)	114 °F (46 °C)	119 °F (48 °C)	124 °F (51 °C)	130 °F (54 °C)	136 °F (58 °C)
45%	80 °F (27 °C)	82 °F (28 °C)	84 °F (29 °C)	87 °F (31 °C)	89 °F (32 °C)	93 °F (34 °C)	96 °F (36 °C)	100 °F (38 °C)	104 °F (40 °C)	109 °F (43 °C)	114 °F (46 °C)	119 °F (48 °C)	124 °F (51 °C)	130 °F (54 °C)	137 °F (58 °C)	
50%	81 °F (27 °C)	83 °F (28 °C)	85 °F (29 °C)	88 °F (31 °C)	91 °F (33 °C)	95 °F (35 °C)	99 °F (37 °C)	103 °F (39 °C)	108 °F (42 °C)	113 °F (45 °C)	118 °F (48 °C)	124 °F (51 °C)	131 °F (55 °C)	137 °F (58 °C)		
55%	81 °F (27 °C)	84 °F (29 °C)	86 °F (30 °C)	89 °F (32 °C)	93 °F (34 °C)	97 °F (36 °C)	101 °F (38 °C)	106 °F (41 °C)	112 °F (44 °C)	117 °F (47 °C)	124 °F (51 °C)	130 °F (54 °C)	137 °F (58 °C)			
60%	82 °F (28 °C)	84 °F (29 °C)	88 °F (31 °C)	91 °F (33 °C)	95 °F (35 °C)	100 °F (38 °C)	105 °F (41 °C)	110 °F (43 °C)	116 °F (47 °C)	123 °F (51 °C)	129 °F (54 °C)	137 °F (58 °C)				
65%	82 °F (28 °C)	85 °F (29 °C)	89 °F (32 °C)	93 °F (34 °C)	98 °F (37 °C)	103 °F (39 °C)	108 °F (42 °C)	114 °F (46 °C)	121 °F (49 °C)	128 °F (53 °C)	136 °F (58 °C)					
70%	83 °F (28 °C)	86 °F (30 °C)	90 °F (32 °C)	95 °F (35 °C)	100 °F (38 °C)	105 °F (41 °C)	112 °F (44 °C)	119 °F (48 °C)	126 °F (52 °C)	134 °F (57 °C)						
75%	84 °F (29 °C)	88 °F (31 °C)	92 °F (33 °C)	97 °F (36 °C)	103 °F (39 °C)	109 °F (43 °C)	116 °F (47 °C)	124 °F (51 °C)	132 °F (56 °C)							
80%	84 °F (29 °C)	89 °F (32 °C)	94 °F (34 °C)	100 °F (38 °C)	106 °F (41 °C)	113 °F (45 °C)	121 °F (49 °C)	129 °F (54 °C)								
85%	85 °F (29 °C)	90 °F (32 °C)	96 °F (36 °C)	102 °F (39 °C)	110 °F (43 °C)	117 °F (47 °C)	126 °F (52 °C)	135 °F (57 °C)								
90%	86 °F (30 °C)	91 °F (33 °C)	98 °F (37 °C)	105 °F (41 °C)	113 °F (45 °C)	122 °F (50 °C)	131 °F (55 °C)									
95%	86 °F (30 °C)	93 °F (34 °C)	100 °F (38 °C)	108 °F (42 °C)	117 °F (47 °C)	127 °F (53 °C)										
100%	87 °F (31 °C)	95 °F (35 °C)	103 °F (39 °C)	112 °F (44 °C)	121 °F (49 °C)	132 °F (56 °C)										

Key to colors: Caution · Extreme caution · Danger · Extreme danger

NOAA national weather service: heat index lookup table

It is worth noting that ***the danger days contain the extreme danger days***. Such an operation has a big advantage that each of them can individually be applied to avoid extracting two data layers from Climate Insights to carry out a complete heat stress assessment. In addition, people will have different feeling for heat if they originate from different regions. That is the reason that some regions have taken their own initiative to increase awareness and educate employers and workers about the serious consequences of heat related illnesses. *To get a more accurate assessment about the impact of heat index, regional temperature and humidity data should be used and regional standards should be followed*. Moreover, this heat index might be not that applicable in mid-hight latitude regions as temperature rarely reaches the hot level in low latitudes. However, it could be a useful indicator for international visitors who come from Europe and other cooler climate regions for planning their travelling paths to hot or extreme hot regions.



A demonstration of spatial distributions of danger days derived from Heat Index (HI). It could be found that HI is hard to get into mid-high latitudes, so it is not that applicable over these regions.

A little More About Heat Stress Indices

Because air temperature alone has not been considered a good indicator of the human thermal environment or heat, thermal indices – most of them two-parameter indices – have been developed to describe the complex conditions of heat exchange between the human body and its thermal environment. For warm conditions, indices usually consist of combinations of dry-bulb temperature and different measures for humidity. Heat Index applied in Climate Insights to identify danger and extreme danger days is a typical heat stress index that belongs to this family. On the other hand, it means there are more similar indices available for thermal assessments (Parsons, 2003; Blazejczyk et al., 2012).

In fact, CLIMsystems maintains quite a few of such heat stress indices and already applied some of them to heat stress assessment projects and weather forecast services hosted by ExtendWeather.com. The following presents a noncomplete list. At present, none of them has been ported into the Climate Insights global dataset because they are designed for specific purposes or occupy strong features only meaningful in some regions, but not suitable for others. Moreover, there are not universal classification schemes available for their application at global scale. However, they could become available for some specific region under request.

Humidex

Humidex was devised by Canadian meteorologists and first used in 1965 to describe how hot, humid weather feels to the average person (Smoyer-Tomic et al., 2003). Humidex combines temperature and humidity into one number to reflect the perceived temperature.

Net effective temperature (NET)

Net effective temperature (NET) is routinely monitored by the Hong Kong Observatory, China (Li and Chan, 2000) and takes into account the effect of air temperature, wind speed and relative humidity.

Simplified Wet-bulb globe temperature (sWBGT)

Wet-bulb globe temperature (WBGT) combines temperature and humidity into a single number (Budd, 2009) and is also affected by wind and radiation. However, the calculation of WBGT requires too many meteorological variables. Therefore, a widely used modification version, namely the simplified Wet Bulb Globe Temperature (sWBGT) is applied (Buzan et al., 2015). sWBGT was designed for estimating heat stress in sports medicine and adopted by the Australian Bureau of Meteorology; however, it is acknowledged that its accuracy of representing the original labour industry index may be questionable (ACSM, 1984, 1987). We chose, however, to implement sWBGT due to its wide use.

Apparent temperature (AT)

Apparent temperature (AT) is defined as the temperature at the reference humidity level, which produces the same amount of discomfort as that experienced under the current ambient temperature and humidity. Basically, AT is an adjustment to the ambient temperature (T) based on the level of humidity. The formula for AT used by BoM is an approximation of the value provided by a mathematical model of the human heat balance. It can include the effects of temperature, humidity, wind speed and radiation.

Wind Chill Temperature Index (WCTI)

Wind-chill or windchill (popularly wind chill factor) is the lowering of body temperature due to the passing-flow of lower-temperature air. WCTI is calculated from the current temperature and wind speed using the formula outlined by the FCM [FCMR192003].

Temperature Humidity Index for Physiology (THIP)

THIP (Ingram, 1965) is calibrated for physiological responses using only meteorological inputs. THIP and THIC are modifications of the THI. Additionally, THIC and THIP have applications beyond heat stress. THIP and THIC threshold levels are computed from both indoor and outdoor atmospheric variables.

Excess Heat Index (EHI)

The Excess Heat Index (EHI) is a new index developed by (BoM) (Nairn and Fawcett, 2013), which considers the relationship of maximum and minimum temperatures averaged over a three-day period to a climate reference value (95th percentile) of observed daily temperature (single day average of maximum and minimum temperature in a common 9 a.m. to 9 a.m. period) to identify and characterize heat events. Positive, contiguous three-day-average daily temperature departures from the 95^{th} percentile reference value indicate a significant excess heat event or heatwave.

Temperature Humidity Index for Comfort (THIC)

The THIC is a modification of the Temperature Humidity Index (THI) (Ingram, 1965). Comfort was quantified for livestock through THIC (NWSCR, 1976). The index is used to describe behavioural changes in large animals due to discomfort (seeking shade, submerging in mud, etc.). The index is in active use by the livestock industry for local heat stress and future climate considerations (Lucas et al., 2000; Renaudeau et al., 2012).

Discomfort Index (DI)

Discomfort Index was developed in the 1950s as a calibration for air conditioners (Thom, 1959). It was adapted by the Israeli Defence Force as a decision-making tool regarding heat stress (Epstein and Moran, 2006).

Environmental Stress index (ESI)

The environmental stress index (ESI) is an alternative (substitute) for the wet bulb globe temperature (WBGT). The correlation coefficients between Moran ESI (Moran et al., 2001) and WBGT were very high ($R^2 > 0.981$).