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APPARENT TEMPERATURE & RELATIVE HUMIDITY IN NEBRASKA: A COMPARATIVE ANALYSIS ON WET BULB GLOBE TEMPERATURE (WBGT) TOOLS

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Disclaimer: The following thesis was produced in the Environmental Studies Program as a student senior capstone project.

APPARENT TEMPERATURE & RELATIVE HUMIDITY IN NEBRASKA: A COMPARATIVE ANALYSIS ON WET BULB GLOBE TEMPERATURE (WBGT) TOOLS

by

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APPARENT TEMPERATURE & RELATIVE HUMIDITY IN NEBRASKA: A COMPARATIVE ANALYSIS ON WET BULB GLOBE TEMPERATURE (WBGT) TOOLS

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Abstract:

Heat waves can lead to illness and death, particularly among older adults, the very young, and other vulnerable populations. More frequent severe heat waves are expected to impact Nebraska. Looking specifically into Lincoln, NE for future climate trends, over the next 100 years, "the number of hot days would increase by 13-22 days during a given summer (depending upon the scenario), and the number of warm nights would increase by 20-35 nights each summer" Bathke et al. (2014). These higher summer temperatures will "increase electricity use, causing higher summer peak loads" as well as "pose physical and mental health challenges…outdoor work will become more difficult, riskier, and less productive" Bathke et al. (2014). Prolonged exposure to excessive heat can lead to other impacts such as damaged crops, injured or dead livestock, and increased risk of wildfires. In order to mitigate some of these effects, adequate tracking and monitoring of apparent temperatures, increased relative humidity, and WBGT must occur. One solution for this is through utilization of online tools, apps, and simple calculators in order to provide warning to vulnerable populations and help better prepare the general public. In this study, through the methods of meta-analysis, visual representation with charts and graphs, and comparative analysis, exploratory-based research was carried out on eight counties (Scotts Bluff, Cherry, Madison, Custer, Lancaster, Keith, Phelps, and Jefferson) with the respective climate divisions of 1, 2, 3, 5, 6, 7, 8, 9 as defined by the Climate Prediction Center (CPC). The cities from each county were: Scottsbluff, Valentine, Norfolk, Broken Bow, Lincoln, Ogallala, Holdredge, and Fairbury. For each location, apparent temperature was calculated in order to observe noticeable summer temperature trends under the last climate normal period (1991-2020). Five wet bulb globe temperature (WBGT) tools were also analyzed in terms of readability, ease of access, amount of information and data available, accuracy, and completeness in order to create and optimize one for the Nebraska area. Cooling Degree Day (CDD) trends were also looked at to determine whether or not increased relative humidity and apparent temperatures had an effect on them. It was determined that the most optimized tool would have advanced equations, sufficient background data, a five day extended outlook, and appropriate work/rest interval and water intake information. Sharp increases in AT were observed in 1995, 2006, 2012, and 2017 with each of these years corresponding to a major heat event: Chicago Heat Wave, North American Heat Wave, Heat Wave/Drought, and the Heat Dome/Record Breaking heat, respectively. These patterns matched the highest recorded CDD in the summer of 2012 at 1,344.4 CDD.

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Introduction

Purpose Statement:

Few studies have considered the importance of relative humidity, and simply studying normal air temperature is not enough since “air temperature alone is not a complete metric of the full near-surface heat content, as it does not account for the heat content changes associated with moisture changes" Pryor & Schoof (2019). Equivalent temperature is a better representation of atmospheric heat content since “TE is more sensitive to surface vegetation, via evapotranspiration, than temperature alone” Younger et al. (2019). Research has also ignored heat stress contributions from increasing humidity. According to Pryor & Schoof (2016), “many projections of heat wave occurrence, intensity, and associated health burdens have ignored elevated heat stress contributions from increasing humidity and therefore may underestimate the future risk, particularly given evidence for increasing near-surface q (and thus Td) as a result of warming of the atmosphere”. Therefore, by studying these concepts more in-depth, these gaps left by other researchers can be filled. Equivalent temperature exploratory research is helpful in identifying uncertainties. According to Na-Yemeh et al. (2020), “using TE along with temperature may help to remove uncertainties in near surface and tropospheric temperature trends".

It can also be stressed that heat waves and high relative humidity days have deadly consequences. According to the Environmental Protection Agency EPA (2021), “when people are exposed to extreme heat, they can suffer from potentially deadly illnesses, such as heat exhaustion and heat stroke. Hot temperatures can also contribute to deaths from heart attacks, strokes, and other forms of cardiovascular disease. Heat is the leading weather-related killer in the United States, even though most heat-related deaths are preventable through outreach and intervention." Therefore, by creating and optimizing protection tools such as a WBGT forecast and outlook, we can help mitigate and prevent heat-related deaths and illnesses in Nebraska.

Objectives:

1. Compare and contrast all current WBGT tools found online in terms of readability, ease of access, amount of information and data available, accuracy, and completeness.
2. Answer the question: "How could one of these temperature tools be modeled and created for the Midwest and Nebraska?"
3. Observe noticeable summer (June-August) temperature patterns and trends for one city from each of Nebraska's nine climate regions under the last climate normal period (1991-2020) and calculate apparent temperature from the data.
4. Assess effect of increased relative humidity and apparent temperature values on number of cooling degree days and energy use/cost in Nebraska

Definitions:

Some terms that will be used throughout this paper include: cooling degree days (CDD), relative humidity, dew point, heat index, wet bulb globe temperature, apparent temperature, and vapor pressure.

Degree days are "measures of how cold or warm a location is. A degree day compares the mean (the average of the high and low) outdoor temperatures recorded for a location to a standard temperature, usually 65° Fahrenheit (F) in the United States. The more extreme the outside temperature, the higher the number of degree days. A high number of degree days generally results in higher levels of energy use for space heating or cooling EIA (2021). This paper will focus on CDD. CDD are "a measure of how hot the temperature was on a given day or during a period of days". For example, a day with a mean temperature of 80°F has 15 CDD. If the next day has a mean temperature of 83°F, it has 18 CDD. The total CDD for the two days is 33 CDD" EIA (2021). A visual representation of CDD normals for Nebraska can be found in Figure 1 below.

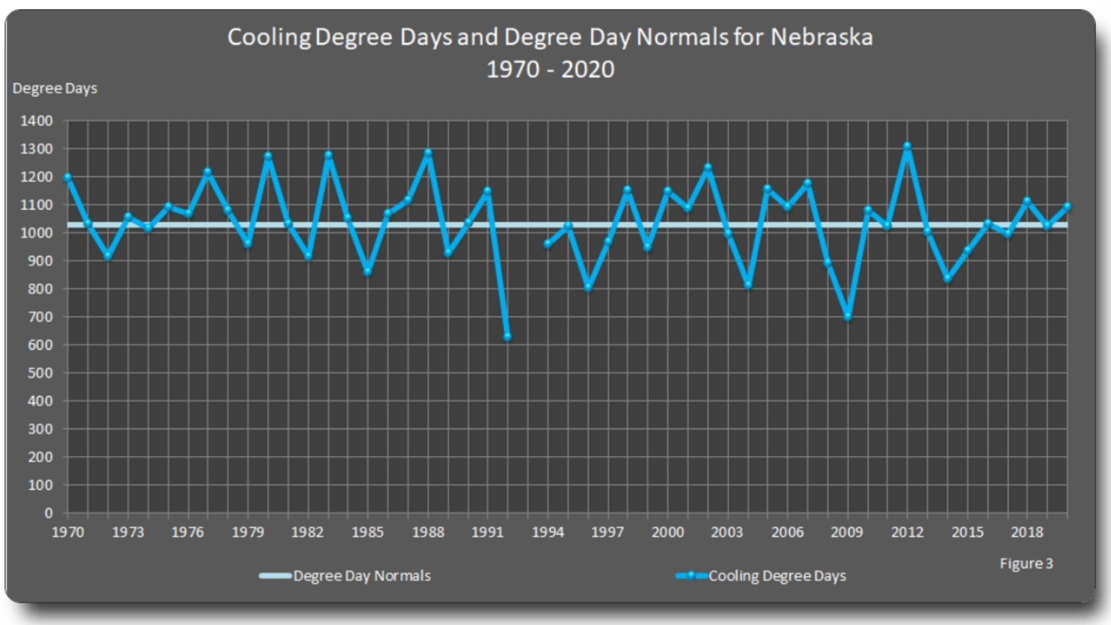


Figure 1: CDD and Degree Day Normals for Nebraska from 1970-2020 with one year of missing data (1993). Degree day normals are the white line and CDD are in blue as indicated by the legend Janksy (2021).

Relative Humidity (RH) is defined as "a ratio that compares the amount of water vapor in the air compared to the total amount of water vapor that can be present in the air at a given temperature" Holt (2020). It is dependent on air temperature and shares an inverse relationship with it; when temperature rises, RH falls and vice versa. To calculate, one would use the formula:

100*(EXP((17.625*TD)/(243.04+TD))/EXP((17.625*T)/(243.04+T)))

which includes known dew point and air temperature values in degrees Fahrenheit McNoldy (2022).

Dew point is the "temperature at which air will condense" Holt (2020) and the value remains somewhat constant throughout the day and does not depend on air temperature. In order to calculate dew point, one would use the formula:

243.04*(LN(RH/100)+((17.625*T)/(243.04+T)))/(17.625-LN(RH/100)-((17.625*T)/(243.04+T))

which includes known RH and air temperature values in degrees Fahrenheit McNoldy (2022). The figures below display the relationship between the variables of air temperature, RH, and dewpoint and show how they interact with one another.

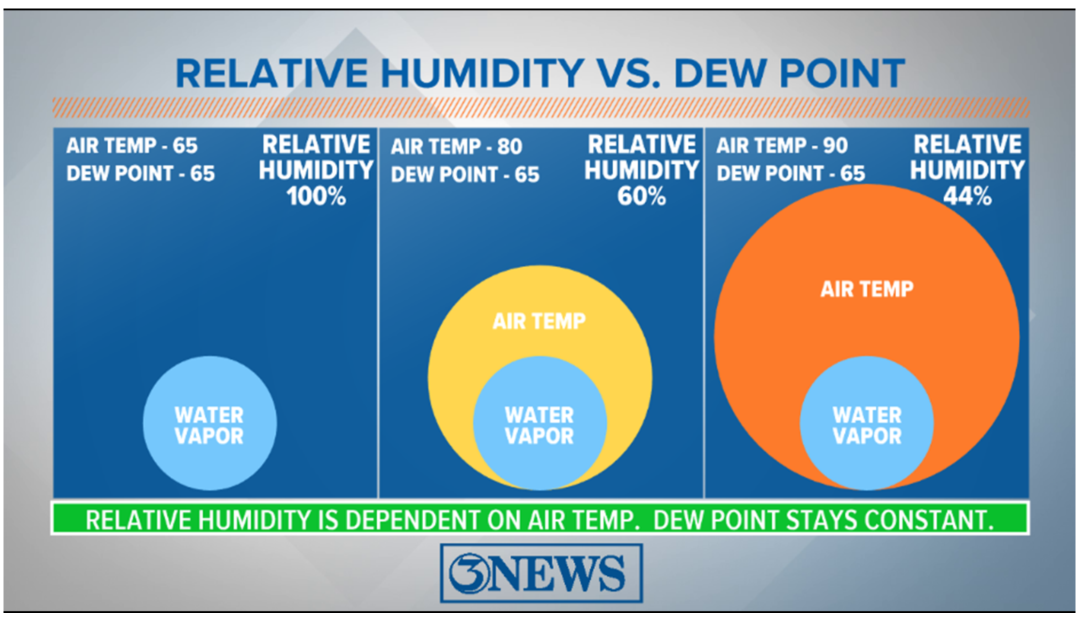


Figure 2: A chart showing how RH and dew point compare; RH is dependent on air temperature whilst dew point stays constant Holt (2020).

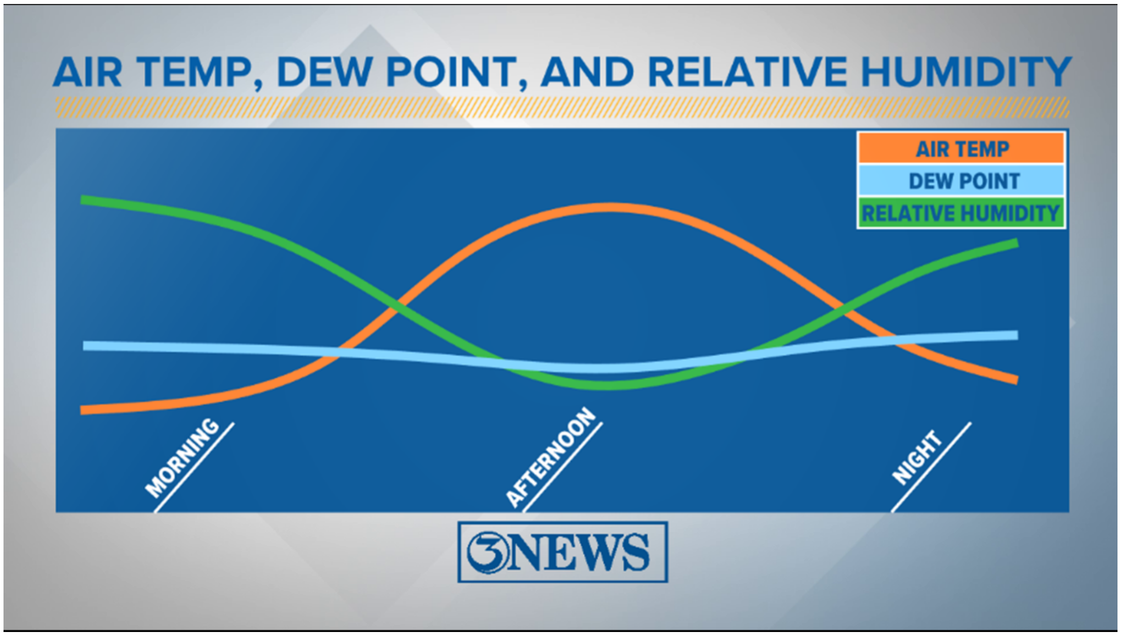


Figure 3: A graphical interpretation of how air temperature, dew point, and RH fluctuate throughout a 24 hour timespan Holt (2020).

The Heat Index (HI) is "a measure of how hot it feels to the human body, taking into account the temperature and the relative humidity". HI should be taken seriously because "high humidity combined with hot temperatures reduce the body's ability to cool itself increasing the risk of heat exhaustion, heat stroke, and other heat related health problems Karsten & Ufkit (2021). With temperature and RH, *The higher either one value is, the higher the heat index and the greater the stress exerted on the body. The index relies on temperature measured in total shade, so measurements taken in full sunlight have more of a negative impact. When sunlight is taken into account, Heat Indices can increase as much as 15°F. Humidity plays a major effect on cooling the body. If the humidity is high, sweat on the surface of the skin does not evaporate as quickly, slowing the cooling of the body. If the humidity is low, sweat evaporates too fast, leading* *to dehydration* Moran (2017). The figure below shows an example of what a HI chart is.

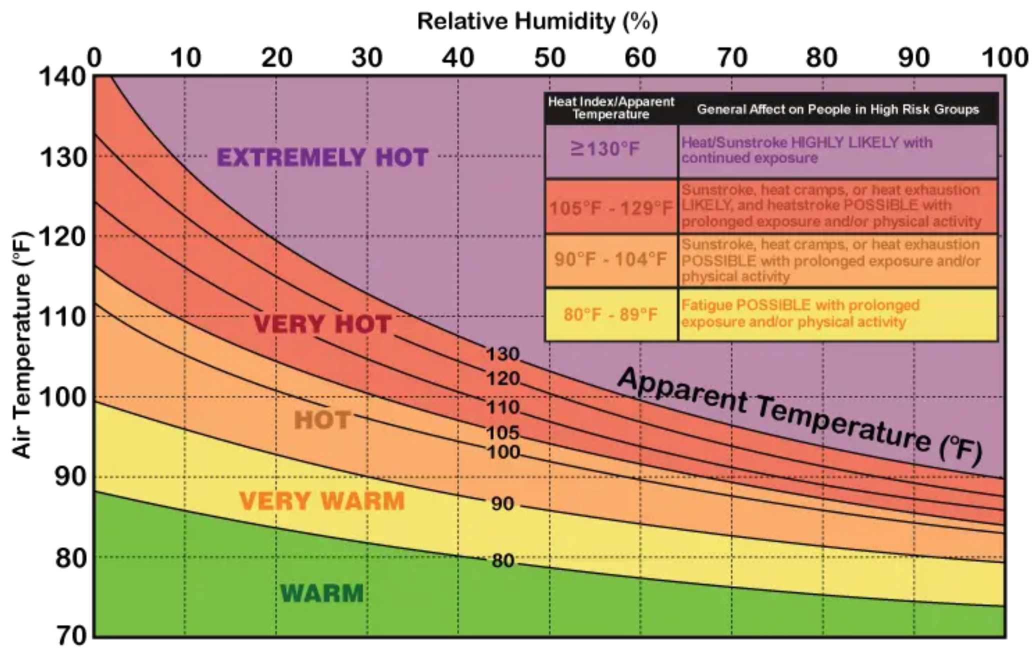


Figure 4: A graphical example of the HI, showing ratings of how exposure will affect people in high risk groups from fatigue to sunstroke. The HI takes into account apparent temperature and RH values in order to calculate the values Moran (2017).

The Wet Bulb Globe Temperature (WBGT) is "a measure of heat stress that combines the effect of heat and humidity" Safina et al. (2018). It is calculated using the formula:

$$WBGT=0.7TW+0.2TG+0.1TD$$

where Tw is the wet bulb temperature, which indicates humidity, Tg is the globe temperature, which indicates radiant heat, and Td is the ambient air (dry) temperature Belval (2015). The use of WBGT in meteorology/climatology is a relatively new concept, as it was invented in the 1950s. As stated by Belval (2015), in order to reduce heat illness in the army; "The use of WBGT as an environmental monitoring measure during exercise in the heat was invented in the early 1950's in response to the number of heat casualties occurring in the United States armed services that occurred during the 1940's and 1950's. For example, from 1942-1944, 198 soldiers died due to heat illness during military training." In order to obtain these measurements, a WBGT device is needed. "A WBGT device is a measurement tool that uses ambient temperature, relative humidity, wind, and solar radiation from the sun to get a measure that can be used to monitor environmental conditions during exercise Belval (2015). By using this tool and by establishing WBGT guidelines (work to rest ratios, hydration breaks, etc.), illnesses and heat stress can be reduced. Below, in Figure 5, is a simple WBGT table based on temperature and RH values.

Wet Bulb Globe Temperature (WBGT) from Temperature and Relative Humidity

Relative Humidity (%) \ Temperature (°C)	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50
0	15	16	16	17	18	18	19	19	20	20	21	22	22	23	23	24	24	25	25	26	27	27	28	28	29	29	30	31	31	32	32
5	16	16	17	18	18	19	19	20	21	21	22	22	23	24	24	25	26	26	27	27	28	29	29	30	31	31	32	33	33	34	35
10	16	17	17	18	19	19	20	21	21	22	23	23	24	25	25	26	27	27	28	29	30	30	31	32	32	33	34	35	36	36	37
15	17	17	18	19	19	20	21	21	22	23	23	24	25	26	26	27	28	29	29	30	31	32	33	33	34	35	36	37	38	39	
20	17	18	18	19	20	21	21	22	23	24	24	25	26	27	27	28	29	30	31	32	32	33	34	35	36	37	38	39			
25	18	18	19	20	20	21	22	23	24	24	25	26	27	28	28	29	30	31	32	33	34	35	36	37	38	39					
30	18	19	20	20	21	22	23	23	24	25	26	27	28	29	29	30	31	32	33	34	35	36	37	39							
35	18	19	20	21	22	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39								
40	19	20	21	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39									
45	19	20	21	22	23	24	25	26	27	27	28	29	30	32	33	34	35	36	37	38											
50	20	21	22	23	23	24	25	26	27	28	29	30	31	33	34	35	36	37	39												
55	20	21	22	23	24	25	26	27	28	29	30	31	32	34	35	36	37	38													
60	21	22	23	24	25	26	27	28	29	30	31	32	33	35	36	37	38														
65	21	22	23	24	25	26	27	28	29	31	32	33	34	36	37	38															
70	22	23	24	25	26	27	28	29	30	31	33	34	35	36	38	39									WBGT > 40						
75	22	23	24	25	26	27	29	30	31	32	33	35	36	37	39																
80	23	24	25	26	27	28	29	30	32	33	34	36	37	38																	
85	23	24	25	26	28	29	30	31	32	34	35	37	38	39																	
90	24	25	26	27	28	29	31	32	33	35	36	37	39																		
95	24	25	26	27	29	30	31	33	34	35	37	38																			
100	24	26	27	28	29	31	32	33	35	36	38	39																			

Note: This table is compiled from an approximate formula which only depends on temperature and humidity. The formula is valid for full sunshine and a light wind

Figure 5: A table showing WBGT values based on an approximate formula that only depends on temperature and humidity and assumes full sunshine and light wind speeds Belval (2015).

Apparent Temperature (AT) stems from Robert Steadman's original definition in 1971. "It was intended as an assessment of what exposed body surfaces feel like in cold, windy conditions. Subsequently he (Steadman, 1979) extended his work on the thermal resistance of an unclothed body to warm, humid conditions" Enloe (2021). One can calculate AT by using the equation A (°C) = -1.3 + 0.92T + 2.2e, where T is ambient air temperature (°C) and e is water vapor pressure (kPa) (Steadman 1984)". This ignores the effect of wind.

Vapor pressure is "a measure of the tendency of a material to change into the gaseous or vapor state, and it increases with temperature" Forest (2022). Vapor pressure can be calculated using Teten's Formula, "the relation between temperature and the partial pressure of water vapor:

e(millibars) = 6.1078 exp((17.269*T) / (237.3+T))

Where, e is saturated vapor pressure in millibars and T is temperature in degrees C" Forest (2022).

Assumptions/Limitations:

This study was limited in terms of data collection, as many rural cities did not have data on dew point or RH values. There were also some gaps and missing data points in the maximum temperature records collected between 1991-2020. Instead of leaving missing values as blank or marked as N/A, the two nearest data points were averaged and the N/A was replaced. There was also no way to find the Globe Thermometer Temperature for any of the chosen locations. That temperature requires a special instrument measurement that is rarely taken and documented. Therefore, even though wet bulb temperature was calculated for Lincoln, NE, the full WBGT measurement could not be found. Most temperature and relative humidity trends were then assumed from apparent temperature and maximum daily temperature alone except for Lincoln, NE, which also utilizes dewpoint, RH, and HI.

Overview:

In this paper, equivalent and apparent temperatures, relative humidity in relation to the heat index, and wet bulb globe temperature will be studied as well as their implications with human health and energy costs in a general sense, as well as focusing specifically on the state of

Nebraska. Daily maximum temperatures and calculated apparent temperatures for eight cities from eight counties in Nebraska (one from each climate division) for every summer from 1991-2020 will be researched to look for high heat days and trends in the data. For Lancaster county specifically, heat index and wet bulb temperatures will be examined and inspected for outlying trends. A general assessment of cooling degree days for June-August for Nebraska from 1991-2020 will also be conducted. Finally, a comparative analysis will be done in order to determine which wet bulb globe temperature (WBGT) tool available online is the most accessible and reliable in providing suggested safety measures and mitigation for dangerous high heat/high humidity days.

Literature Review

This research is exploratory in that there isn't much data or papers published on the subject. Therefore it is imperative for the generation of new knowledge that more work is done on studying equivalent temperature and relative humidity and identifying uncertainties and trends with it. By analyzing data and finding these answers, the system being studied will be better understood and this work can be applied to future projects such as developing tools to identify high heat days and adverse heat conditions in order to preserve safety of vulnerable populations in Lincoln, NE and the surrounding areas.

High Heat Risks, Deaths, Occurrences:

High heat is a serious risk to communities all across the world in multiple ways. "Prolonged periods with high temperature (T) and high humidity (q) result in excess human morbidity and mortality, while those associated with high temperatures and low humidity are often associated with forest drought stress and wildfire risk and lower agricultural yields. In the context of human health, Sherwood and Huber (2010) and Coffel et al. (2018) note that the combined effects of changes in extreme temperature and humidity may be too severe for human adaptation" Schoof & Pryor (2019). In fact, Rennie et al. (2021) states that; "extreme heat is one of the most pressing climate risks in the United States and is exacerbated by a warming climate and aging population, causing an estimated average of 140 deaths per year, with some studies attributing approximately 5000 annual deaths to heat". In Figure 6 below, annual death rates due to heat are shown. According to the EPA (2021), exposure to extreme heat can lead to a whole host of complications, including heat exhaustion, heat stroke, and death although a majority of these complications are preventable. *"When people are exposed to extreme heat, they can suffer from potentially deadly illnesses, such as heat exhaustion and heat stroke. Hot temperatures can also contribute to deaths from heart attacks, strokes, and other forms of cardiovascular disease. Heat is the leading weather-related killer in the United States, even though most heat-related deaths are preventable through outreach and intervention".* The results from the research done by the EPA (2021) are shocking; "Overall, a total of more than 11,000 Americans have died from heat-related causes since 1979, according to death certificates".

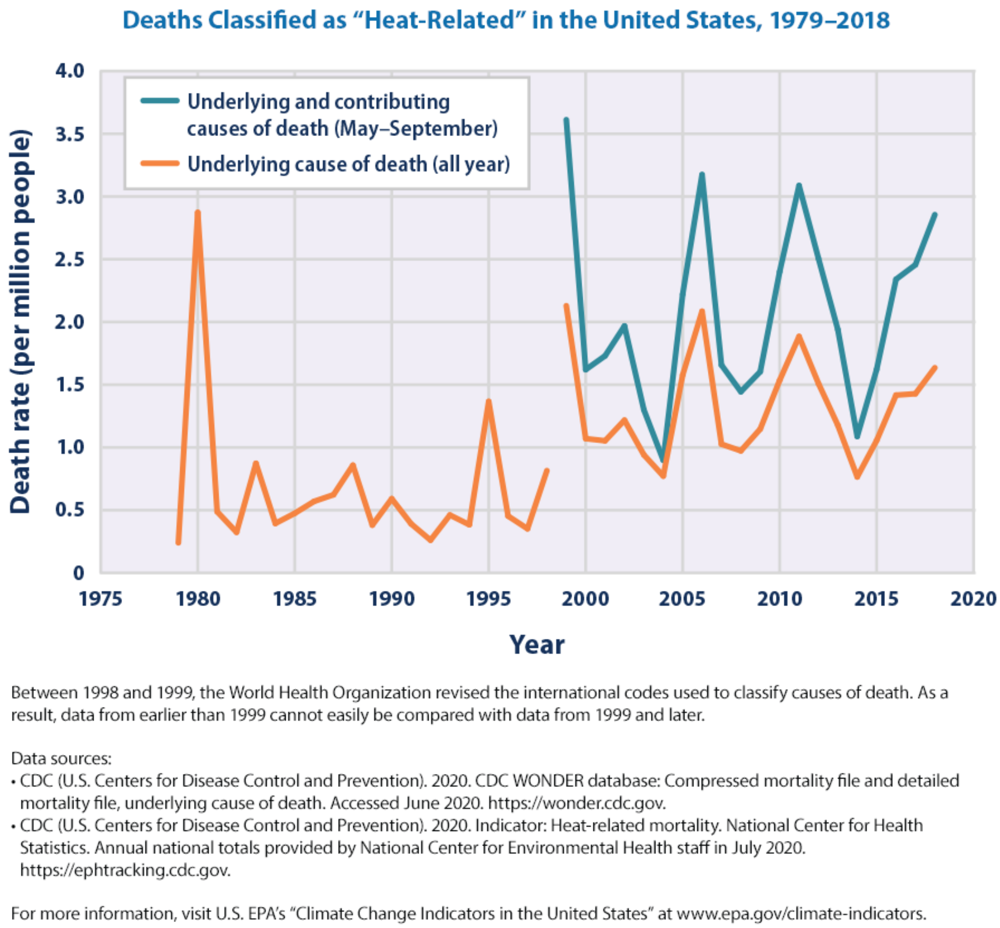


Figure 6: Annual rates for heat-related deaths according to medical professionals. The orange line shows where heat is the main underlying cause of death while the blue line shows where heat is a contributing factor but isn't the only main underlying cause EPA (2021).

Humidity is an important component of extreme heat, one that cannot be ignored. Adjusting for humidity is important because "when humidity is high, water does not evaporate as easily, so it is harder for the human body to cool off by sweating. That is why health warnings about extreme heat are often based on the "heat index," which combines temperature and humidity" EPA (2021).

Not only are there many deaths associated with high heat, their occurrence is rapidly increasing too. According to the EPA (2021), "Heat waves are occurring more often than they used to in major cities across the United States. Their frequency has increased steadily, from an average of two heat waves per year during the 1960s to six per year during the 2010s”. This can be seen in Figure 7 below. The average length and intensity of a heat event has increased recently as well. According to the EPA (2021) “the average heat wave in major U.S. urban areas has been about four days long, a day longer than the average heat wave in the 1960s and the average heat wave season is 47 days longer”. Longer heat waves and heat events increase risk for vulnerable populations in terms of heat-related illness and death. In urban areas, the projected effect is predicted to be worse due to the “urban heat island” effect. “The “urban heat island” effect accentuates the problem by causing even higher temperatures in densely developed urban areas” EPA (2021). Some deaths can be prevented through adequate adaptive actions and resilient planning efforts, however.

Heat is a killer since it affects our ability to effectively cool down, sweating. “When atmospheric moisture content is high, human sweat cannot evaporate efficiently, limiting the removal of latent heat from the body. This lack of evaporative cooling allows overall body temperature to reach higher levels when exposed to heat and/or physical activity (Sherwood 2018). Raymond et al. (2020) found some locales have already exceeded the upper physiological limit of humidity for human tolerance, with values of wet-bulb temperature Tw exceeding 35.0°C, although not for long durations. Limaye et al. (2018) estimate these increases could cause 12,000 excess deaths in the eastern United States by 2050” Rennie et al. (2021).

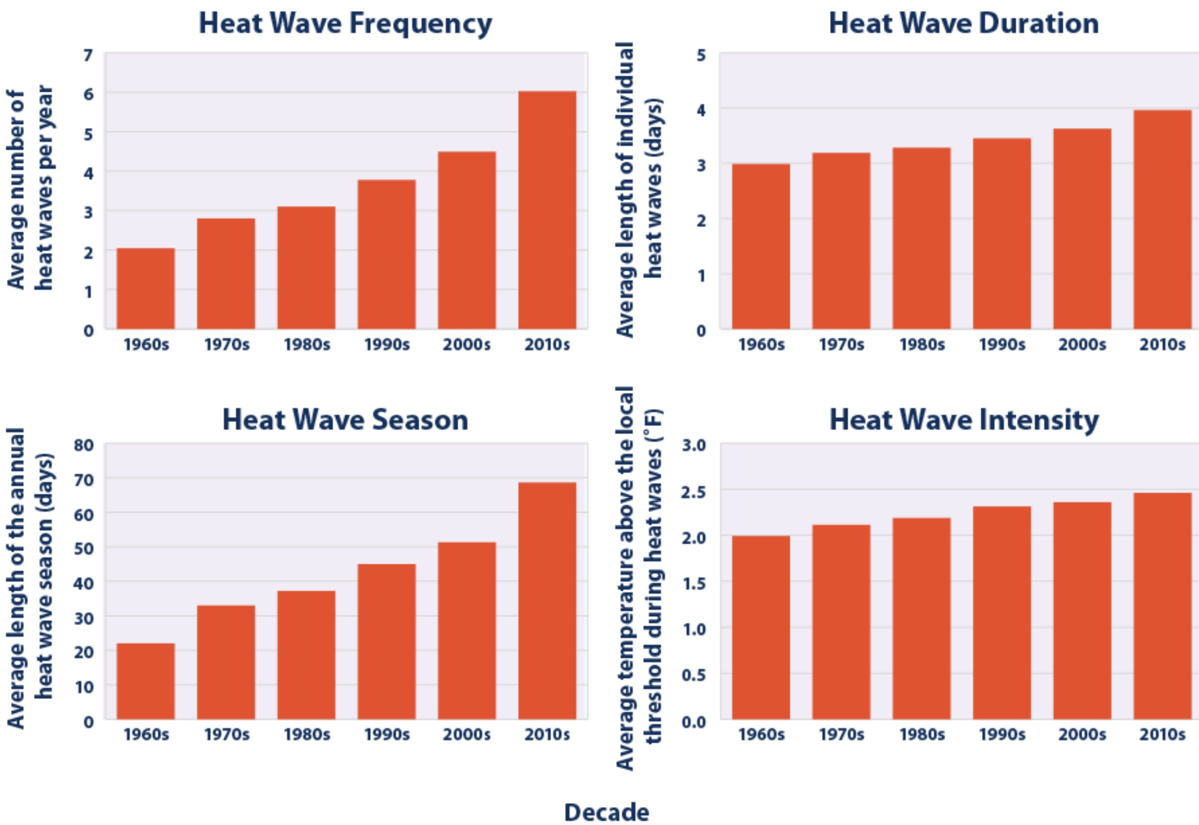


Figure 7: “Changes in the number of heat waves per year (frequency); the average length of heat waves in days (duration); the number of days between the first and last heat wave of the year (season length); and how hot the heat waves were, compared with the local temperature threshold for defining a heat wave (intensity). These data were analyzed from 1961 to 2019 for 50 large metropolitan areas. The graphs show averages across all 50 metropolitan areas by decade” EPA (2021).

Not only have the occurrence of heat waves increased recently, they have also happened outside of the summer season; “Heat waves that occur earlier in the spring or later in the fall can catch people off-guard and increase exposure to the health risks associated with heat waves” EPA (2021). Their intensity has also increased over time. “Heat waves have become more intense over time. During the 1960s, the average heat wave across the 50 cities was 2.0°F above the local 85th percentile threshold. During the 2010s, the average heat wave has been 2.5°F above the local threshold (see Figure 1)” EPA (2021). This trend is not expected to slow down anytime soon. Our climate is changing, normally hot weather and heat waves are natural and not unusual to witness. With a warming climate, “hotter-than-usual days and nights are becoming more common and heat waves are expected to become more frequent and intense” EPA (2021). These increases are serious since “even small increases in extreme heat can result in increased deaths and illnesses” EPA (2021). Therefore, adaptation measures and prevention planning needs to take place.

Currently, “30% of the global human population is at risk of exposure to heat conditions exceeding a lethal threshold, and this percentage will increase to 48% and 74% by 2100 respectively under the low (RCP2.6) and high (RCP8.5) greenhouse gas emissions scenarios" Rennie et al. (2021). Other researchers such as Pryor & Schoof (2019) agree with these projections. In their research, they highlight that there is a “high probability of temperatures of unprecedented severity over large parts of the contiguous United States by the end of the century under a high emissions scenario and a 3–8°C increase in the annual maximum 3-day T over the western United States. Substantial changes in extreme temperatures in the United States could occur much sooner, within just two to three decades". And once relative humidity is considered, the projections are expected to grow. “Projections in which the combined future impacts of temperature and humidity are found to be greater than those associated with changes in temperature alone. However, it has also been demonstrated that uncertainties in projections of some health-related metrics combining temperature and humidity are smaller than if temperature and humidity were independent” Pryor & Schoof (2019). There are projections for higher wet bulb globe temperatures too. According to Safina et al. (2018); “By late this century, climate change could even occasionally cause wet bulb conditions of 95 degrees Fahrenheit — a level equivalent to nearly 170 degrees of “dry” heat, which would make it difficult to survive without artificial cooling”. This applies to Nebraska as well.

Severe Heat Wave Events:

"A series of unusually hot days is referred to as an extreme heat event or a heat wave. Heat waves are more than just uncomfortable: they can lead to illness and death, particularly among older adults, the very young, and other vulnerable populations. Prolonged exposure to excessive heat can lead to other impacts as well—for example, damaging crops, injuring or killing livestock, and increasing the risk of wildfires. Prolonged periods of extreme heat can lead to power outages as heavy demands for air conditioning strain the power grid" EPA (2021).

One major well-known heat event was the 1995 Chicago Heat Wave. According to Semenza et. al (1996), the heat wave lasted four days and led to hundreds of deaths. "From July 12 through July 16, 1995, in Chicago, the maximal and minimal temperatures reached unprecedented highs, and the high temperatures were accompanied by extremes of relative humidity. Within a few days of the onset of the heat spell, the Cook County Medical Examiner's Office reported a sharp increase in the number of heat-related deaths". It was later discovered that those who were most at risk of dying were "people with medical illnesses who were socially isolated and did not have access to air conditioning" , Semenza et. al (1996).

It was stressed in the study by Semenza et. al (1996) that many of the deaths attributed to the Chicago Heat Wave could have been avoided and in general that morbidity and mortality can be reduced. They recommended that for future events, "interventions directed to such persons (those most at risk) should reduce deaths related to heat". Interventions the researchers listed in the study included providing access to air conditioning, spreading information via media coverage as soon as possible since "excess deaths do not typically occur until the second, third, or fourth day of a heat wave" , Semenza et. al (1996) and finally emphasizing the importance via home health care workers and friends of high-risk groups. In Figure 8 below, total deaths of the

Chicago Heat Wave are listed as well as the cause of death, whether or not they were due to heat alone.

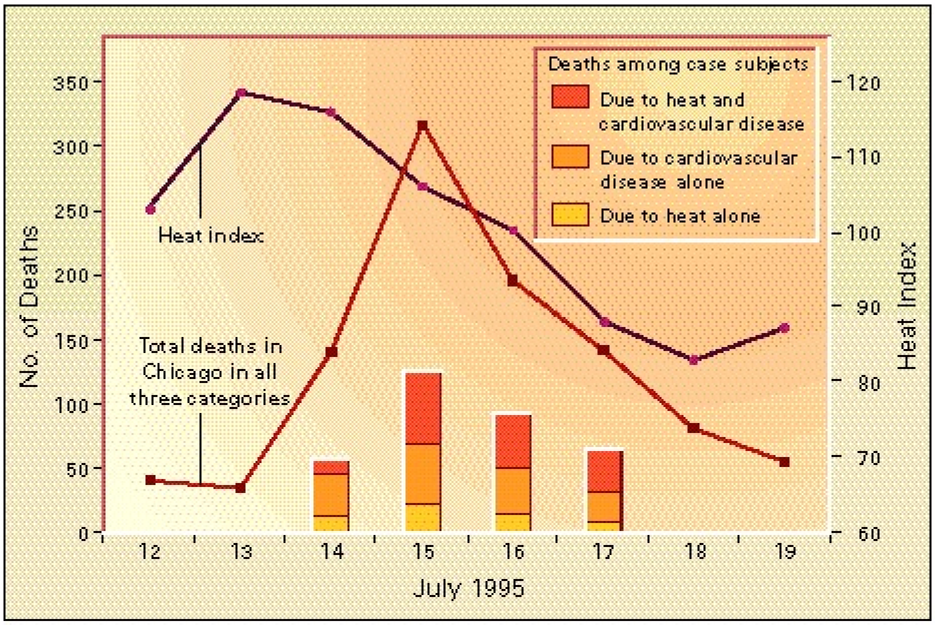


Figure 8: Chart depicting the number of deaths and the HI with the July 1995 Heat Wave that impacted Chicago, IL. Total deaths in all three categories (heat and cardiovascular disease and heat, cardiovascular disease alone, and heat alone) are listed in comparison to HI values spanning the four days of the heat event Semenza et. al (1996).

Local Impacts/Importance:

Locally, we have seen several instances of increasing temperature trends as well as effects from high heat. According to the recent *Understanding and Assessing Climate Change: Implications for Nebraska,* published in 2014, Nebraska faces: “Projected temperature increase of 4-5F (low emissions scenario) or 8-9F (high emissions scenario) by 2100, projected summer of 2100 will have 13-25 days over 100F, number of nights over 70F will increase by 20-40 days by 2100, and so far temperatures have only risen about 1F since 1895” Bathke et al. (2014). This is important to note because we have not lived in a world where temperatures have risen this high this fast.

Looking specifically into Lincoln, NE for future climate trends, over the next 100 years, “the number of hot days would increase by 13-22 days during a given summer (depending upon the scenario), and the number of warm nights would increase by 20-35 nights each summer” Bathke et al. (2014). These higher summer temperatures will “increase electricity use, causing higher summer peak loads” as well as “pose physical and mental health challenges…outdoor work will become more difficult, riskier, and less productive” Bathke et al. (2014).

In general, for average annual temperatures, “Nebraska shows an increase of 1.8°F over the 122- year period. There is high year-to-year variability, with significant warmth during the 1930’s Dust Bowl era, and generally warm conditions since the mid-1980s. 2012 was the warmest year on record, followed closely by 1934 and then 2016. Four of the top ten warmest years on record have occurred since 2005. The annual warming trend is greater for minimum temperatures (2.5°F) than for maximum temperatures (1.2°F)” Heartland Sustainability Directors Network. (2018). A visualization for this is in Figure 9 below.

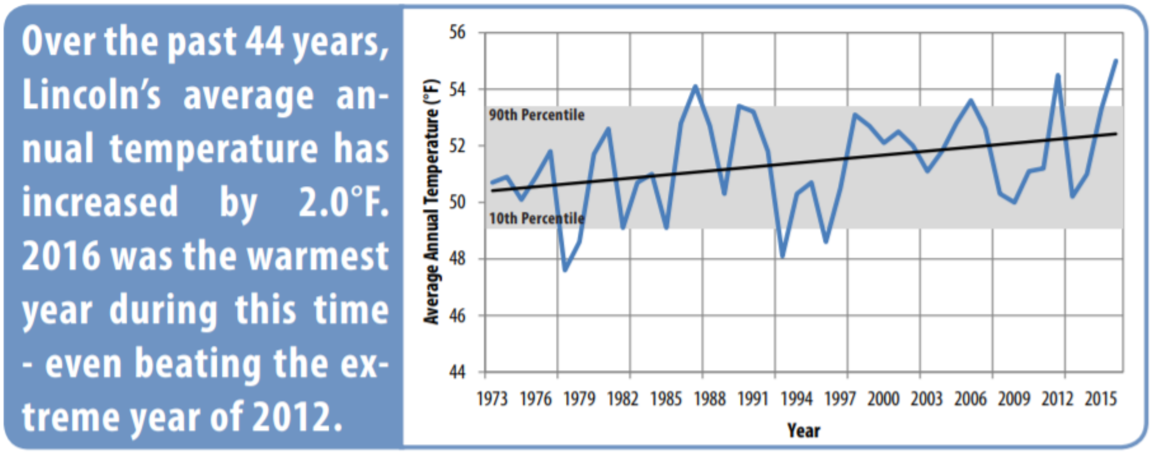


Figure 9: Graph showing the average annual temperature trend for Nebraska from 1973-2015 Heartland Sustainability Directors Network (2018).

For the future, projected changes vary based on the emission scenario. "Projected changes in temperature for Nebraska range from 4°F to 5°F (low emission scenarios) to 8°F to 9°F (high emission scenarios) by the last quarter of the twenty-first century (2071-2099) Under both the lower and higher emissions scenarios, the projected number of high temperature stress days over 100°F is expected to increase substantially Heartland Sustainability Directors Network (2018). Also, "projected high temperature stress days will increase to 13-16 additional days for the lower emissions scenario and 22-25 days for the higher emissions scenario" Heartland Sustainability Directors Network (2018). Currently, "the average number of days exceeding 100°F, based on the 1980- 2010 normals, is 2.1 days/year for Omaha, 4.6 days/ year for Lincoln, 3.5 days/year for Grand Island, 10.9 days/year for McCook, and 5.3 days/year for Scottsbluff. This increase for Nebraska in the number of high temperature stress days would equate to experiencing typical summer temperatures by midcentury (2041-2070) equivalent to those experienced during the 2012 drought and heat wave" Heartland Sustainability Directors Network (2018).

Daytime highs aren't the only thing being impacted either. "The number of warm nights, defined as the number of nights with the minimum temperature remaining above 80°F for the southern Plains states and above 60°F for the northern Plains states, is expected to increase dramatically. For Nebraska, the number of warm nights is expected to increase to an additional 20-25 nights for the lower emissions scenario and 25- 40 nights for the higher emissions scenario Heartland Sustainability Directors Network (2018). These increases in the number of days exceeding 100°F will also change energy demands and needs in Nebraska. "Trends in cooling degree days show an 8% increase overall, with the largest increase, by percentage, in the spring (47%)" Heartland Sustainability Directors Network (2018). These trends are concerning, since they can have serious impacts on utilities and vulnerable populations in Nebraska.

Methods

Research for this project was exploratory-based, as there is limited data and information published on the subject matter. The main methods used were meta-analysis, visual representation with charts and graphs, and comparative analysis. Research began with choosing counties by climate division in Nebraska to have an even distribution of data across a broad area. Eight counties were chosen: (Scotts Bluff, Cherry, Madison, Custer, Lancaster, Keith, Phelps, and Jefferson) with the respective climate divisions of 1, 2, 3, 5, 6, 7, 8, 9 as defined by the Climate Prediction Center (CPC). Higher populated cities were then selected from within those counties in order to ensure that enough data would be available. The cities from each respective county are as follows: Scottsbluff, Valentine, Norfolk, Broken Bow, Lincoln, Ogallala, Holdredge, and Fairbury.

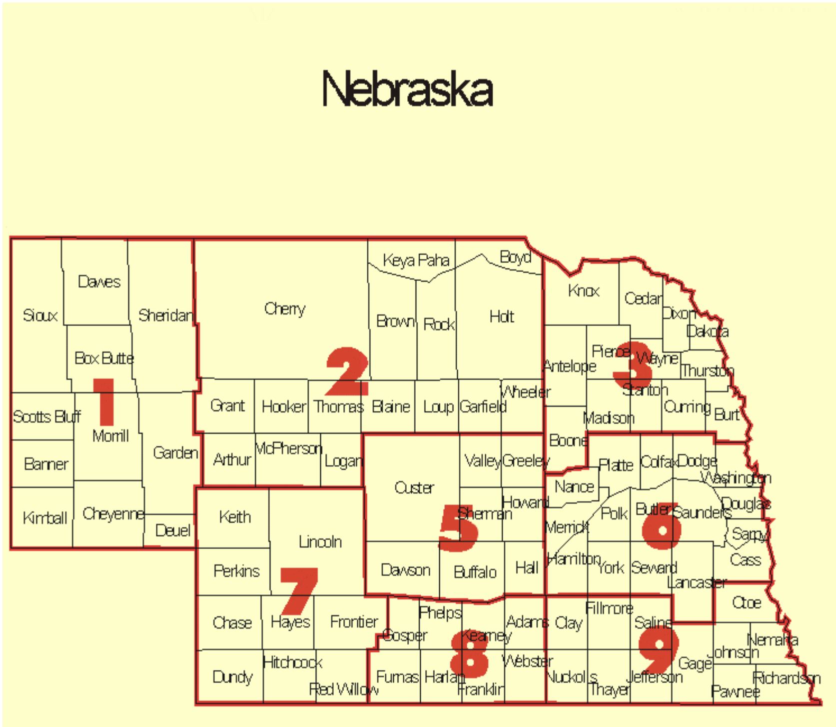


Figure 10: A map of Nebraska's climate divisions broken down in eight sections labeled 1,2,3,5,6,7,8,9. There is no section four. Climate Prediction Center (2005)

After confirming which locations to focus on, I then proceeded to the xmACIS2 database in order to find maximum high temperature data for the meteorological summer months (June-August) over the last climate normal period (1991-2020). On the xmACIS2 database, you start by clicking the single station tab and then you select daily data listing. Afterwards, you select CSV for the output and put 6/1/1991 for the start date and 8/31/20 for the end date. Then, under "variable", you checkmark the box that says max temp value. Finally, under "station selection", you can either search for your desired city and click the station you want on the map or change the CWA to the general location of where you are looking for and then select the specific location above. The stations and CWA locations used were as follows: SCOTTSBLUFF W B HEILIG FIELD AP, NE, VALENTINE MILLER FIELD AP, NORFOLK KARL STEFAN

MEMORIAL AP, BROKEN BOW 2 W, LINCOLN AIRPORT, OGALLALA, HOLDREGE, and FAIRBURY 5S. For the Fairbury location, from 6/28/19 - 8/27/19 a different source was used to procure temperature records since information was missing for those two months from the original station.

After receiving the CSV output of values, only the daily data listing from June 1st until August 31st for each year was manually selected. These values were uploaded to an Excel spreadsheet, formatted the data for text to column, and repeated these actions for all eight of the cities. The temperature value outputs were in degrees fahrenheit. In order to have complete data and no missing values, all values marked with "M" or not available data entries were changed by taking the average of the two surrounding day's temperatures to fill in the missing data gap.

For this project, I wanted to measure and find answers to specific formulas which included: Dewpoint (Td), Relative Humidity (RH), Heat Index (HI), Wet Bulb Globe, Temperature (WBGT), Tw=Wet Bulb Temperature (Celsius), Apparent Temperature (AT), and Vapor Pressure (e).

In order to find the answers to these variables, temperature values were first converted into celsius using the Excel convert function (=CONVERT,(cell #,"F","C")) for all eight cities. After converting, celsius temperatures were used as an input to find vapor pressure (as vapor pressure is an important and necessary component to calculate apparent temperature). Using the formula $e(\text{millibars}) = 6.1078 \exp((17.269*T) / (237.3+T))$, vapor pressure in millibars for all eight cities was calculated. Next, vapor pressure was converted into kilopascals (kpa) in order to use the value for the apparent temperature formula since “ignoring wind effects, one can estimate apparent temperature as A (°C) = $-1.3 + 0.92T + 2.2e$, where T is ambient air temperature (°C) and e is water vapor pressure (kPa) (Steadman 1984)”. Conversion from mb to kpa is simply dividing the mb answer by ten. Once this was completed, the inputs were plugged into the apparent temperature formula as stated above.

Once the values for time, maximum temperature in fahrenheit and celsius, vapor pressure in mb and kpa, and apparent temperature in degrees celsius were found, maximum temperature (in degrees celsius) vs time, apparent temperature vs time, and a combined graph of both maximum temperature (in degrees celsius) vs time for every city were graphed in order to visually demonstrate the changes over the past 30 year climate normal and to see if outliers or trends could be found and/or explained. The graphs were completed via Excel with the data that had been previously found with the line graph option. The graphs were then formatted with appropriate axis titles and apparent temperature was color-coded to be orange and maximum temperature in celsius was blue, this was also shown on the legend for the combined graphs. Exploratory research was then conducted by visually comparing the completed graphs to a figure by Diffey, (2018) on air temperature, relative humidity, and health risks in order to find instances of seriously high heat index values from 1991-2020.

Research for Lincoln in Lancaster county was further extended by finding and calculating dew point, relative humidity, heat index, and wet bulb temperature. These formulas could only be calculated for the Lincoln location since documented climatological records of average dew point or average relative humidity values for any of the other cities could not be found. First, daily average dewpoint values in fahrenheit were located on the Southeastern Lincoln weather website https://www.gwwilkins.org/wxabout.php powered by a Davis Wireless Vantage Pro2™ Plus with 24-Hr Fan Aspirated Radiation Shield located near 66th and South Streets in SE Lincoln. It held records for average dewpoint values from June 1st 2008-August 31st 2020, which is short of what was originally desired but it was accepted regardless. After copying these values down in Excel, which are coded by color key, they were then used along with the maximum high temperature values in degrees fahrenheit as inputs to calculate relative humidity using the formula: 100*(EXP((17.625*TD)/(243.04+TD))/EXP((17.625*T)/(243.04+T))). Then, heat index values were found using the formula:

$-42.379+2.04901523\cdot Tf+10.14333127\cdot RH-0.22475541\cdot (Tf)\cdot (RH)-6.83783\cdot 10-3\cdot (Tf\^{}2)-5.481717\cdot 10-2\cdot (RH\^{}2)+1.22874\cdot 10-3\cdot (Tf\^{}2)\cdot (RH)+8.5282\cdot 10-4\cdot (Tf)\cdot (RH\^{}2)-1.99\cdot 10-6\cdot (Tf\^{}2)\cdot (RH\^{}2)$

After finding the heat index values, they became color coded green, yellow, orange, red, purple, or blue based on how high they were (green=below 80 degrees fahrenheit, yellow=80-85.0, orange=85.01-88.0, red=88.01-90.0, purple=90.01-100.0, and blue=over 100). The heat index results were color-coded according to human comfort levels and effects/danger of high heat. Then, heat index data was displayed in a histogram in Excel that showcases the frequency of specific heat index values within the thirty year dataset.

The wet bulb temperature was calculated using the formula:

$T * \arctan[0.151977 * (rh\% + 8.313659)\^{}(1/2)] + \arctan(T + rh\%) – \arctan(rh\% – 1.676331) + 0.00391838 *(rh\%)\^{}(3/2) * \arctan(0.023101 * rh\%) – 4.686035$

The full wet bulb globe temperature could not be calculated as Globe Thermometer Temperature for any of the chosen locations could not be found. That temperature requires a special instrument measurement that is rarely taken and documented.

Finally, information on the number of CDD in Nebraska was located and the values for June-August for the years 1991-2020 were copied over onto Excel and made into a simple column graph to visually depict trends of CDD for the timeframe. The year 1993 was absent from the dataset.

The second part of the project was a comparative analysis of wet bulb globe temperature calculators and outlook tools. Five online calculators were chosen: Caribou, ME (NWS), OSHA, CISA Convergence, Tulsa, OK (NWS), and the OK Mesonet and compared them to one another in order to discover similarities, differences, reliability, ease of access, amount of information and data available, accuracy, and completeness all to answer the question “How could one of these temperature tools be modeled and optimized for the Midwest and Nebraska?”

The terms chosen to evaluate the following calculators included: standard inputs, preparedness & safety tips, map of location, outlooks, solar irradiance, graphs and data tables, whether it was a prototype or not/was it fully supported?, does it give a heat index, does it ask for cloud cover, does it require wind speed values, does it ask for lat/lon coordinates, does it suggest water intake, and does it give workload suggestions based on heat values.

The answer to these prompts was determined by visiting each website and going through all information available and thoroughly examining and scrutinizing each one, checking off each box if the calculator met the requirement. Afterwards, they were given a score based on the amount of boxes checked off in order to determine the “best” calculator for analyzing WBGT and therefore being the best calculator to model for a Lincoln-based one.

Results

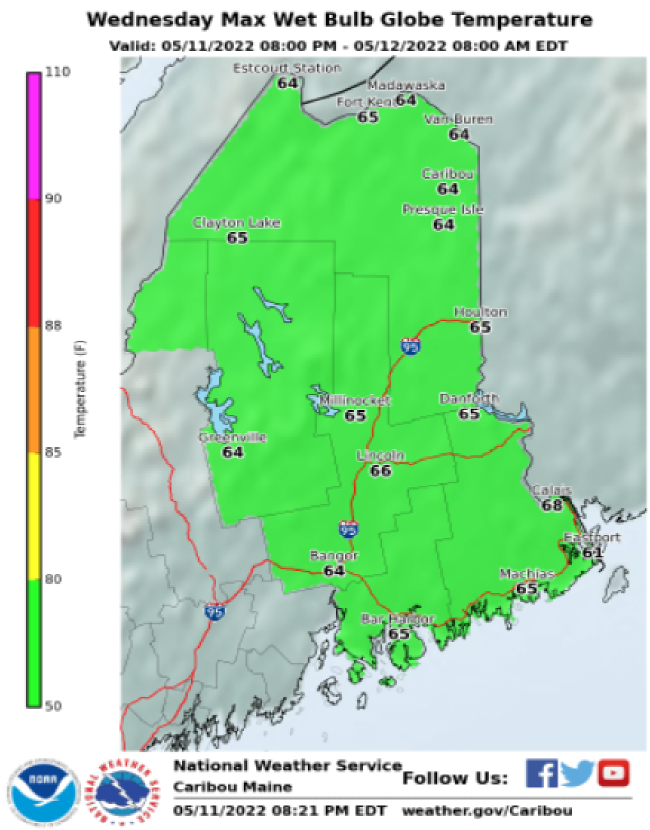
The first objective was to “compare and contrast all current WBGT tools found online in terms of readability, ease of access, amount of information and data available, accuracy, and completeness. These results would then help answer the question of the second objective: How could one of these temperature tools be modeled and created for the Midwest and Nebraska?”

The first tool chosen to analyze was the Caribou, ME National Weather Service (NWS) which was sponsored by the U.S. Department of Congress. The WBGT tool they had took into account temperature, humidity, wind speed, sun angle and cloud cover (solar radiation). This tool is currently experimental and has not launched fully. Some key features of this tool included a three day outlook of WBGT for the upper half of the state of Maine. The key cities listed for this tool included: Estcourt Station, Fort Kent, Madawaska, Van Buren, Caribou, Presque Isle, Clayton Lake, Houlton, Millinocket, Lincoln, Danforth, Greenville, Bangor, Calais, Eastport, Machias, and Bar Harbor. To the left of the map showing the featured cities is a temperature legend with ratings from green to pink which indicate severity of WBGT in degrees fahrenheit. Underneath the map is a table showing suggested actions and impact prevention depending on WBGT value. A screenshot of the website is listed below.

Day 1	Day 2	Day 3

Wet Bulb Globe Temperature (WBGT) is a measure of the heat stress in direct sunlight, which takes into account: temperature, humidity, wind speed, sun angle and cloud cover (solar radiation). This differs from the heat index, which takes into consideration temperature and humidity and is calculated for shady areas. For more background info on WBGT, click here.

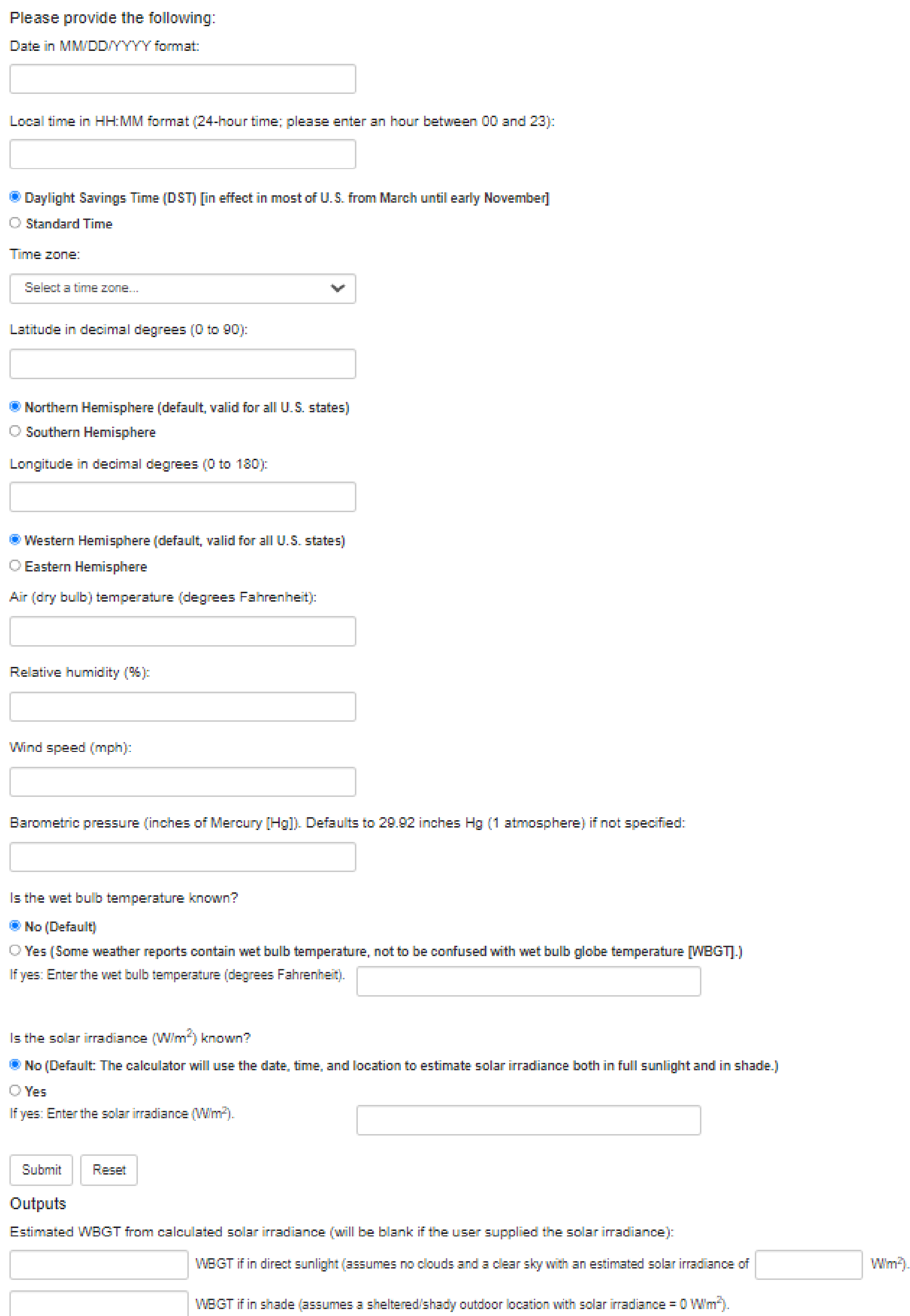
*****Experimental*****



Suggested Actions and Impact Prevention		
WBGT(F)	Effects	Precautionary Actions
< 80		
80-85	Working or exercising in direct sunlight will stress your body after 45 minutes.	Take at least 15 minutes of breaks each hour if working or exercising in direct sunlight
85-88	Working or exercising in direct sunlight will stress your body after 30 minutes.	Take at least 30 minutes of breaks each hour if working or exercising in direct sunlight
88-90	Working or exercising in direct sunlight will stress your body after 20 minutes.	Take at least 40 minutes of breaks each hour if working or exercising in direct sunlight
>90	Working or exercising in direct sunlight will stress your body after 15 minutes.	Take at least 45 minutes of breaks each hour if working or exercising in direct sunlight

Figure : WBGT for Caribou, ME with three day outlook, map, and impact prevention chart USDC (2018).

The second WBGT tool I chose to analyze was the OSHA Calculator. Sponsored by the United States Department of Labor, the OSHA calculator “estimates outdoor wet bulb globe temperature (WBGT) from standard meteorological inputs" OSHA (2008). The Kasten-Czaplak algorithm is used for estimating clear sky solar irradiance and the WBGT is estimated via the heat and mass transfer algorithm of Liljegren et al. (2008) OSHA (2008). Software for this tool was created by the United States Department of Energy. The tool asks for the user to input the information of date in MM/DD/YYYY format, local time in HH:MM format, indicate if its daylight savings or not, input latitude and longitude in decimal degrees, indicate which hemispheres (N/S, E/W), air (dry bulb) temperature in degrees fahrenheit, relative humidity (%), wind speed (mph), barometric pressure (inches of Mercury [Hg]), and indicate whether wet bulb temperature and/or if solar irradiance (w/m^2) is known. With these user inputs, the estimated WBGT and HI are given. A screenshot of the tool is listed below:



Please provide the following:

Date in MM/DD/YYYY format:

Local time in HH:MM format (24-hour time; please enter an hour between 00 and 23):

(•) Daylight Savings Time (DST) [in effect in most of U.S. from March until early November]

( ) Standard Time

Time zone:

Select a time zone...

Latitude in decimal degrees (0 to 90):

(•) Northern Hemisphere (default, valid for all U.S. states)

( ) Southern Hemisphere

Longitude in decimal degrees (0 to 180):

(•) Western Hemisphere (default, valid for all U.S. states)

( ) Eastern Hemisphere

Air (dry bulb) temperature (degrees Fahrenheit):

Relative humidity (%):

Wind speed (mph):

Barometric pressure (inches of Mercury [Hg]). Defaults to 29.92 inches Hg (1 atmosphere) if not specified:

Is the wet bulb temperature known?

(•) No (Default)

( ) Yes (Some weather reports contain wet bulb temperature, not to be confused with wet bulb globe temperature [WBGT].)

If yes: Enter the wet bulb temperature (degrees Fahrenheit).

Is the solar irradiance (W/m^2) known?

(•) No (Default: The calculator will use the date, time, and location to estimate solar irradiance both in full sunlight and in shade.)

( ) Yes

If yes: Enter the solar irradiance (W/m^2).

Submit Reset

Outputs

Estimated WBGT from calculated solar irradiance (will be blank if the user supplied the solar irradiance):

WBGT if in direct sunlight (assumes no clouds and a clear sky with an estimated solar irradiance of W/m^2).

WBGT if in shade (assumes a sheltered/shady outdoor location with solar irradiance = 0 W/m^2).

Figure : A snippet showing the WBGT tool where the user inputs a variety of data in order to get a highly accurate and specialized reading OSHA (2008).

The third tool analyzed was the CISA Convergence WBGT tool. The website included a definition of the term, showed how it is measured, gave background on how to understand the results, and answered some FAQs. The tool itself included three directions on how to use it. First was “type your location/address in the white box or select a location within the states on the map below” which included a list of viable states: “ND, SD, NE, KS, OK, TX, MN, IA, MO, AR, LA, WI, IL, MI, IN, KY, TN, MS, AL, OH, ME, NH, VT, MA, RI, CT, NJ, DE, MD, DC, NY, PA, WV, VA, NC, SC, GA, FL”. Next, the site instructs you to “Click the “Submit” button at the bottom of the map and scroll down the page to see the forecast” and gives the option of “If you would like to see an earlier forecast, select a model time in the white box (at the bottom) and click the “Submit” button”. Finally, it states “scroll further down the page to see the WBGT activity guidelines”. After the instructions is an interactive map of the United States where you can click on a specific location. Following the map is a forecast with a five day outlook of WBGT based on time of day. Lastly, there is a “WBGT Activity Guidelines and Rest/Break Guidelines for Athletes” which you refer to based on the “colors” forecast for your area. The chart includes heat category, WBGT index in degrees Fahrenheit, and activity guidelines involving rests and water breaks. Screenshots of the tool are posted below:

1. Type your location/address in the white box or select a location within the states on the map below.

- ND, SD, NE, KS, OK, TX, MN, IA, MO, AR, LA, WI, IL, MI, IN, KY, TN, MS, AL, OH, ME, NH, VT, MA, RI, CT, NJ, DE, MD, DC, NY, PA, WV, VA, NC, SC, GA, FL

2. Click the "Submit" button at the bottom of the map and scroll down the page to see the forecast.
If you would like to see an earlier forecast, select a model time in the white box (at the bottom) and click the "Submit" button.

3. Scroll further down the page to see the WBGT activity guidelines.

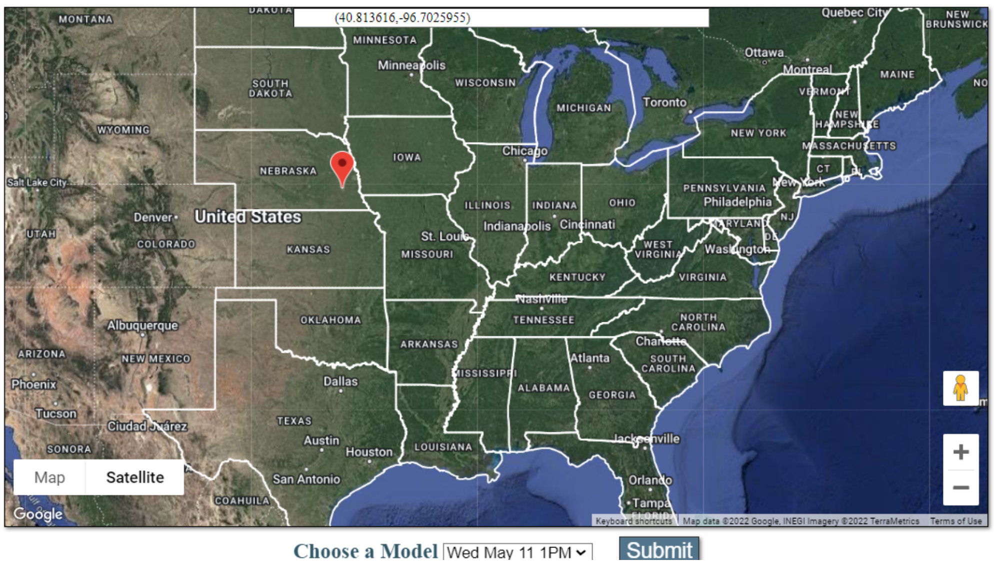
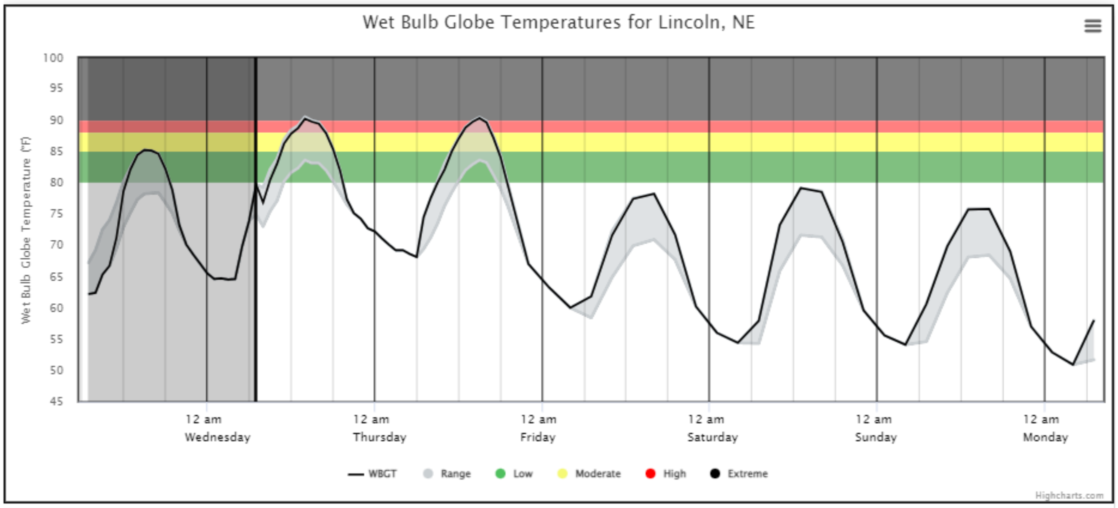


Figure : Interactive map and directions for how to use the WBGT tool, there is also an option for choosing which model run of the data is requested Convergence (2022).



Conditions are expected to reach the black flag category for the forecast period. Please look below to view WBGT guidelines.

WBGT Activity Guidelines and Rest/Break Guidelines for Athletes

Heat Category	WBGT Index (F)	Activity Guidelines
No Flag	Under 80	Unlimited activity with primary cautions for new or unconditioned athletes or extreme exertion; schedule mandatory rest/water breaks. (5 min rest/water break every 30 min)
Low (Green Flag)	80-84.9	Normal practice for athletes; closely monitor new or unconditioned athletes and all athletes during extreme exertion. Schedule mandatory rest/water breaks. (5 min water/rest break every 25 min)
Moderate (Yellow Flag)	85-87.9	New or unconditioned athletes should have reduced intensity practice and modifications in clothing. Well-conditioned athletes should have more frequent rest breaks and hydration as well as cautious monitoring for symptoms of heat illness. Schedule frequent mandatory rest/water breaks. (5 min rest/water break every 20 min) Have cold or ice immersion pool on site for practice.
High (Red Flag)	88-89.9	All athletes must be under constant observation and supervision. Remove pads and equipment. Schedule frequent mandatory rest/water breaks. (5 min rest/water break every 15 min) Have cold or ice immersion pool on site for practice.
Extreme (Black Flag)	Over 90	SUSPEND PRACTICE

Source: North Carolina High School Athletics Association

Figure : Second part of the CISA WBGT tool showing the five day outlook based on time of day and recommendations for prevention of heat-related illness in the activity guideline chart below.

The fourth tool looked at was the WetBulb Globe Temperature tool for Tulsa, OK sponsored once again by the USDC. This tool is also a prototype under development and is not meant for operational use at this time. This website featured a definition and importance of WBGT, and then proceeded to have a map for selecting a location via latitude/longitude coordinates. Next, you could adjust month, day, latitude, forecasted maximum temperature in degrees fahrenheit, dew point in degrees fahrenheit, RH, wind speed (mph), and cloud cover (%) via sliders. Once adjusted, both a HI and WBGT value would be displayed. The website also contained two maps showing the difference between HI and WBGT as well as a comparison table, and examples of both. Then, at the bottom, preparedness, safety measures, and suggested actions and impact prevention advice was given. Finally, there is a list of hyperlinks for other resources about WBGT such as the OSHA work load manual. Snippets of the tool are displayed below:

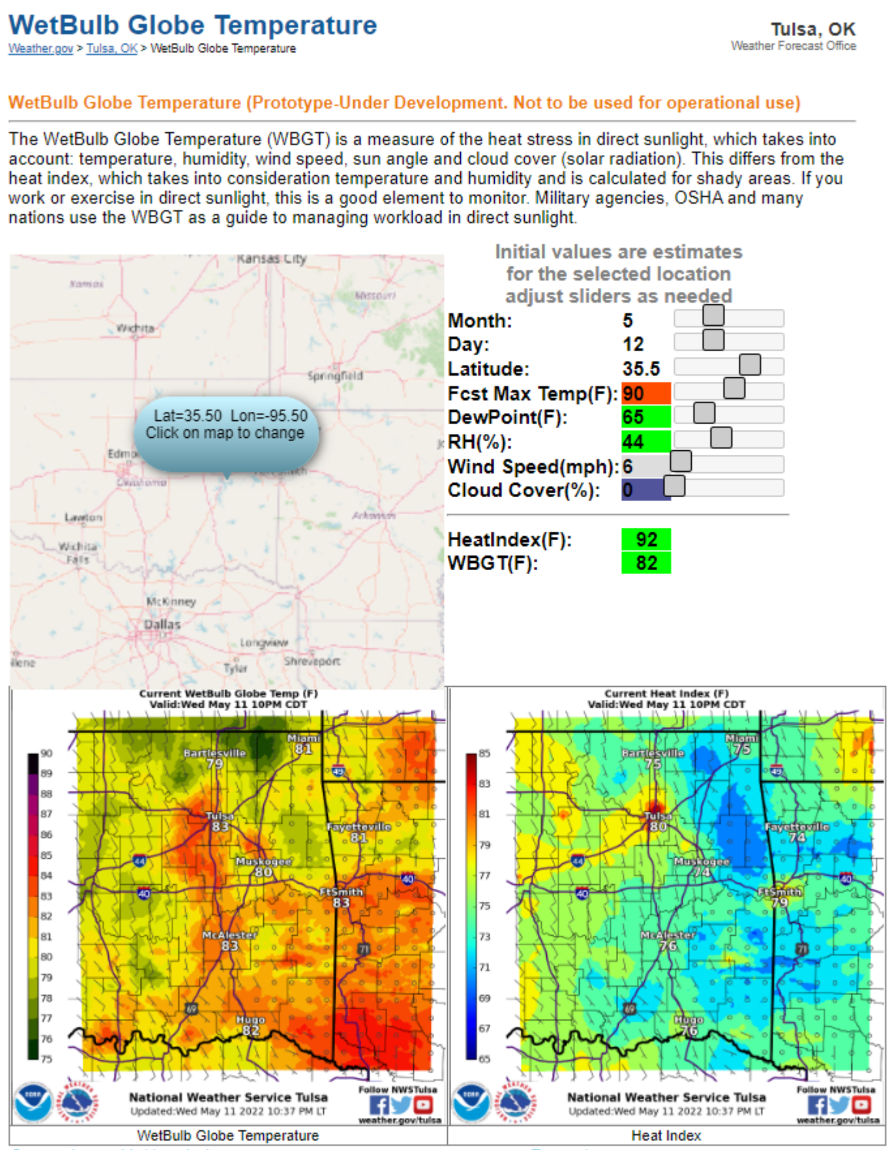


Figure : Part 1 of the Tulsa, OK WBGT tool showing an interactive coordinate-based map of the US, slider bars to change various inputs, and maps showing the differences between current HI and current WBGT values USDC (2019).

Comparison with Heat Index

	WBGT	Heat Index
Measured in the sun	✓	✗
Measured in the shade	✗	✓
Uses Temperature	✓	✓
Uses RH	✓	✓
Uses Wind	✓	✗
Uses Cloud Cover	✓	✗
Uses Sun Angle	✓	✗

Examples

Temp F	Dwpt F	RH %	Sky %	Wind mph	HeatIdx F	WBGT F
90	65	42	05	03	92	89
90	65	42	05	13	92	83
90	65	42	65	13	92	81
90	70	52	10	06	96	88
90	70	52	60	06	96	86
90	70	52	60	13	96	85
100	70	39	10	13	108	90
100	70	39	10	5	108	94
100	70	39	65	05	108	91

Other Resources

More WBGT Information
WBGT Research Paper
OSHA work load and WBGT Manual

***Preparedness** - What to do before doing outdoor activities when the WBGT is high -*

- Wear a hat and light weight, light fitting, light colored clothes.
- Plan to take frequent breaks in shady areas.

***Safety** - What to do while doing outdoor activities when the WBGT is high -*

- **Take breaks in the shade**. Strenuous outdoor activities should be reduced, especially in direct sunlight where there is little ventilation.
- **Drink plenty of water or other non-alcohol fluids.** Your body needs water to keep cool. Drink plenty of fluids even if you don't feel thirsty.
- **Don't get too much sun**. Sunburn makes the job of heat dissipation that much more difficult

Suggested Actions and Impact Prevention		
WBGT(F)	**Effects**	**Precautionary Actions**
< 80		
80-85	Working or exercising in direct sunlight will stress your body after 45 minutes.	Take at least 15 minutes of breaks each hour if working or exercising in direct sunlight
85-88	Working or exercising in direct sunlight will stress your body after 30 minutes.	Take at least 30 minutes of breaks each hour if working or exercising in direct sunlight
88-90	Working or exercising in direct sunlight will stress your body after 20 minutes.	Take at least 40 minutes of breaks each hour if working or exercising in direct sunlight
>90	Working or exercising in direct sunlight will stress your body after 15 minutes.	Take at least 45 minutes of breaks each hour if working or exercising in direct sunlight

Figure : Second part of Tulsa, OK tool showing a comparison chart between HI and WBGT, examples of each, and preparedness/safety advice USDC (2019).

The last tool that was looked into further was the Wet Bulb Globe Temperature Risk tool published by the Oklahoma Mesonet. The tool lists an interactive map of the state of Oklahoma showing every city's WBGT for the day in accordance to its risk value. It is updated every five minutes and requires no input from the user. There is an additional informative handout that details the history of WBGT and shows a Unacclimated and Acclimated Work/Rest and Water Intake Chart which recommends work/rest intervals and suggested water intake based on heat risk category, WBGT, and type of work done (light, moderate, heavy). There are also additional warnings based on type of clothing worn and gives examples showing what types of activities equal what work level. Variables included in the Oklahoma Mesonet's WBGT calculation include: “air temperature at 1.5 meters; wind speed at 2 meters; relative humidity at 1.5 meters; and solar radiation” Mesonet (2022). A screenshot of the tool is below:

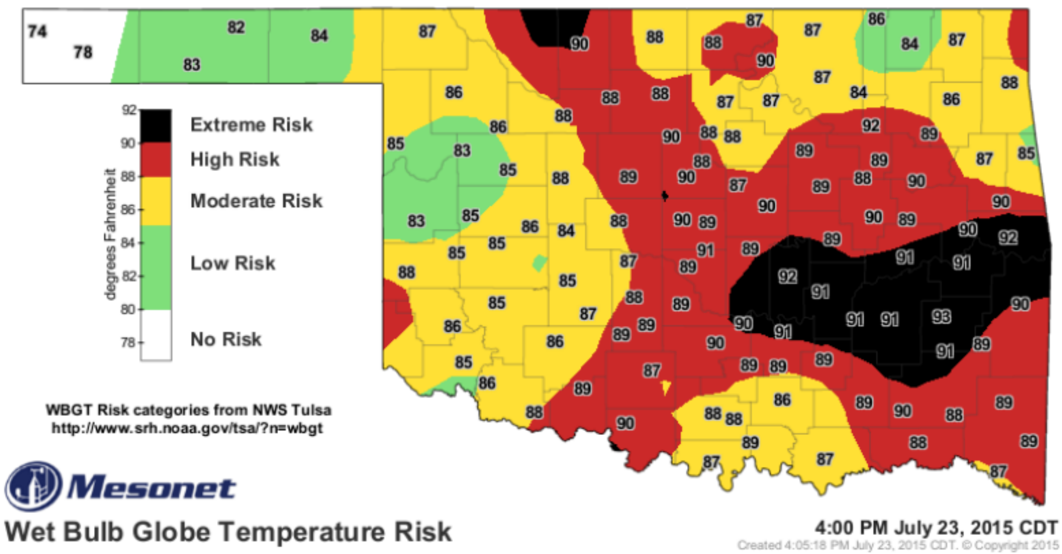


Figure : The Oklahoma Mesonet WBGT risk assessment tool featuring risk categories from the NWS Tulsa office Mesonet (2016).

Unacclimated and Acclimated Work/Rest and Water Intake Chart

Heat Risk Category		Wet Bulb Globe Temp	Light Work		Moderate Work		Heavy Work	
			Work/Rest	Water Intake (quart/hr)	Work/Rest	Water Intake (quart/hr)	Work/Rest	Water Intake (quart/hr)
No Risk	Unacclimated	78 – 79.9	50/10 min	½	40/20 min	¾	30/30 min	¾
	Acclimated	78 – 79.9	continuous	½	continuous	¾	50/10 min	¾
Low	Unacclimated	80 – 84.9	40/20 min	½	30/30 min	¾	20/40 min	1
	Acclimated	80 – 84.9	continuous	½	50/10 min	¾	40/20 min	1
Moderate	Unacclimated	85 – 87.9	30/30 min	¾	20/40 min	¾	10/50 min	1
	Acclimated	85 – 87.9	continuous	¾	40/20 min	¾	30/30 min	1
High	Unacclimated	88 – 90	20/40 min	¾	10/50 min	¾	avoid	1
	Acclimated	88 – 90	continuous	¾	30/30 min	¾	20/40 min	1
Extreme	Unacclimated	> 90	10/50 min	1	avoid	1	avoid	1
	Acclimated	> 90	50/10 min	1	20/40 min	1	10/50 min	1

Adapted from: 1) USGS Survey Manual, Management of Occupational Heat Stress, Chapter 45, Appendix A. 2) Manual of Naval Preventive Medicine, Chapter 3: Prevention of Heat and Cold Stress Injuries. 3) OSHA Technical Manual Section III: Chapter 4 Heat Stress. 4) National Weather Service Tulsa Forecast Office, Wet Bulb Globe Temperature.

Figure: Unacclimated and Acclimated Work/Rest and Water Intake Chart for the Oklahoma Mesonet WBGT tool showcasing the difference between heat category and light, moderate, and heavy work Mesonet (2016).

Work Level	Activity examples
Rest	Sitting or standing
Light	Sitting with light manual work Driving on paved surface Walking 2 mph on hard surface
Moderate	Painting with brush Lawn mowing with walk behind power mower on flat area Pushing light wheelbarrow Weeding or hoeing Walking 3.5 mph on hard surface
Heavy	Digging or shoveling Hand sawing wood Chopping wood Walking 4 mph on hard surface or 2.5 mph in sand

Adapted from: USGS Survey Manual, Management of Occupational Heat Stress, Chapter 45, Appendix A. OSHA Water.Rest.Shade. Estimating Work Rates or Loads, 2015, osha.gov/SLTC/heatillness/heat_index/work_rates_loads.html

Figure: Work level vs activity examples for the Oklahoma Mesonet WBGT tool Mesonet (2016).

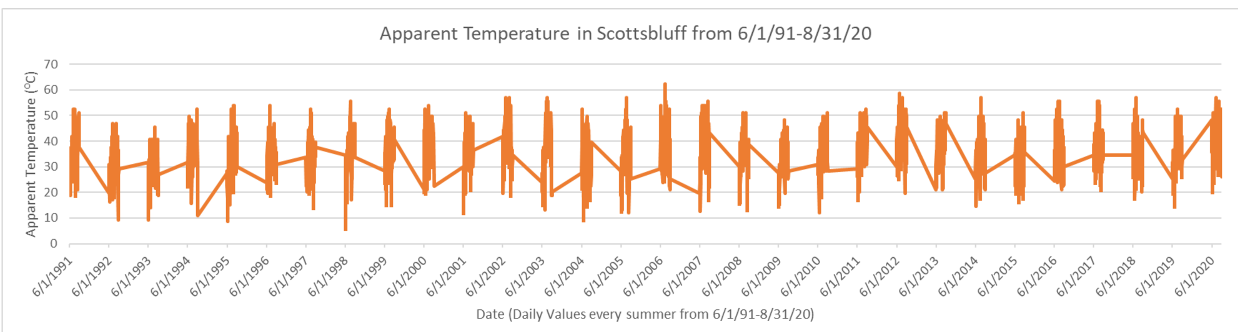
A final comparison between all of the WBGT tools resulted in this graph:

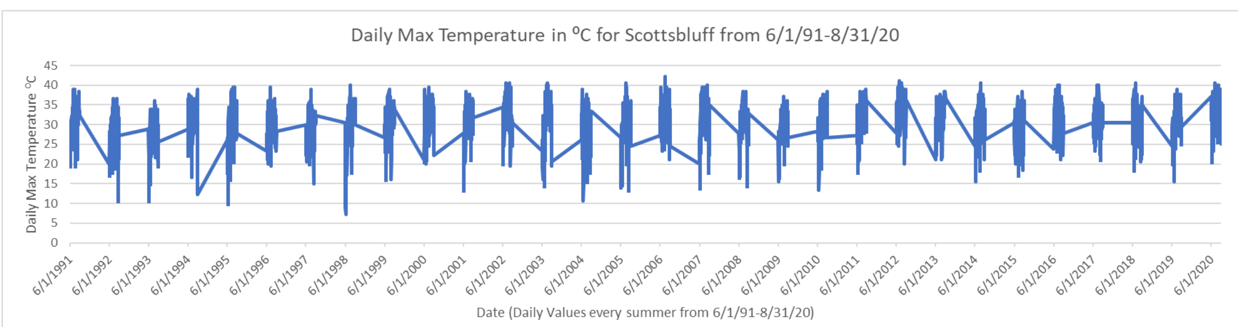
	Caribou, ME NWS	OSHA Calculator	CISA Convergence	Tulsa, OK NWS	OK Mesonet
Standard Inputs	×	×		×	
Preparedness & Safety tips	×		×	×	×
Map of Location	×		×	×	×
Outlooks	×		×		
Solar Irradiance		×			
Graph and Data Tables			×	×	
Prototype/Not fully supported	×			×	×
Gives Heat Index too		×		×	
Asks for Cloud Cover				×	
Asks for Wind Speed		×		×	
Asks for Lat/Lon coordinates		×		×	
Suggests water intake					×
Gives workload examples with heat					×

Figure: Table showing how each WBGT compares and contrasts with one another based on specific traits.

The third objective was to "observe noticeable summer (June-August) temperature patterns and trends for one city from each of Nebraska's nine climate regions under the last climate normal period (1991-2020) and calculate apparent temperature from the data". Below are apparent temperature values in degrees celsius, daily maximum temperature values in degrees celsius, and a comparison between the two from June 1st, 1991-August 31st, 2020 for the cities of Scottsbluff, Valentine, Norfolk, Broken Bow, Ogallala, Holdredge, Fairbury, and Lincoln in Nebraska.

Scottsbluff:





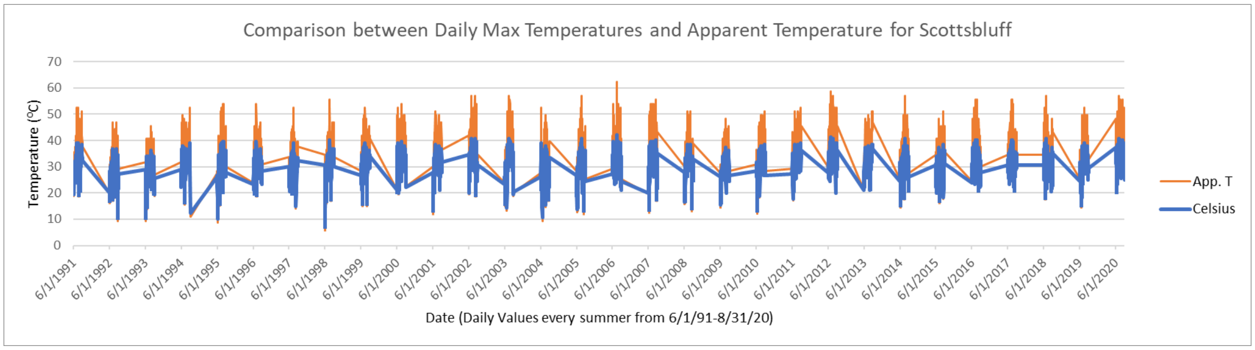
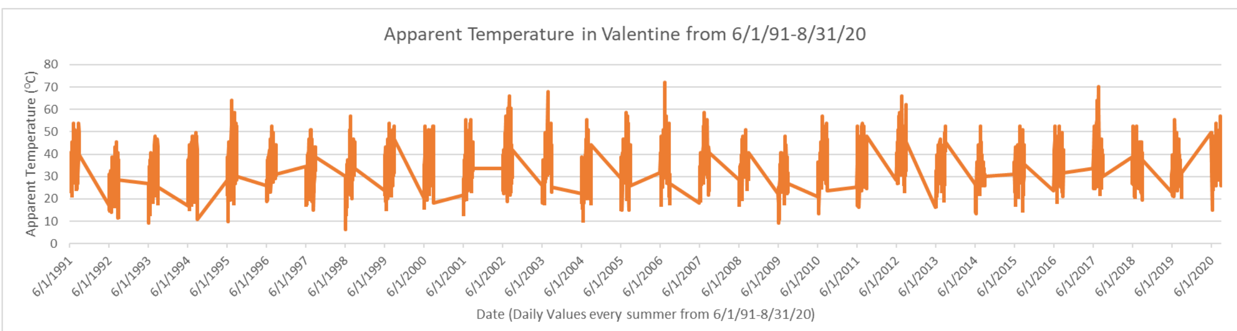
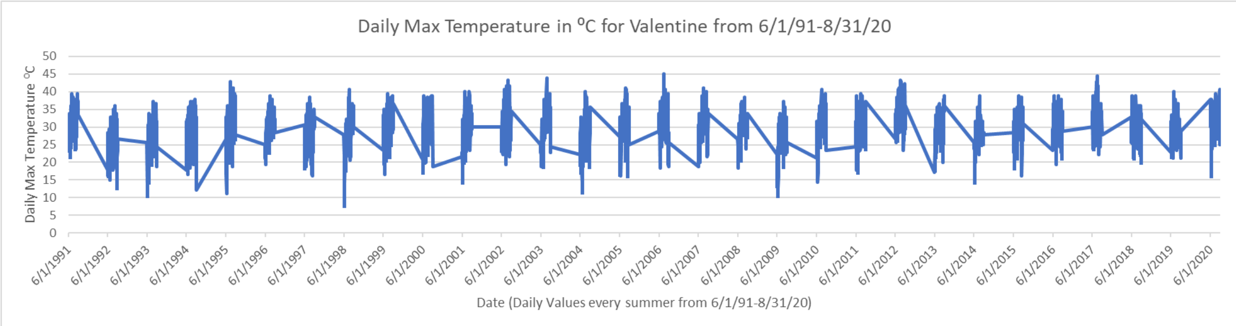


Figure : Apparent temperature, daily max temperature, and comparison between daily max temperatures and apparent temperature in degrees celsius for every summer (Jun-Aug) from 6/1/90-8/31/20 for Scottsbluff.

Valentine:





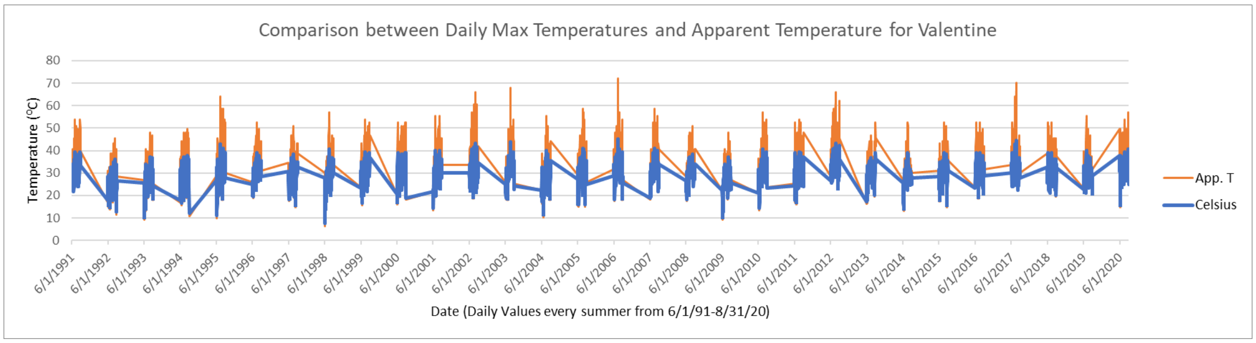
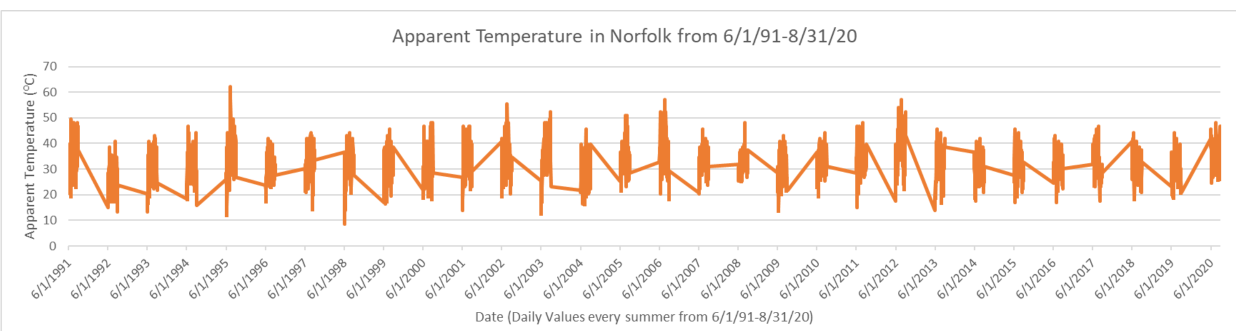
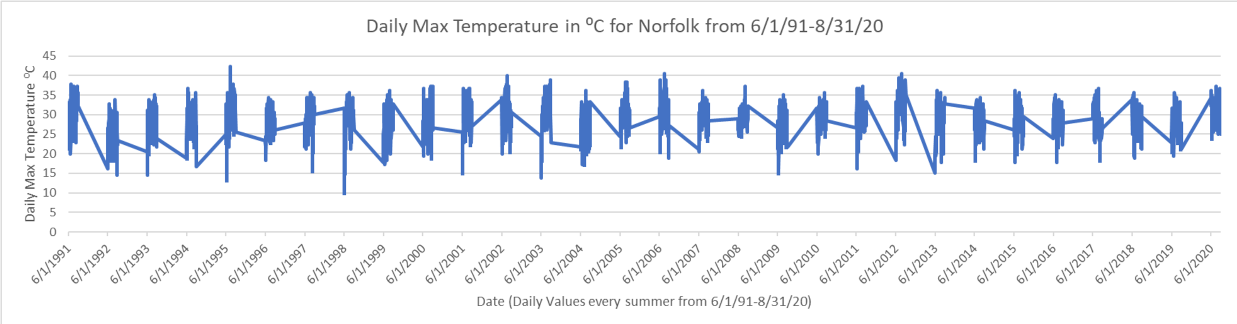


Figure : Apparent temperature, daily max temperature, and comparison between daily max temperatures and apparent temperature in degrees celsius for every summer (Jun-Aug) from 6/1/90-8/31/20 for Valentine.

Norfolk:





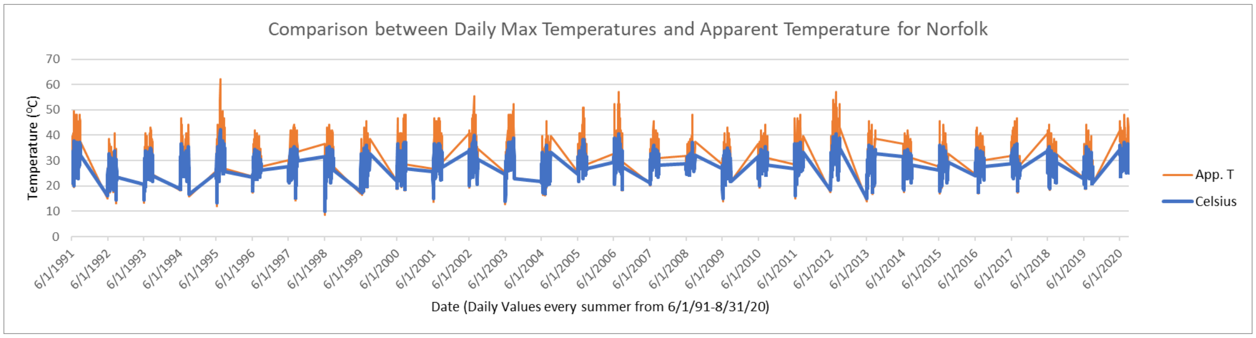
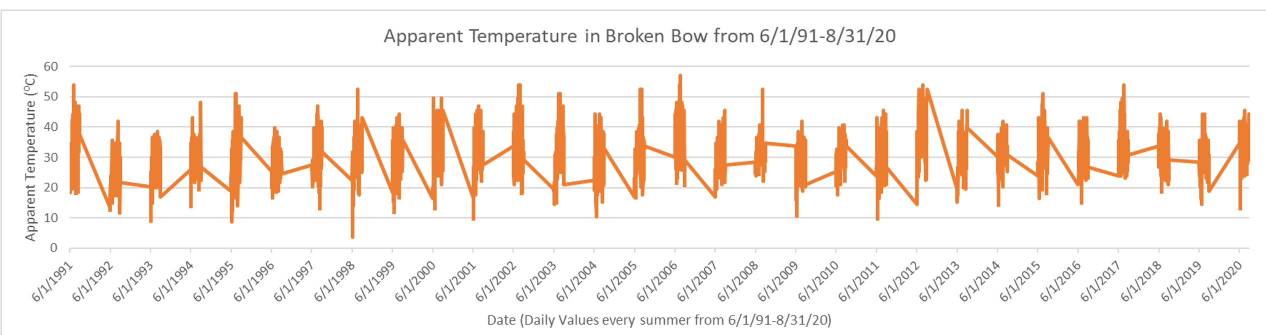
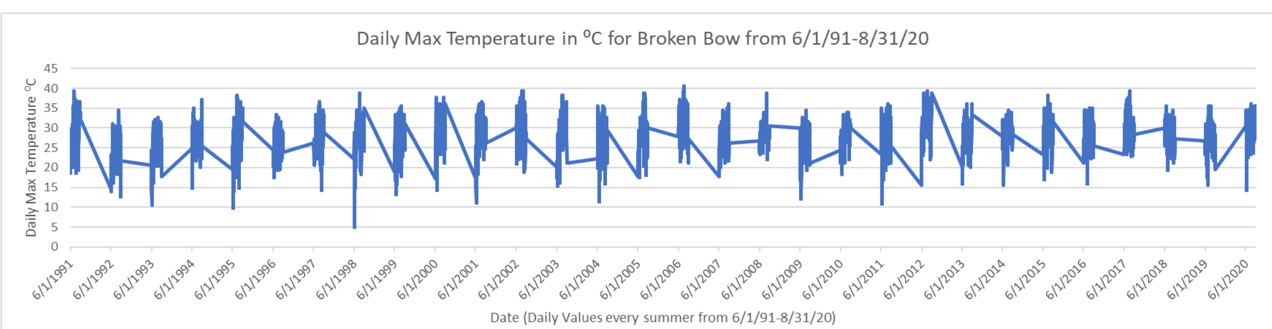


Figure : Apparent temperature, daily max temperature, and comparison between daily max temperatures and apparent temperature in degrees celsius for every summer (Jun-Aug) from 6/1/90-8/31/20 for Norfolk.

Broken Bow:





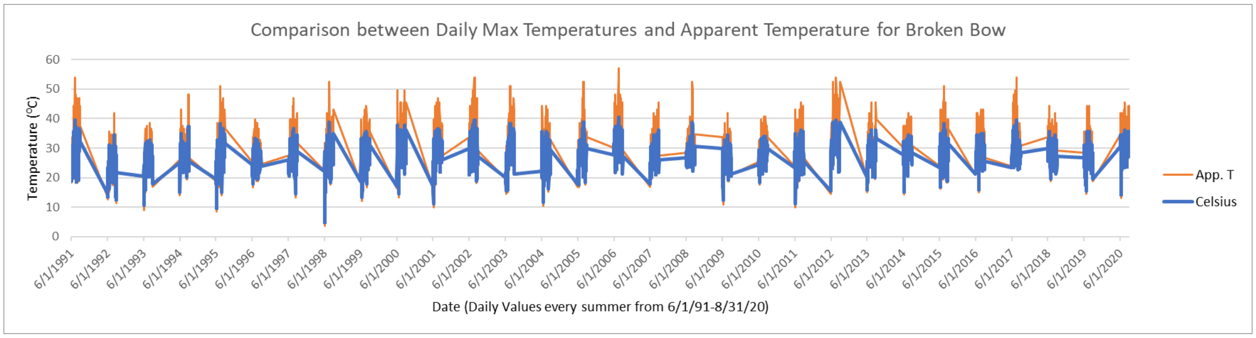
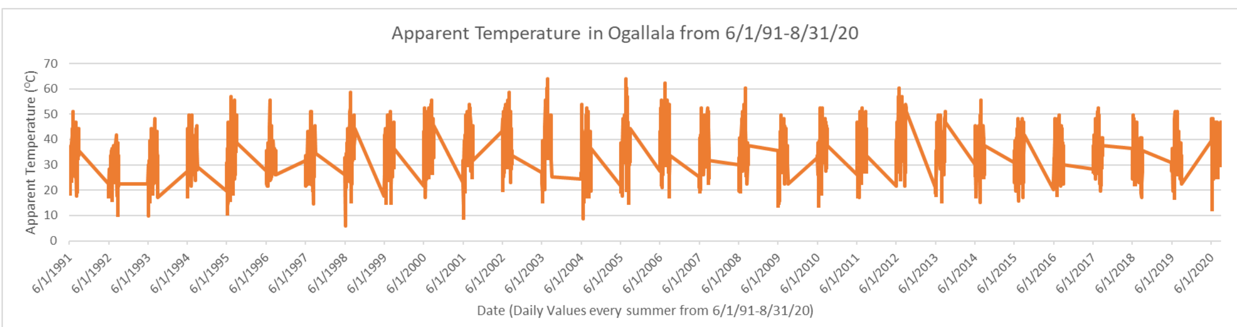
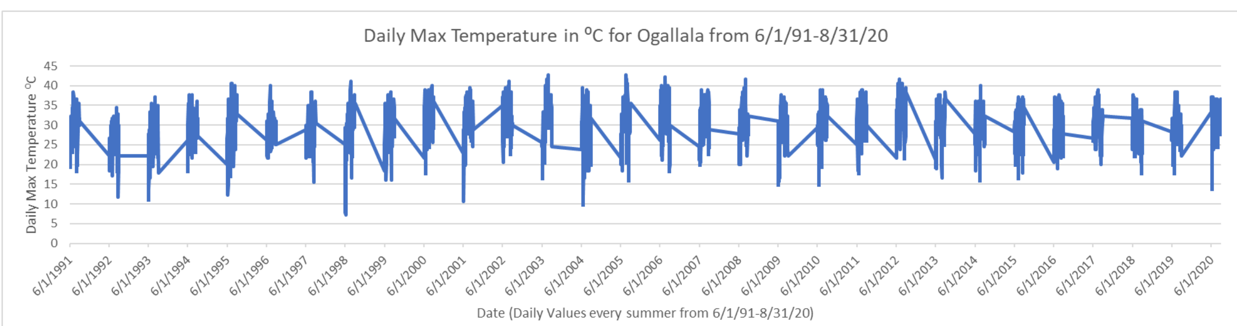


Figure : Apparent temperature, daily max temperature, and comparison between daily max temperatures and apparent temperature in degrees celsius for every summer (Jun-Aug) from 6/1/90-8/31/20 for Broken Bow.

Ogallala:





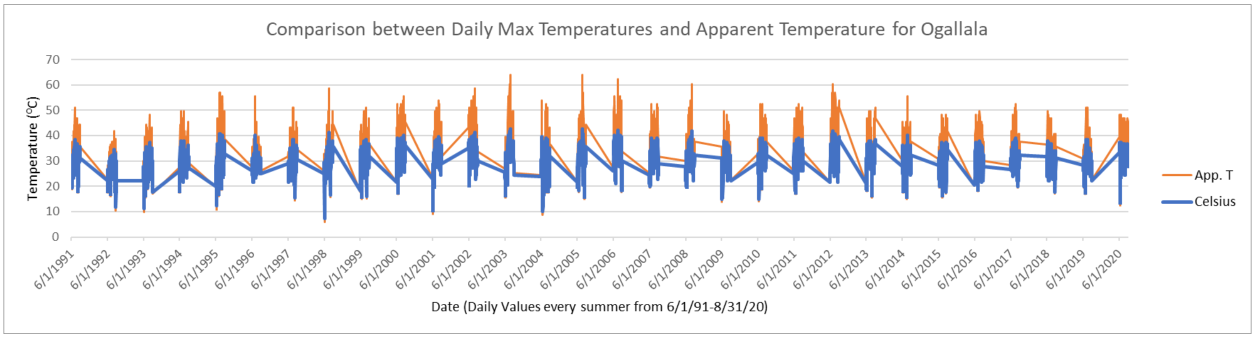
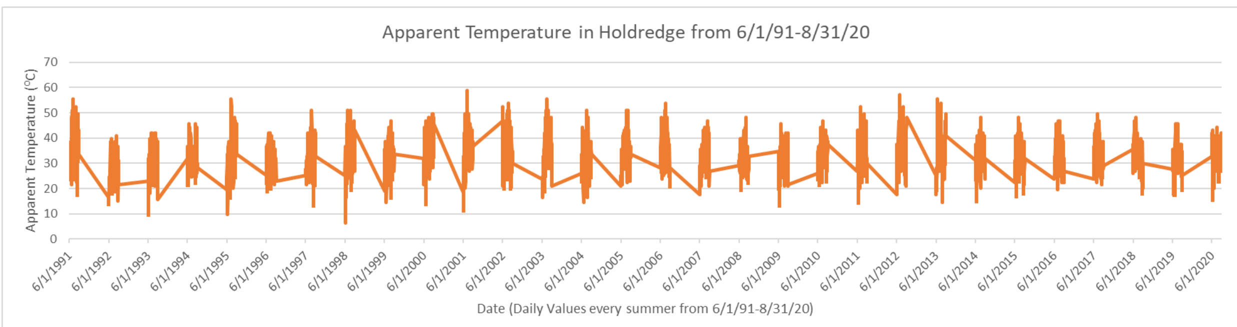
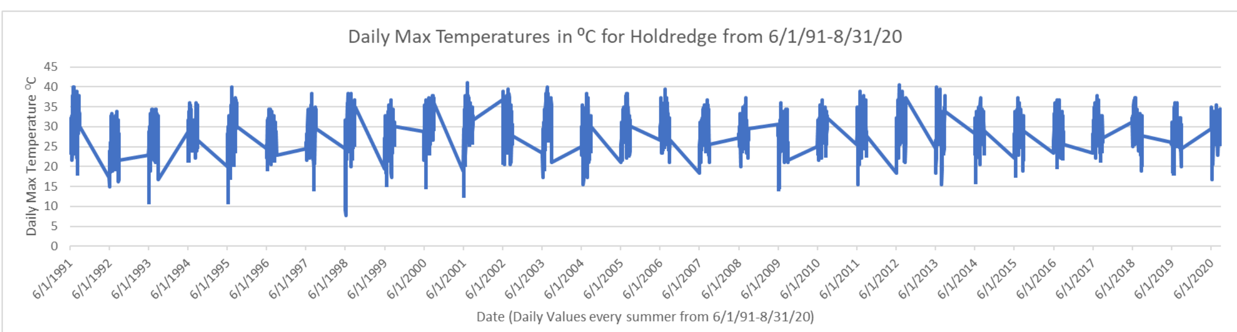


Figure : Apparent temperature, daily max temperature, and comparison between daily max temperatures and apparent temperature in degrees celsius for every summer (Jun-Aug) from 6/1/90-8/31/20 for Ogallala.

Holdredge:





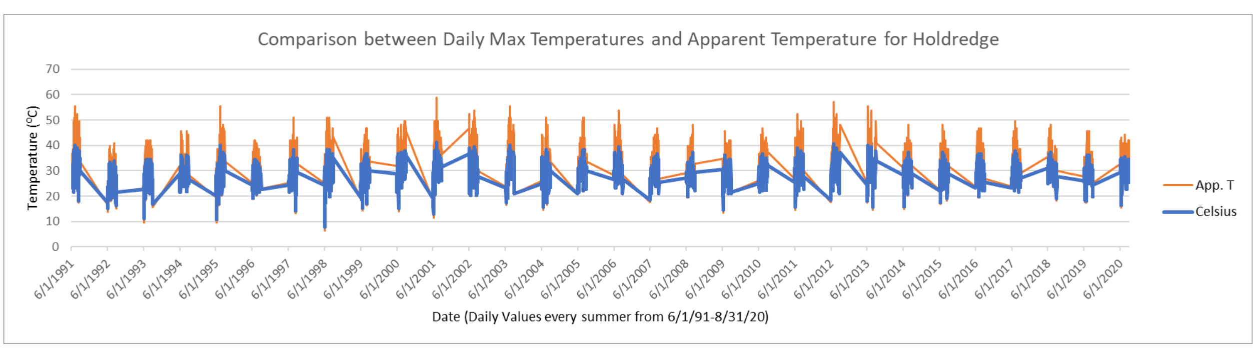
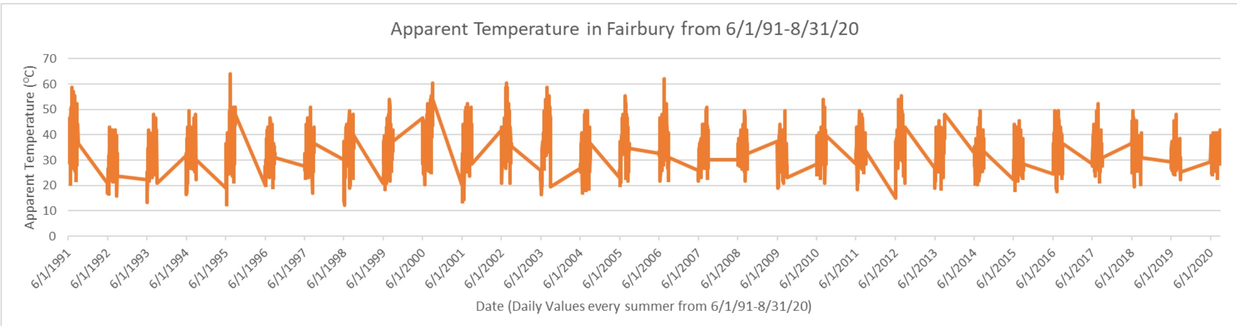
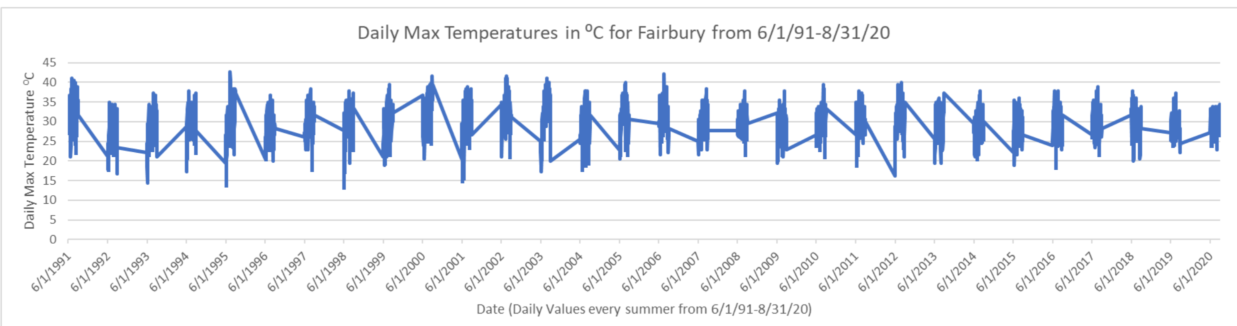


Figure : Apparent temperature, daily max temperature, and comparison between daily max temperatures and apparent temperature in degrees celsius for every summer (Jun-Aug) from 6/1/90-8/31/20 for Holdredge.

Fairbury:





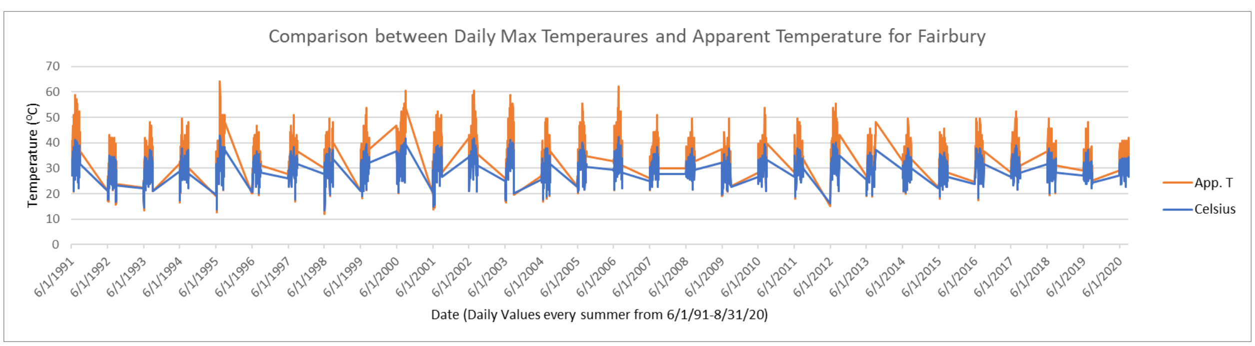


Figure : Apparent temperature, daily max temperature, and comparison between daily max temperatures and apparent temperature in degrees celsius for every summer (Jun-Aug) from 6/1/90-8/31/20 for Fairbury.

Lincoln:

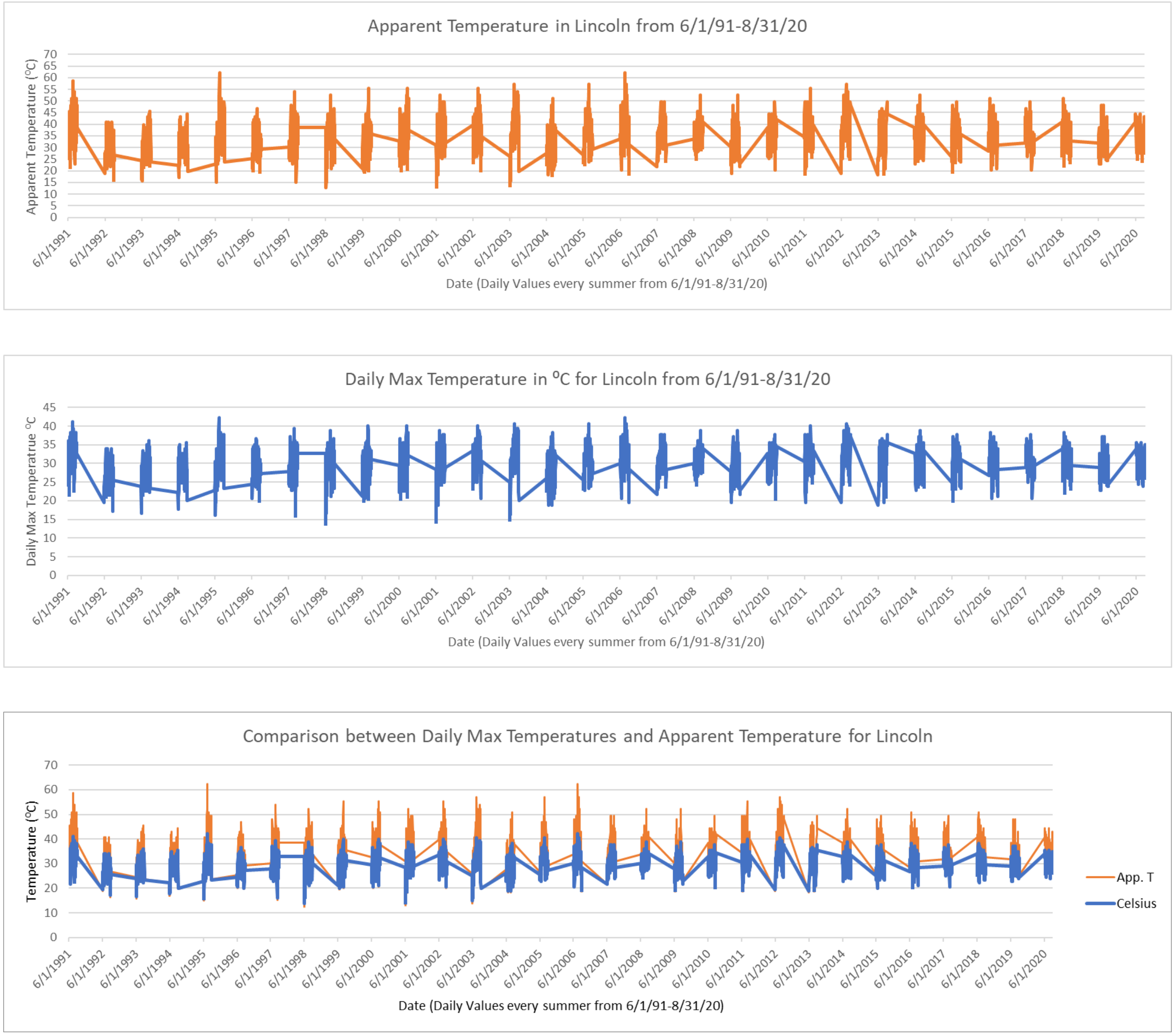


Figure : Apparent temperature, daily max temperature, and comparison between daily max temperatures and apparent temperature in degrees celsius for every summer (Jun-Aug) from 6/1/90-8/31/20 for Lincoln.

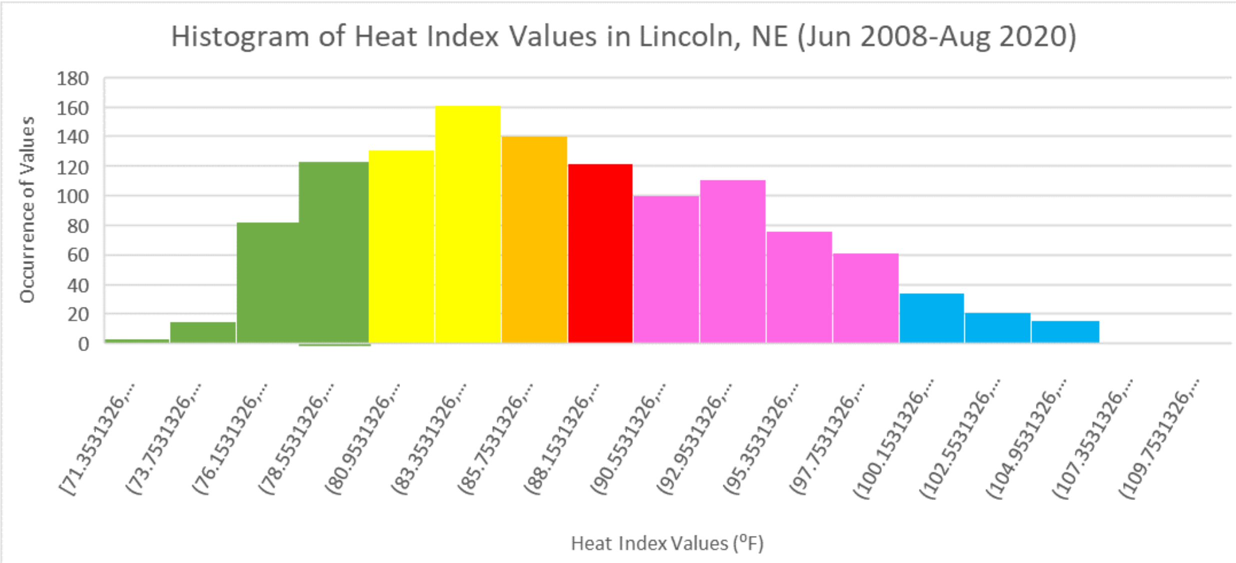


Figure: Histogram of HI values in Lincoln, NE from Jun 2008-Aug 2020.

Lastly, the fourth objective was to "assess the effect of increased relative humidity and apparent temperature values on the number of cooling degree days and, consequently, energy use/cost in Nebraska". Below are CDD graphs showing the past documented CDD in Nebraska, Lancaster county and predictions for the future for future CDD values and energy costs for electricity.

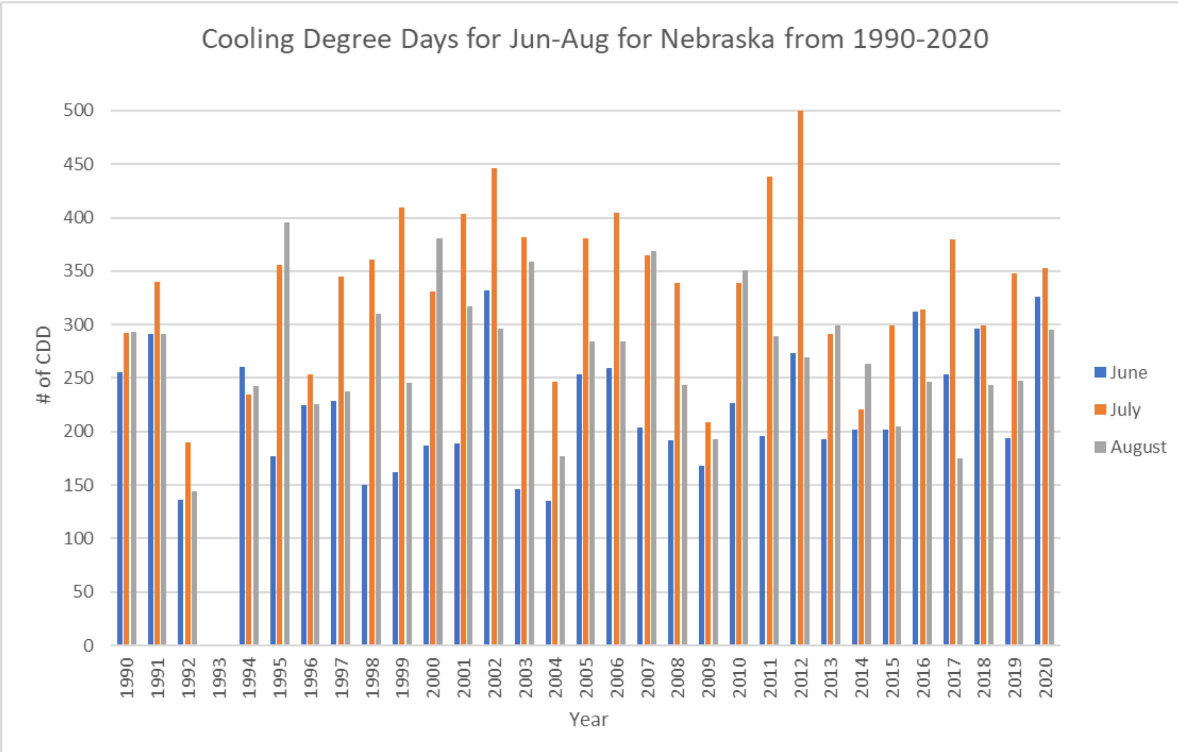


Figure : CDD days for June-August for Nebraska from 1991-2020 with one year of missing data in 1993.

Date	Cooling Degree Days				
	Winter	Spring	Summer	Fall	Year
Dec 2021 / Nov 2022	0.0	57.0* ↓	---	---	57.0* ↓
Dec 2020 / Nov 2021	0.0	108.7 ↓	1243.7 ↑	239.3 ↑	1591.7 ↑
Dec 2019 / Nov 2020	0.0	54.3 ↓	1229.7 ↑	157.2 ↓	1441.2 ↑
Dec 2018 / Nov 2019	0.0*	92.2 ↓	1058.6 ↓	298.1 ↑	1448.9* ↑
Dec 2017 / Nov 2018	0.0	247.4 ↑	1157.2 ↑	210.8 ↑	1615.4 ↑
Dec 2016 / Nov 2017	0.0	102.4 ↓	1093.1 ↓	248.4 ↑	1443.9 ↑
Dec 2015 / Nov 2016	0.0	79.7 ↓	1229.6 ↑	234.6 ↑	1543.9 ↑
Dec 2014 / Nov 2015	0.0	49.8 ↓	994.6 ↓	275.6 ↑	1320.0 ↓
Dec 2013 / Nov 2014	0.0	149.7 ↑	896.9 ↓	128.5 ↓	1175.1 ↓
Dec 2012 / Nov 2013	0.0	107.6 ↓	1019.0 ↓	234.1 ↑	1360.7 ↓
Dec 2011 / Nov 2012	0.0	251.0 ↑	1344.4 ↑	123.7 ↓	1719.1 ↑
Dec 2010 / Nov 2011	0.0*	106.2 ↓	1150.7 ↑	130.4* ↓	1387.3* ↑
Dec 2009 / Nov 2010	0.0	124.0 ↑	1202.5 ↑	124.9 ↓	1451.4 ↑
Dec 2008 / Nov 2009	0.0	117.5 ↑	774.0 ↓	67.6* ↓	959.1* ↓
Dec 2007 / Nov 2008	0.0*	44.3 ↓	912.7 ↓	105.3* ↓	1062.3* ↓
Dec 2006 / Nov 2007	---	---	---	0.0* ↓	0.0* ↓
Max	0.0	251.0	1344.4	298.1	1719.1
Avg	0.0	112.8	1093.3	171.9	1378.0
Min	0.0	44.3	774.0	0.0	0.0

Figure : CDD values for winter, spring, summer, fall, and yearly averages for Lincoln, NE from December 2006-May 2022. Summer is highlighted in neon green Wilkins (2022).

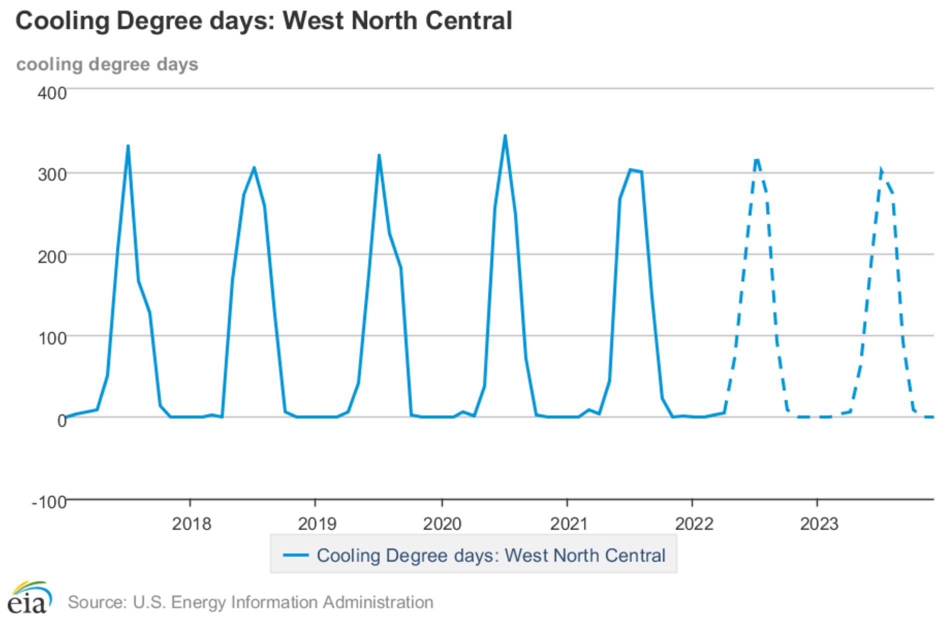


Figure : Chart depicting CDD values for the West North Central United States (NE included) from 2017-2023 future prediction EIA (2021).

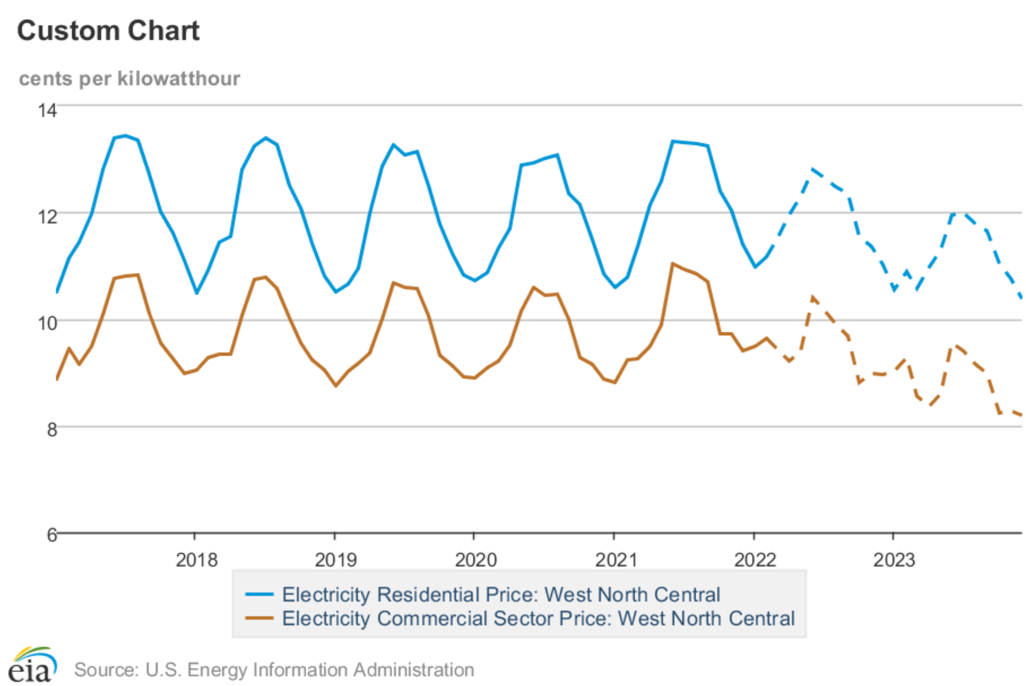


Figure : Chart depicting residential and commercial sector price of electricity in cents per kilowatt hour from 2017-2023 future predictions for the West North Central U.S. EIA (2021).

Discussion

Analysis, interpretation, explanation of data

The first objective was to "compare and contrast all current WBGT tools found online in terms of readability, ease of access, amount of information and data available, accuracy, and completeness. These results would then help answer the question of the second objective: How could one of these temperature tools be modeled and created for the Midwest and Nebraska?"

In the results, it was found that the Caribou, ME WBGT tool used the values of temperature, humidity, wind speed, sun angle, and cloud cover to calculate WBGT. It was a prototype calculator. Other features it had were a three day outlook and a suggested actions and impact prevention table. All in all, it was simple and fast but not very detailed.

The OSHA WBGT tool was more technically advanced and relied on the Kasten-Czaplak algorithm and the WBGT equation by Liljegren. It required a lot of user input such as date, time, lat/lon coordinates, hemisphere location, air temperature, RH, wind speed, and barometric pressure. The tool also gave the user more advanced options such as self-inputting the wet bulb temperature and/or solar irradiance values. Overall, it was extremely thorough, detailed, accurate, and relatively easy to use, but it required a bit of prior knowledge and relied on you knowing specific details about the location you wanted to find a WBGT value for. Also, it had no future outlook or prediction system in place, the WBGT value would only be valid for the present date.

The CISA tool gave lots of background information so anyone could understand what WBGT is and know how exactly it is measured. The only inputs needed were the location and model time (if you wanted to see a past run). The tool gave great visual representation of WBGT and its five day outlook was the longest out of all the tools analyzed. The outlook was also down to the hour and it could pinpoint when exactly you would not want to be outside practicing sports. If your prediction ran into the black (high danger zone), the tool would tell you to look at the activity guidelines for heat-illness prevention measures. Even though it is athlete-centered, the tool was simple and easy to follow with its specific instructions and it was full of useful information and tips regarding rest and water breaks based on WBGT values that could be utilized by anyone, not just athletes.

The Tulsa, OK tool was also a prototype like the Caribou, ME tool, but it contained more information and a more sophisticated platform. The website began by describing the definition and importance of WBGT and then allowed the user to choose lat/lon coordinates from a map. The main difference with this tool was that you could adjust input values for month, day, latitude, maximum temperature, dew point, RH, wind speed, and cloud cover using sliders which changed the WBGT data in real time. Both HI and WBGT were given as were maps and tables that showed the comparisons between the two with accurate examples of each. Not only that but preparedness/prevention tips against high heat such as wearing a hat, light and loose clothing, and taking frequent shade breaks were provided as well as safety advice of limiting sun and drinking water. Other resources were linked at the bottom of the page for those wishing to learn more and this tool had a suggested action table like the Caribou, ME one. The one con was that the suggested action table was all dark blue and was hard to read and distinguish the different WBGT risk levels.

Lastly, the OK Mesonet tool may have been solely focused on the state of Oklahoma, but it did contain many cities and required no manual input of values. Also, the WBGT automatically updated every five minutes so it was extremely up-to-date and accurate. The tool included a handout with more information that contained important information about work/rest intervals, suggested water intake, workload, and acclimated vs unacclimated actions. The acclimated vs unacclimated chart was a smart addition since it accounts for people who may not be as susceptible to heat or who have adapted to their environment well. The tool also gave activity examples for each level of workload which was helpful in order to get a better sense of what work/rest interval would be the best/how much water should be consumed.

The most optimized tool for the Lincoln and greater Nebraska area would have the technical advances and accuracy of the OSHA tool, sufficient background data and a five day extended outlook like the CISA tool, sliders to adjust input information and all the safety/preparedness messages of the Tulsa tool, and the acclimated vs unacclimated and work/rest interval and water intake information of the OK Mesonet tool. By combining the strengths of every available WBGT tool online and specifying it for a Great Plains regional climate, one could easily construct and model the “perfect” WBGT tool for Nebraska.

The third objective was to “observe noticeable summer (June-August) temperature patterns and trends for one city from each of Nebraska’s nine climate regions under the last climate normal period (1991-2020) and calculate apparent temperature from the data”. In all of the graphs created via Excel for apparent temperature, daily maximum temperature, and combined AT and maximum temperature in celsius, several patterns arose in all 24 graphs for all eight cities. Apparent temperature was always higher, which was to be assumed. However, sharp increases in AT were observed in 1995, 2006, 2012, and 2017. Each of these years corresponds to a major heat event: Chicago Heat Wave, North American Heat Wave, Heat Wave/Drought, and Heat Dome/Record Breaking heat, respectively. Aside from the few historical heat events, results were pretty consistent across all graphs.

Lastly, in the histogram done for Lincoln, NE for HI values, the most common value found over the climate normal period of 1991-2020 was 83 degrees fahrenheit or “caution” on a HI chart. The least common values were those under 73 degrees fahrenheit and the rarest values were 107 and 109 degrees fahrenheit which each occurred only once in the entire thirty year period. Those values are in the “danger” category of a HI chart. In this climate normal there were no “extreme danger” or values over 128 degrees fahrenheit.

The fourth and final objective was to “assess the effect of increased relative humidity and apparent temperature values on the number of cooling degree days and, consequently, energy use/cost in Nebraska”. In the first graph made personally via Excel, the highest CDD values in NE occurred in the month of July followed by August and then June values. The highest ever CDD month was July of 2012, where over 500 CDD occurred. This pattern matches the results of highest AT and daily maximum temperatures for 2012 in the graphs made for each city under each respective climate division.

In the chart created by Wilkins (2022), the timeframe stretches from 2007-2021 (14 years). Seven/half of the years were recorded as having higher than average CDD values. The marked average for summer was 1,093.3 CDD. Following, seven/half of the years were under the average summer CDD amount. Again, the highest recorded CDD amount was the summer of 2012 at 1,344.4 CDD and 2012 also had the highest annual CDD amount of 1,719.1. Again, this matches the patterns of abnormally high AT, and daily maximum temperature values and supports the data in the first chart about CDD.

Finally, CDD predictions were made by EIA (2021). In their first graph, they state that CDD will remain consistent for 2022 and 2023 for the West North Central area. Also, costs of electricity for the predicted future for the West North Central area are expected to continue trending downward. Both residential and commercial sectors prices will decrease, with residential changing from 12.5 to 12 cents/kwh by 2023 and commercial changing from 10.5 to 9.75 cents/kwh EIA (2021). Beyond 2023, the graphs show even lower costs. This may be due to massive switches to renewable energy sources and may not be solely dependent on temperature values.

Compared to Previous Research:

Other research found on methods conducted by other researchers include using piecewise and multivariate quantile mapping. Schoof & Pryor (2019) used these methods as well as looked into "humidity projections from a subset of models from the Fifth Coupled Model Intercomparison Project" in order to "analyze the resulting climatology of extreme heat days with explicit consideration of prevailing humidity" Schoof & Pryor (2019). Another way equivalent temperature was calculated included using the method of collecting high quality observations from 33 weather and climate observing stations that tracked hourly air temperatures, and pressure. Moist enthalpy (heat content) was found using the equation H=cpT+Lvq where "cp is the isobaric specific heat of air (1005 Jkg−1 K−1), T is the air temperature (K), Lv is the latent heat of vaporization (2.5 × 106 Jkg−1), and q is the specific humidity" Younger et al. (2019). They wanted to compare moist enthalpy with air temperature so the equation used to understand equivalent air temperature in Kelvin is: TE=Hcp. As stated by Younger et al. (2019), since "the products available from the mesonet do not include a direct measure for specific humidity (q), it is calculated from the dew point temperature (Td) and the vapor pressure of the air (e), using Bolton's (1980) empirical relationship: e=6.112exp[17.67TdTd+243.5]. From this, q is calculated as q=0.622eP−0.37e, where P is the station pressure in hectopascals, obtained from the nearest ASOS”. This is an update from their original article in 2016, where they used the equation shown in Figure 10 below. In their previous research they had concluded that; “Te is thus an integrative metric of T and q (and hence is related to the loss of surface net radiation through H and LE). It represents the T that a sample of air would have if all of its latent heat were isobarically converted to sensible heat. So Te increases linearly with T and increases by ~2.5°C for every additional gram of water vapor per kilogram of air” Pryor & Schoof (2016).

$$T_e = \frac{H}{c_p} = T + \frac{L \times q}{c_p}$$

Figure 10: Equation used to calculate equivalent temperature. “T is air temperature (°C), L is latent heat of vaporization estimated as L = 2.5 × 106 (J kg−1), q is specific humidity (kg kg−1), and cp is the specific heat of air at constant pressure (1005 J kg−1 K−1)” Pryor & Schoof (2016).

Other researchers defined their own equation for calculating equivalent temperature. In a research publication by Na-Yemeh et al. (2020), “TE was calculated utilizing the following equation: H=CPT+LV where H is heat content, cp is the isobaric specific heat of air (1005 J kg−1 K−1), T is the air temperature (K), Lv is the latent heat of vaporization (2.5 × 106 J kg−1), and q is the specific humidity”. Again, they used an empirical relationship in order to calculate specific humidity (q) since it cannot be directly measured easily. “it is calculated from the dew point temperature (Td) and the vapor pressure of the air (e), using an empirical relationship:

e=6.112exp[17.67 Td/Td+243.5] From this, q is calculated as q= 0.622e/P−0.378e where P is the station pressure in hPa, obtained from the nearest Automated Surface Observation Systems (ASOS) stations" Na-Yemeh et al. (2020). This is nearly an identical process as used by Younger et al. (2019). The article expanded further and stated that "specific humidity can be calculated from measurements of relative humidity, dew point temperature, or wet bulb temperature. H has units of Joules per kilogram, so, to enable comparison with air temperature, equivalent temperature in Kelvin is calculated by: TE=(CPT+LVq)/CP As well as; TE=H/CP". Also, daily TE averages for this research were calculated from the hourly TE data Na-Yemeh et al. (2020).

The American Meteorological Society has a much lengthier method of calculating potential equivalent temperature. Shown in Figure 11 below, "θe is the equivalent potential temperature, cpd is the heat capacity at constant pressure of dry air, rt is the total water mixing ratio, c is the heat capacity of liquid water, T is the temperature, Rd is the gas constant for dry air, pd is the partial pressure of dry air, p0 is a reference pressure (usually 100 kPa), Lv is the latent heat of vaporization, rv is the vapor mixing ratio, Rv is the gas constant for water vapor, and H is the relative humidity". They concluded that "neglect of the quantity rtc, where it appears, yields a simpler expression with good accuracy" which is the expression other researchers stated above used AMS (2012).

$$\theta_e = T\left(\frac{p_0}{p_d}\right)^{R_d/(c_{pd} + r_t c)} \mathrm{H}^{-r_v R_v/(c_{pd} + r_t c)} \exp\left[\frac{L_v r_v}{(c_{pd} + r_t c)T}\right],$$

Figure 11: The calculation used for potential equivalent temperature as used by the AMS. AMS

(2012).

Another value that was looked into more was the physiological equivalent temperature (PET) and its limitations. Lin et al. (2019) decided that the PET was lacking and needed to be modified into a better version. For instance they stated that the three limitations of PET currently are: "(i) the physiological mechanism of the two-node Munich Energy-balance Model for Individuals (MEMI) model is over 30 years old and is therefore out of date, (ii) clothing mechanism has a weak influence due to the one-node model, and (iii) PET underestimates the influence of vapor pressure in warm and humid regions" Lin et al. (2019). The new modified physiological equivalent temperature (mPET) accounts for this and is an updated model that includes considerations for clothing and includes more nodes. They used these methods in order to update the old PET model: "(i) by applying a bio-heat equation and multi-segment body model (16–26 nodes) to improve the thermo-physiological and thermoregulation of PET, (ii) by using multi-layer clothing based on total clothing insulation, (iii) by modifying the mechanism used to transfer latent heat fluxes from the skin and clothing to air, and (iv) by developing the modified PET (mPET) to adapt to climatic conditions, particularly those of hot and humid regions" Lin et. al (2019).

For general calculation, Rennie et al. (2021) calculates heat exposure (HI, AT, and the WBGT) using a method used by the National Weather Service (NWS). "The equation is a

$$\mathrm{HI} = -42.379 + 2.049\,015\,23 \times T + 10.143\,331\,27 \times \mathrm{RH} - 0.224\,755\,41 \times T \times \mathrm{RH} - 0.006\,837\,83 \times T^2 - 0.054\,817\,17 \times (\mathrm{RH})^2$$

polynomial fit to the apparent temperature using only air temperature and RH inputs:

where RH is the relative humidity (%), and T is the dry-bulb temperature (°F). There are two adjustment factors applied to the HI under certain conditions in which the basic formula fit is less accurate. The first is if RH is less than 13% and the dry-bulb temperature is between 26.7° and

44.4°C Rennie et al. (2021). A difference in their studies was that there are two equations based on whether the RH value is over 85% or less than 13% and what the dry-bulb temperature is. “The second adjustment occurs if the RH is greater than 85% and the dry-bulb temperature is between 26.7° and 30.6°C. For cases in which the heat index is below 26.7°C (80°F), the equation is simplified as $HI=0.5\{T+61.0+[1.2(T-68.0)]+(RH\times 0.094)\}$ Rennie et al. (2021). Another unique feature about their research is that sometimes it is necessary to take measurements of the globe temperature (Tg) which requires a black globe thermometer which “is not standard”.

Lastly, Enloe (2021) defines the equation and method for calculating heat index (apparent temperature) to be $AT = -1.3 + 0.92*T + 2.2*e$, where AT and T (air temperature) are °C and e is vapor pressure in kPa”. Since apparent temperature can be fine tuned to account for indoors, outdoors in shade with wind, or outdoors exposed to wind and sun, the one above is formatted for outdoors in shade.

Summary & Conclusions

Through the methods of meta-analysis, visual representation with charts and graphs, and comparative analysis, exploratory-based research was carried out on eight counties (Scotts Bluff, Cherry, Madison, Custer, Lancaster, Keith, Phelps, and Jefferson) with the respective climate divisions of 1, 2, 3, 5, 6, 7, 8, 9 as defined by the Climate Prediction Center (CPC). The cities from each county were: Scottsbluff, Valentine, Norfolk, Broken Bow, Lincoln, Ogallala, Holdredge, and Fairbury. For each location, apparent temperature was calculated in order to observe noticeable summer temperature trends under the last climate normal period (1991-2020). It was found that sharp increases in AT were observed in 1995, 2006, 2012, and 2017 with each of these years corresponding to a major heat event: Chicago Heat Wave, North American Heat Wave, Heat Wave/Drought, and Heat Dome/Record Breaking heat, respectively.

A comparative analysis was then carried out on five online WBGT tools (Caribou, ME, OSHA, CISA Convergence, Tulsa, OK, and OK Mesonet) in order to determine the readability, ease of access, amount of information and data available, accuracy, and completeness of the tool in order to choose the best qualities in which to model and optimize a WBGT tool for the Lincoln and Greater Nebraska area. It was found that the most optimized tool for the Lincoln and greater Nebraska area would have the technical advances and accuracy of the OSHA tool, sufficient background data and a five day extended outlook like the CISA tool, sliders to adjust input information and all the safety/preparedness messages of the Tulsa tool, and the acclimated vs unacclimated and work/rest interval and water intake information of the OK Mesonet tool.

Lastly, in order to assess the effect of increased relative humidity and apparent temperature values on the number of cooling degree days and energy use/cost in Nebraska, past recorded CDD value and future predictions were observed and analyzed. It was found that the highest recorded CDD amount was the summer of 2012 at 1,344.4 CDD and 2012 also had the highest annual CDD amount of 1,719.1. This result matches the patterns of abnormally high AT, and daily maximum temperature values seen in 2012 in the graphs made for each city under each respective climate division. It was also discovered that CDD values will remain consistent for 2022 and 2023 for the West North Central area and costs of electricity for the predicted future for the West North Central area are expected to continue trending downward. Both residential and commercial sectors prices will decrease, with residential changing from 12.5 to 12 cents/kwh by 2023 and commercial changing from 10.5 to 9.75 cents/kwh EIA (2021). Beyond 2023, the graphs show even lower costs. However, this may be due to massive switches to renewable energy sources and may not be solely dependent on temperature values.

Overall, the research done was exploratory in nature but churned out informative results and inspires future work. Some recommendations would be to assess the connections AT, relative humidity, WBGT, and HI have with the cattle comfort index as well as look at different variables to measure such as precipitation and wind speed. Finally, another recommendation would be to personally go measure WBGT temperatures with a Kestrel device in local areas and keep a record of a year of observations and then compare those findings with the past data records.

Heat is a climate extreme that can pose a serious threat to the health and well-being of everyone impacted by it. Extreme heat can lead to an increase in emergency room visits, increase cases of heat-related illness such as heat stroke or heat stress, an increased threat of brownouts and blackouts due to increased electricity use, and in general pose physical and mental health challenges, especially to those who are required to work or exercise outdoors frequently. In order to mitigate some of these effects, adequate tracking and monitoring of apparent temperatures, increased relative humidity, and WBGT must occur. One simple solution for that is by utilizing online tools, apps, and simple calculators in order to provide warning to vulnerable populations and help better prepare the general public. Although not widely available in Nebraska today, one of these tools would help bolster resilience to high heat events in the state.

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