LATE-SUMMER HEAT WAVES AND THEIR IMPACT ON HYPERTHERMIA-RELATED DEATHS IN FOOTBALL PLAYERS

by

MYRON THOMAS PETRO

(Under the Direction of John A. Knox)

ABSTRACT

Extreme heat is the leading cause of U.S. weather-related fatalities in most years. This study examines late-summer heat waves in the state of Georgia to assess their impact on the general population. Late-summer heat waves across the entire United States are then investigated to determine if deaths due to hyperthermia in football players are caused by heat waves, or just natural variation. Finally, cases of death due to hyperthermia in football players are modeled using BioKlima, an energy-balance modeling software, in order to determine the exact conditions that put players in danger during the day they were exposed to extreme heat. In addition, the effectiveness of predicting dangerous conditions for three different perceived temperature indices is evaluated in order to allow coaches and administrators to make better educated decisions in the future as to whether or not football activities should take place.

INDEX WORDS: Heat Waves, Late-Summer Heat Waves, Hyperthermia, Heat Stroke, Football, Biometeorology, Georgia, Wet Bulb Globe Temperature

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DEDICATION

This thesis is first and foremost, dedicated to my parents. To my mom, who always kept me going, especially when times were rough. Your constant words of encouragement and support meant more to me than you could ever know. To my dad, who never let me quit at anything, and set me on the path that gave me all the tools I needed to be successful and confront any problem I am faced with. It has been a joy to call you my coach, my scoutmaster, and above all else, the best mentor I could have asked for. To everyone else that has helped me at some point along the way, from the early days of teaching me how to tie a square knot, to hitting a low inside single leg takedown, to studying for a mesoscale final, and everything in between, I thank you from the bottom of my heart for getting me to where I am today. For it is said that he who serves his fellows, is of all his fellows, greatest.

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CHAPTER 1

INTRODUCTION

Heat waves are regarded by the National Weather Service (NWS) as the major cause of weather-related fatalities in most years. For the period 1980-2008, a total of 90 billion-dollar weather disasters occurred in the United States (Fig. 1.1). Of these, seven were heat waves and accounted for 18,458 deaths, or 81% of all deaths attributed to these disasters (NCDC 2008). They also caused approximately $145.9 billion in damage, about 29% of the total. Although infrequent and usually short lived, heat waves can have a substantial impact on the areas they affect. Several studies (e.g. Balafoutis 2007, Changnon 2003, Chen and Konrad 2006, Huth et al. 2000) have noted that climate change, whether anthropogenic or naturally forced, can increase the frequency and duration of heat waves in the future. This highlights a critical need in understanding the variability and persistence of extreme temperature days to enhance climate impact studies and act as a baseline for global climate change scenarios (Henderson and Muller 1997).

The general population does not halt its day-to-day activities despite the presence of extreme heat, which often leads to higher mortality during these events. This is all too common in the realm of athletics, where fixed practice schedules mandate that athletes begin training as early as allowed to be competitive in their respective seasons. Football players are at greatest risk, beginning their training regimen during the late summer, wearing equipment that establishes a microclimate above their skin that reduces heat dissipation to the environment via radiation, convection and evaporation (Armstrong et al. 2010). This predisposes players to exerciseinduced hyperthermia due to their body's decreased ability for thermoregulation. Hyperthermia, or heat stroke, occurs when a person's core body temperature rises above 40°C and causes central nervous system dysfunction in addition to compromising the body's ability to cool itself effectively. Despite the recognized benefits of sufficient fluid intake and precautionary measures to optimize performance while reducing the risk of heat illness, heat and dehydration related problems persist on the football field (Bergeron et al. 2005).

Late-summer heat waves, defined in this thesis as those that occur during August or September, are a poorly understood phenomenon, primarily due to the lack of heat wave climatologies for sites across the U.S. These heat waves are especially hazardous to football players, who often do not begin their training and practice regimens until the beginning of August. The first goal of this study is to establish what these heat waves look like and how they potentially differ from traditional heat waves. In addition, late-summer heat waves are analyzed with regard to football player deaths due to hyperthermia, to assess if heat waves or natural variability are the root cause of extreme conditions that players are exposed to and subsequently die from. The main focus of this thesis are cases of football-related hyperthermia that afford the greatest level of detail, and are subsequently analyzed using a biometeorological model. This allows insight as to how hyperthermia evolves throughout the course of football practice and how it is related to the activity a player is participating in, the clothing the player was wearing, and the conditions the player was facing.

1.1 Motivations

1.1.1 Better Understanding of Heat Waves

Heat waves affect thousands of lives in the United States alone each and every year. Despite this, no clear definition exists to quantify a heat wave in terms of its potential impacts on an area. This can be largely attributed to the spatial variability of these events. Put simply, a heat wave in Mountain Top, PA is a different event entirely from one that occurs in Athens, GA, primarily due to the difference in seasonal temperature averages that these two locations experience. This problem is addressed in this study, using an approach that can be applied to any location, allowing for heat wave severity and duration to be compared across sites that exhibit differences in latitude, topography, and other variables that affect climate.

1.1.2 Increased Awareness Among Football Coaches

Young football players should not have to suffer heat injuries or die from heatstroke; Heat injury can be reduced if parents, coaches, and other adults involved with youth football programs have access to and utilize the right information (Bergeron et al. 2005). Knowledge of whether players in this study are dying as a result of a heat wave or simply the extreme conditions they are exposed to on an unusually hot day will assist coaches in making better informed decisions when planning early season practices. Awareness of whether or not heat waves are the cause of hyperthermia is key because if extreme heat in the form of a heat wave is not forecast, coaches are presumably less likely to be more cautious during practices. In addition, highlighting the effect of equipment worn by players that have suffered heat stroke will reinforce the benefits of acclimatizing players by gradually increasing the level of equipment worn during the beginning of the season.

1.2 Research Objectives

The primary objectives of this research are as follows:

- To determine the characteristics of a late-summer heat wave in the state of Georgia
- To determine how often a late-summer heat wave is present when a football player is exposed to extreme heat conditions and subsequently dies from complications due to heat stroke
- To identify conditions, using an energy-balance model, that put specific players in danger during different ranges of extreme heat

This thesis begins by determining the presence of late-summer heat waves in the state of Georgia. The late-summer period is often seen as a transition from the heat of the summer to the cooler fall season, where heat waves are not expected to occur. Quantifying not only the presence of these events, but their frequency and duration during the months of August and September shows the significance of their potential impacts on the public.

The meteorological conditions during a football player's exposure to extreme late-summer heat and subsequent death due to hyperthermia are examined. The goal is to determine if the excessive heat present at the time of a player's exposure and symptomatic response is the result of a heat wave or just natural variation. As an added result, a heat wave climatology is developed for each site, fostering future research into heat wave effects.

The scope of this research is similar in concept to the "forecasting funnel" methodology used in weather analysis and forecasting (Snellman 1982, Figure 1.2). The initial phase involves looking at heat waves as broader climatological events on the synoptic scale. The latter phase looks at specific meteorological variables and conditions associated with deaths due to hyperthermia. These events occur at the mesoscale and microscale, with much higher temporal and spatial resolution than that of heat waves. As the funnel tapers, heat waves are noted as a potential cause of the extreme heat experienced, but a closer look at the local effects and processes determine the specific causes of hyperthermia on the football field. With regard to the time period, analyzing each individual case is a much more time intensive process than identifying heat waves present at the time of exposure.

The ultimate objective of this research is to educate football coaches at all levels of play of the dangers and inherent risk involved in beginning practice during the late-summer season. Hyperthermia is the most preventable of all catastrophic injuries resulting from participation in football. The awareness that this thesis provides will help to emphasize the importance of acclimatization and the risk associated with adding full equipment to a practice regimen too early in the season. In the process, we will also observe the trends of late-summer heat waves on a much broader scale and be able to assess their impacts accordingly.

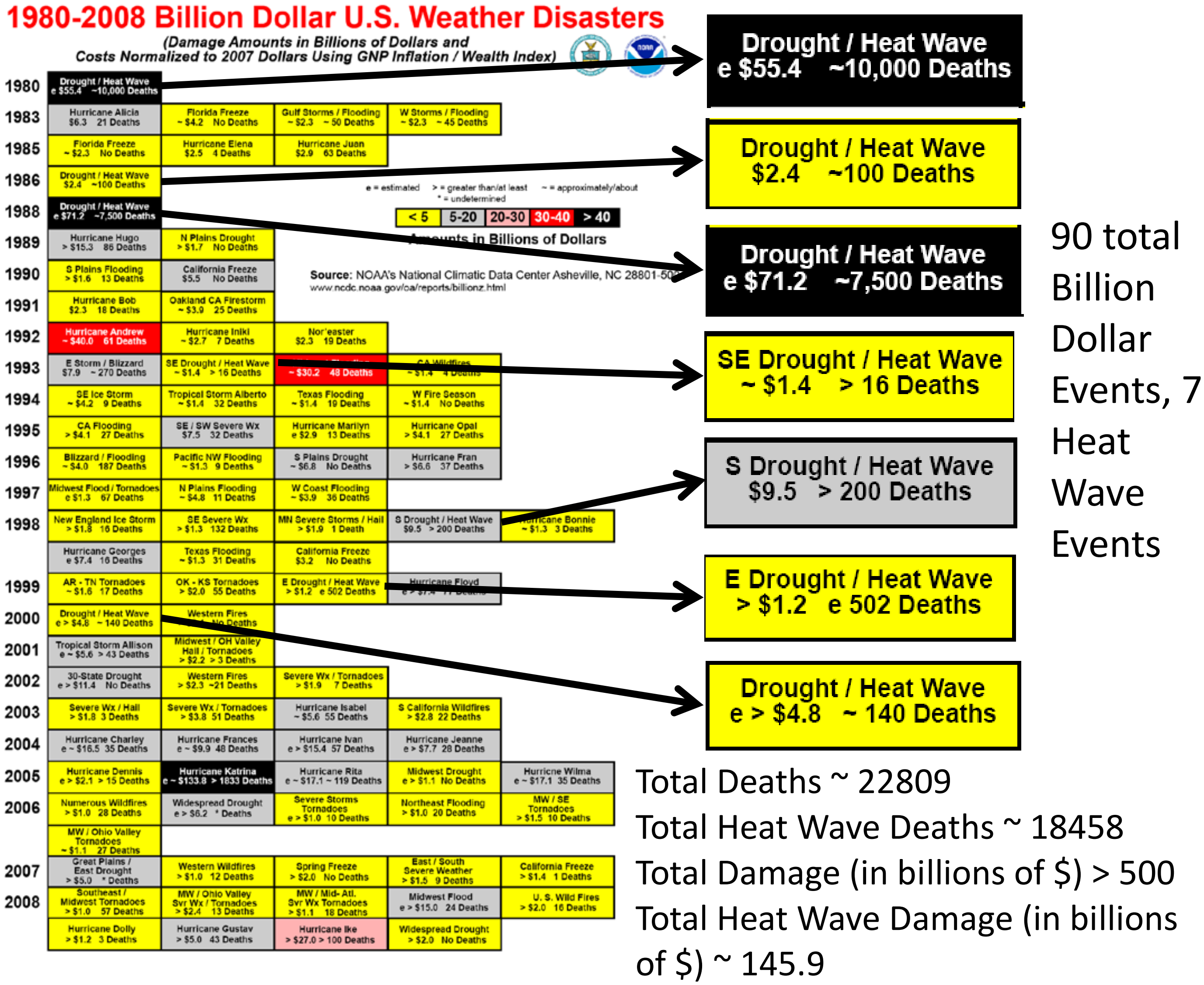

Figure 1.1. 1980-2008 Billion Dollar U.S. Weather Disasters, with heat wave specifics (from NCDC 2008)

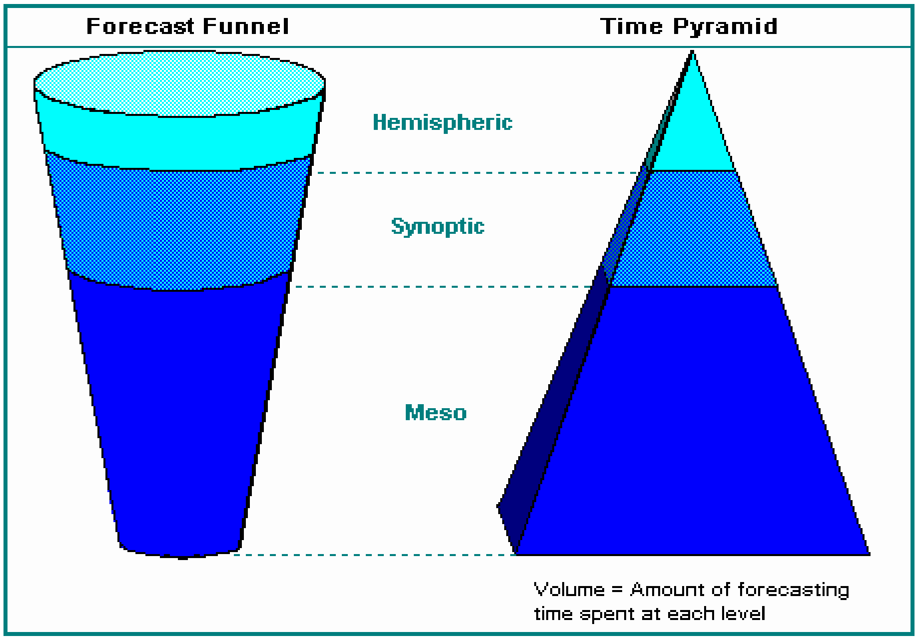

Figure 1.2. Analogy with the forecasting funnel, (pictured) as used in this study: less time is spent looking at heat waves on a synoptic level, while individual cases with conditions occurring at the mesoscale are investigated in greater detail. Adapted from Snellman (1982)

CHAPTER 2

LITERATURE REVIEW

2.1 Heat Waves

A heat wave is generally defined as an extended period of time where temperatures are much higher than the climatic normals for a given area. Heat waves vary geographically in both their nature and their impacts (Robinson 2001). This is the main reason that no universal definition exists to quantify them (Meehl and Tebaldi 2004, Robinson 2001). The generally accepted standard is the Heat Index, a product used primarily by the NWS in the United States to issue guidance when oppressive heat conditions are expected. The heat index is a model resulting from extensive biometeorological studies (Rothfusz 1990). It is comprised of different equations, using 20 different atmospheric and physical parameters in order to calculate the apparent temperature one feels when outside (Equation 1). After careful manipulation and regression analyses, the equation appears in its final form requiring only two input variables to calculate heat index: T, the ambient dry bulb temperature and R, the relative humidity.

$$\begin{aligned} HI = \; & -42.379 + 2.04901523T + 10.14333127R - 0.22475541TR - 6.83783\text{x}10^{-3}T^2 \\ & - 5.481717\text{x}10^{-2}R^2 + 1.22874\text{x}10^{-3}T^2R + 8.5282\text{x}10^{-4}TR^2 - 1.99\text{x}10^{-6}T^2R^2 \end{aligned} \quad (1)$$

Much of the methodology in deriving and computing the heat index originated from the results of Steadman (1984). This study focused on preparing a scale that produced the apparent temperature for any combination of dry-bulb temperatures, vapor pressure, wind speed and extra solar radiation likely to be encountered meteorologically. The scale is based on total thermal resistance required by a modeled human to achieve equilibrium, effectively assessing the comfort level of a given set of meteorological variables. Steadman makes no claims as to the health effects of extreme temperatures, calling for the need of the Heat Index to do so.

Local NWS forecast offices issue Excessive Heat Watches, Warnings and Heat Advisories using the Heat Index based on criteria determined by the local or regional weather service office. These issuances are deficient for a number of reasons: they assume that people respond to a combination of only two meteorological variables; the present system does not factor in the negative impact of several consecutive days of oppressive temperatures; and the heat index values that define dangerous conditions have not been proven as estimators of morbidity or mortality (Kalkstein et al. 1996). Due to these limitations, efforts have been made to develop and implement a Hot Weather-Health Watch/Warning system using a synoptic level climatology that identifies oppressive air masses historically associated with higher mortality (Kalkstein et al. 1996). The first system of this type was implemented and tested during the summer of 1995 in Philadelphia. The occurrence of an extreme heat event could be forecast up to 48 hours in advance, and proper watches/warnings were disseminated by the Philadelphia Department of Public Health with concurrence by the NWS. Health alerts were still issued on days when the NWS was not in agreement. Six such days during the summer of 1995 resulted in increased mortality, suggesting that NWS forecasters should have more flexibility in issuing excessive heat warnings. It was later estimated that with the system's use during the period 1995-1998, 117 lives were saved due to advisement and public awareness made possible on days when the NWS would not have issued Excessive Heat guidance (Ebi et al. 2004).

Despite being a more comprehensive method of forecasting extreme heat events and issuing watches and warnings (Sheridan and Kalkstein 2004), the Hot Weather-Health

Watch/Warning is limited by its current use. Approximately 20 such systems are currently in use worldwide, and are only effective in providing public awareness in the major cities that they serve. The placement in major cities is due largely to the enhancement of extreme heat events by the Urban Heat Island effect (Johnson and Wilson 2009, Smargiassi et al. 2009, Zhou and Shepherd 2010). A comprehensive method of defining a heat wave for other areas is still needed.

The typical issuance of an excessive heat watch by the NWS occurs when daytime highs greater than or equal to 105°F and nighttime lows greater than or equal to 80°F are forecast to occur during a consecutive two-day period. This definition holds for much of the United States, but no definitions are immediately available in climates where the NWS thresholds are frequently exceeded or for extreme events in cooler climates (Robinson 2001). Due to this disparity, Robinson (2001) used a 40-year climatology (1951-1990) for each of 178 stations across the United States to establish percentile thresholds based on temperature. This resulted in defining four distinct sequences for a heat wave including both the percentile thresholds as well as the NWS criteria. By classifying each station by its sequence, regional patterns in temperatures required for a heat wave are also observed.

Henderson and Muller (1997) used daily maximum and minimum temperature data from 16 stations in the south-central United States and calculated the average daily maximum and minimum temperature for each day of the year over an 88-year study period (1901-1987). An extreme warm day was defined as a daily maximum that exceeded one standard deviation above the average daily maximum for that specific day. Results indicated that extreme warm days during the summer are highly variable and closely linked to subtropical and regional circulations, indicating the importance of the Atlantic Subtropical High and its effect on climate in the southern U.S.

Changnon (1993) used 13 first-order National Weather Service stations chosen from the District of Columbia through Alabama, representing latitudinal and topographic constraints across the region, to determine the spatial variability in the frequency and duration of hours and days where temperatures were equal to or exceeded 32°C. Sites are located south and east of the Appalachian Mountain chain, and far enough inland for only minimal influence by the ocean. The study determined that average maximum temperature is a more appropriate indicator of high heat conditions than the average temperature, extreme high temperature characteristics from individual stations should not be combined into a regional or statewide average, and that the frequency and duration of high-heat hours and days between cool and warm summer seasons range from 70% to 997%.

Meehl and Tebaldi (2004) used a similar concept of exceeding specific thresholds, allowing analyses of heat wave duration and frequency. The seasonal climatology of a location is used to obtain the distribution of maximum temperatures and two thresholds are calculated: Threshold 1 (T1) is defined as the 97.5th percentile of the distribution and Threshold 2 (T2) is defined as the 81st percentile for the same distribution. Three criteria were used to define a heat wave, relying on these two thresholds:

1) The daily maximum temperature must be above T1 for at least 3 days
2) The average daily maximum temperature must be above T1 for the entire period
3) The daily maximum temperature must be above T2 for every day of the entire period

Using the Parallel Climate Model, Meehl and Tebaldi simulate present climate (1961-1990) as well as a “business as usual” scenario for the future (2080-2099) which assumes little mitigation of greenhouse gas emissions. They found for Paris that the average frequency of heat waves increases 25%, while increasing by 31% in Chicago. A corresponding increase in duration occurred at both locations.

Mortality with respect to heat waves seems to be higher in regions where summer heat is less common, suggesting acclimatization is key in preventing death (Kalkstein and Davis 1989). A general decline in heat-related mortality was observed from the 1970’s to the 1990’s with the number of oppressive days staying the same or increasing in most major metropolitan cities (Davis et al. 2002, Sheridan et al. 2009). This decline is generally attributed to the increased availability of air conditioning to the population. Being an urban resident however, does not make one more vulnerable to heat-related mortality (Sheridan and Dolney 2003). During extreme events, such as the European heat wave in August of 2003, mortality does increase above the average (Anderson and Bell 2009, Hajat et al. 2006, Vandentorren et al. 2004). However, there is an observed lag of one to three days between the onset of the event and the increase of deaths. The mortality effect per °F is much higher during a heat wave than that reported during non-heat wave periods (Ostro et al. 2009). This suggests that increased mortality during a heat wave is as much an effect of duration as the intensity of temperatures. In the wake of the 1995 heat wave in Chicago, many cities realized the necessity of a comprehensive action plan in mitigating and reducing morbidity and mortality (Bernard and McGeehin 2004). The death toll during a similar event in July of 1999 was about 25% of that seen in the 1995 Chicago event, showing that the city was effective in mitigating its response plan for an event that was very similar meteorologically (Palecki et al. 2001).

2.2 Late-Summer Heat Waves

It is difficult to find much research on heat waves in the Southeast, with Changnon (1993), Chen and Konrad (2006) and Zhou and Shepherd (2010) comprising the bulk of the literature. Chen and Konrad (2006) developed a synoptic level climatology of heat and humidity during the summertime (June-August) across the piedmont region of North Carolina. They defined a hot event as a single day with the highest average daily temperature within a surrounding 5-day window. Composite difference maps were developed, illustrating the difference in synoptic patterns between extreme events and the remainder of the sample. Zhou and Shepherd (2010) investigated the relationship between heat waves and the Atlanta Urban Heat Island (UHI). Using the same approach as Meehl and Tebaldi (2004) to define a heat wave in the city of Atlanta, Zhou and Shepherd found that, on average, heat waves lasted 14.18 days with sizeable variability (standard deviation of 9.89). The mean number of heat waves in a given year was 1.83, and the mean maximum temperature during heat wave events was 35.85°C. UHI magnitude with respect to heat wave days was also examined by Zhou and Shepherd. Between Atlanta and Athens, the UHI magnitude difference between heat wave days and non-heat wave days is not statistically significant, but between Atlanta and Monticello the UHI magnitude during heat wave days is almost 100% certain to be larger than non-heat wave days.

In particular, there has been no attention to heat waves that are the focus of this study, namely late-summer heat waves that occur in August or early September, such as the one in 2007 (Figure 2.1). An analysis of the eight latest all-time state record daily maximum temperatures across the U.S. reveals that the records in the Southeast occur later than in any other region of the country, followed by the south-central U.S. (Henderson and Muller 1997). These records are evidence of recurring and extreme late-summer heat waves that preferentially target the

Southeast. The reasons for and societal implications of this phenomenon are largely unexplored, however.

2.3 Heat Illness in Football Players

Heat stroke is a life-threatening illness, and the most extreme form of hyperthermia, characterized by an elevated core body temperature that rises above 40°C and central nervous system dysfunction (Bouchama and Knochel 2002). Heat stroke results from exposure to a high environmental temperature or from strenuous exercise. From 1955 through 2009, 128 football players have died due to complications from heat stroke as a result of participating in football activities (Mueller 2010). A number of factors are cited as leading to increased risk and incidence of heat stroke on the football field. Maintaining fluid balance is often difficult for football players, primarily due to intensity and duration of practice, scheduling of water breaks, number of sessions per day and uniform configuration (Bergeron et al. 2005). Over-motivated athletes can overheat by trying to do too much too fast and by striving to endure too long. Football inherently breeds a warrior mentality and the victims of heat stroke are often described as “the hardest worker” or “determined to prove himself” (Eichner 2002). Athletes with no or minimal physiologic acclimatization to hot conditions are at an increased risk to heat stroke (Binkley et al. 2002). Other reasons cited in the literature are the high heat and humidity present in the late summer period when practices begin, the insulation factor the football uniform adds to the body, and higher Body Mass Index measurements. It comes as no surprise that some variation of all of these factors is mentioned by Knochel (1975) in his article “How to Kill a Football Player.”

Football practices begin in late summer, usually the last week of July or the first week of August. The hot conditions present in late summer predispose athletes who begin training during this time of year to a greater likelihood of experiencing heat-related illness than those who begin training regimens in the winter or spring (Binkley et al. 2002). Traditional approaches for determining safe environmental conditions for football have relied on guesswork or simply noted the environments in which fatalities had occurred and assumed that less extreme conditions are "safe" (Kulka and Kenney 2002). This is a common practice among coaches at the high-school level in the United States. The National Federation of State High School Associations (NFHS), the governing body of all state high school associations in the United States, leaves all regulation of practices to the state associations. The NFHS does provide guidance and education on sport related risk management, issuing recommendations on preventing heat illness.

The Georgia High School Association specifically mandates only that during the first five days of practice at least two days must have practices with players dressed in shorts, helmets, shoulder pads, mouthpieces and shoes only. The other three days *may* include practices that have players in full pads, but no more than two consecutive days of the first five days may have full pads in use. Coaches are not required to have any practices in full pads during the first five days of practice (GHSA 2009). Beyond this, regulation and safety measures are implemented within local school systems, primarily by coaches. The situation is similar in other states across the country.

Due to this lack of specificity in how practices should progress, coaches often use as much time as possible within the confines of these rules, holding two-a-day practices despite the lack of acclimatization to the high heat and humidity by most of their athletes. An athlete's risk of extreme heat illness decreases after the conclusion of two-a-day practices (Cooper et al. 2006) and an athlete's ability to acclimate is severely hindered once full pads and equipment are added to their practice regimen.

The first effort to quantify the effect football equipment has on thermal balance and energy cost in athletes was a study done by Fox et al. (1961). Of the nine cases of death they examined, all were wearing full football equipment, all were interior linemen, and seven were stricken during the first two days of practice. To simulate the effects of equipment, they used five subjects running on a treadmill to simulate work load in a controlled environment, once while wearing a scrub-suit and once while wearing a full football uniform. (It should be noted here that the study never mentions what equipment is included in a full football uniform.) They found that the uniform results in a loss of over 50% of the evaporative surface area and the added weight increases the work load. Thus, while heat production is increased during football activities, there is a decrease in the effectiveness of evaporative heat loss by an athlete. The study recommended a period of gradual acclimatization to heat and a gradual introduction to full football equipment before full practice is allowed.

Kulka and Kenney (2002) modernized Fox et al.'s approach and attempted to establish safe zones of ambient air temperature and humidity where activity was allowable considering the athletes' clothing. The resulting data (Figure 2.2) were compared to the fatalities studied by Fox et al. and three documented heat-related deaths that occurred among football players during the summer of 2001. In the Fox et al. study, with one exception where the values fall on the limit line, all deaths occurred in environments of uncompensable heat stress for exercise in a full football uniform, meaning the players' bodies could not compensate for the thermo-regulatory imbalance present. For the heat-related deaths in the summer of 2001, all three occurred well above the limit line for possible heat balance in a full football uniform.

Ainsworth (2000) is an update to the Compendium of Physical Activities, which is a database containing multiple physical activities and the metabolic equivalent (MET) for each. MET is defined as the ratio of the metabolic rate experienced by a person performing an activity to a standard resting metabolic rate, where 1 MET is considered a resting metabolic rate obtained while a person is quietly sitting. The MET value for a given activity can be multiplied by a person's base metabolic rate (BMR) to determine their caloric expenditure while performing that activity. MET values range from 0.9 for a person sleeping up to 18 MET's for a person running at 10.9 mph. The Compendium identifies the MET for competitive football at 9.0, meaning someone participating in competitive football is burning nine times as many calories as they would if they were sedentary.

McCullough and Kenney (2003) measured the thermal and evaporative resistance of five different uniform types commonly worn during American football practices and games. The various uniform configurations are defined in Table 2.1. A reference ensemble, consisting only of shorts and a t-shirt, is also included. Thermal resistance of clothing is more commonly expressed in clo units, where one clo of insulation is equal to 0.155 m^2 °C W^{-1}. Total thermal resistance (R_t) is the total resistance to dry heat loss from the body, which includes the resistance provided by both clothing and the air layer around the clothed body. Using a heated manikin to test for thermal resistance, they found the intrinsic clothing insulation factor (I_t, in clo units) for each equipment ensemble (Table 2.2). This allows for the effect football uniforms have on thermoregulation to be quantified based on how much equipment is being worn by the player.

Table 2.1 Different Football Uniform Configurations, from McCullough and Kenney (2003)

Uniform	G1. Game Uniform (Warm Weather)	G2. Game Uniform (Temperate)	G3. Game Uniform (Cold Weather)	P1. Practice Uniform (with Hip Girdle)	P2. Practice Uniform (Shorts Only)
Upper body	Helmet + chin strap Shoulder pads Sleeveless cut-off T-shirt Short-sleeved mesh jersey (tucked into pants)	Helmet + chin strap Shoulder pads Long-sleeved knit shirt Short-sleeved knit jersey (tucked into pants) Gloves	Helmet + chin strap Shoulder pads Thick long-sleeved shirt Short-sleeved knit jersey (tucked into pants) Gloves	Helmet + chin strap Shoulder pads Sleeveless cut-off T-shirt Short-sleeved mesh jersey (cut off at waist and hanging loose)	Helmet + chin strap Shoulder pads Sleeveless cut-off T-shirt Short-sleeved mesh jersey (cut off at waist and hanging loose)
Lower body	Jock strap Hip girdle with hip, thigh, and tail bone pads Football pants with knee pads + belt Ankle-length socks Turf shoes	Jock strap Hip girdle with hip, thigh, and tail bone pads Football pants with knee pads + belt Knee-length socks Turf shoes	Jock strap Hip girdle with hip, thigh, and tail bone pads Knit long underwear Football pants with knee pads + belt Knee-length socks Turf shoes	Jock strap Hip girdle with hip, thigh, and tail bone pads Mesh shorts Ankle-length socks Turf shoes	Jock strap Mesh shorts Ankle-length socks Turf shoes

Table 2.2 Thermal Insulation Values for Various Uniform Combinations, from McCullough and Kenney (2003)

	Thermal Resistance and Total Insulation		Intrinsic Clothing Thermal Resistance and Insulation[a]		Clothing Area Factor
Ensemble Tested	R_t ($m^2 \cdot °C \cdot W^{-1}$)	I_t (clo)	R_{cl} ($m^2 \cdot °C \cdot W^{-1}$)	I_{cl} (clo)	f_{cl} (unitless)
G1: game uniform (warm weather)	0.199	1.28	0.124	0.79	1.25
G2: game uniform (temperate)	0.228	1.47	0.153	0.98	1.25
G3: game uniform (cold weather)	0.233	1.50	0.158	1.02	1.26
P1: practice uniform (with hip girdle)	0.190	1.22	0.112	0.71	1.20
P2: practice uniform (shorts only)	0.178	1.14	0.100	0.63	1.20
Reference ensemble (T-shirt and shorts)	0.140	0.90	0.055	0.35	1.10

Grundstein et al. (2010) performed the most comprehensive study to date of football related hyperthermia, analyzing the geographic, temporal, and meteorological conditions of 58 documented cases of football players dying due to hyperthermia during the period 1980-2009 (Figure 2.3). Data on heat-related deaths in football players were obtained from the National Center for Catastrophic Sports Injury Research (NCCSIR), including information on the death date, age of the player, height, weight, school, city and state. Extensive research was conducted to fill in missing data and expand on additional information within the NCCSIR dataset, using media reports as the primary source of information. Additional data fields included exposure date, time of day the athlete was participating in football activities, time of football season, position, any pre-existing medical conditions, type of activity (practice, conditioning, workout, etc.), clothing or equipment worn, and latitude/longitude coordinates of the exposure location. The exposure date is the most critical field added to the dataset, allowing for the assessment of meteorological conditions surrounding the onset of hyperthermia in a player.

The first key result of Grundstein et al. (2010) is the determination that increased participation is not a major factor in the increased number of deaths in football players due to hyperthermia over time. The number of high school football players has increased by almost 18% from 1980-2006 to 1,105,583 players (NFHS 2010). The pattern of deaths per 100,000 players is similar to that of overall deaths (Figure 2.4). Looking at an overall climatology for each site, in an effort to discern potential impacts of climate change, it was determined that the number of days in August where morning practices pose stressful meteorological conditions have increased over time, consequently increasing the risk of heat-related illness. Of the original 58 cases, only 33 could be analyzed with respect to meteorological conditions because of their inclusion of the approximate time during which the player was exposed to conditions leading to hyperthermia.

According to thresholds established by both the American College of Sports Medicine and Sports Medicine Australia, all 33 deaths occurred under conditions considered to be high or extreme, based on the Wet Bulb Globe Temperature (WBGT). It is also important to note that no deaths occurred on days categorized as danger or extreme danger (the most dangerous) by the Heat Index (HI). This is likely related to the assumptions made in calculation of the HI, that a person is in the shade, of average size (1.7 m and 67 kg), lightly dressed, and engaged in light activity (Rothfusz 1990). These assumptions are not representative of any aspect relating to players participating in football activities, most notably with respect to size of the players, activity level, and level of clothing.

It should be noted here that while the author was a co-author on Grundstein et al. (2010), the research contained in this thesis takes a different path toward the same end of analyzing deaths in football players due to hyperthermia. The only overlap lies in the use of the updated NCCSIR dataset and calculation of certain indices (notably WBGT) used in this work for the biophysical modeling of conditions present during the onset of hyperthermia. This thesis represents an independent modeling-based effort to discern what actually caused the onset of hyperthermia in specific cases in an effort to reinforce the need for gradual acclimatization to both conditions and equipment.

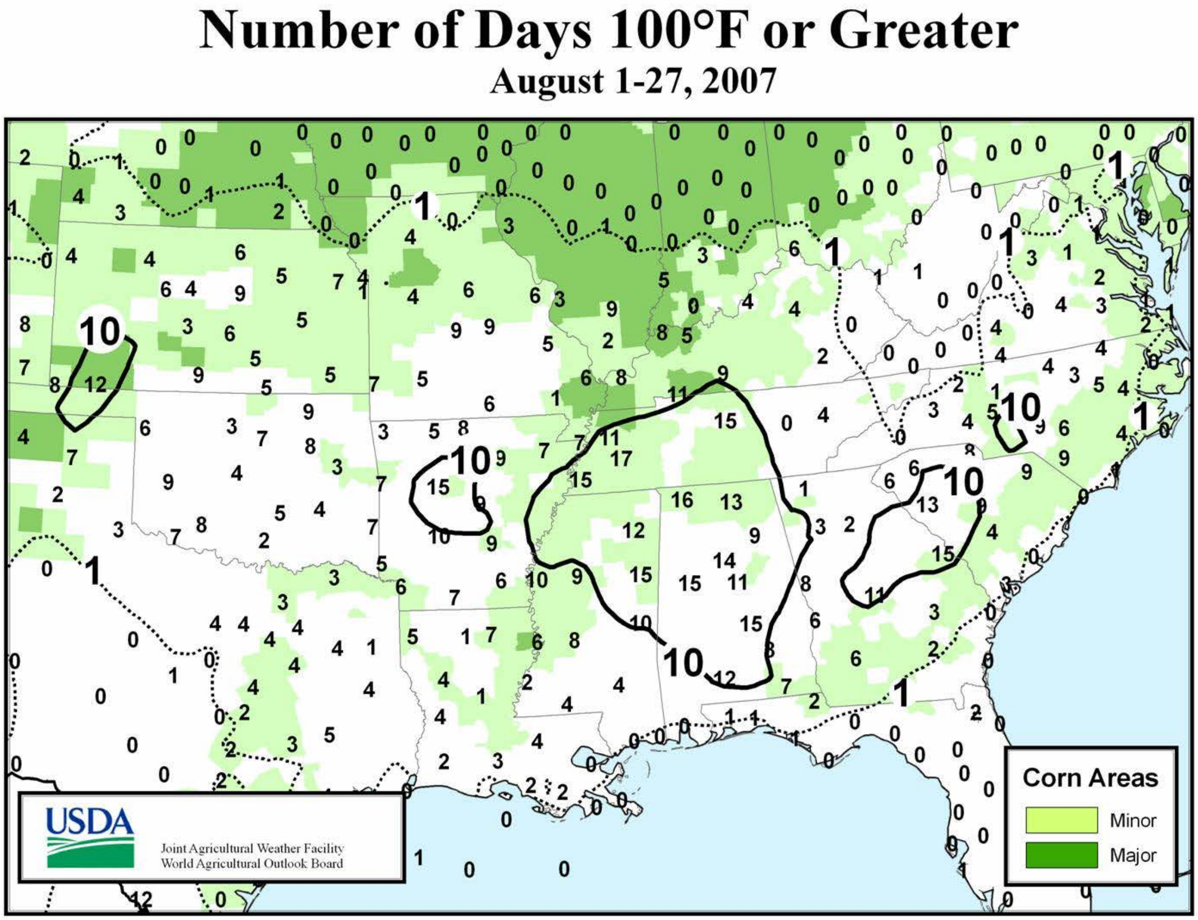

Figure 2.1. Number of days with high temperatures at or above 100°F during the August 2007 heat wave (from NCDC 2007, "August 2007 Heat Wave Summary.")

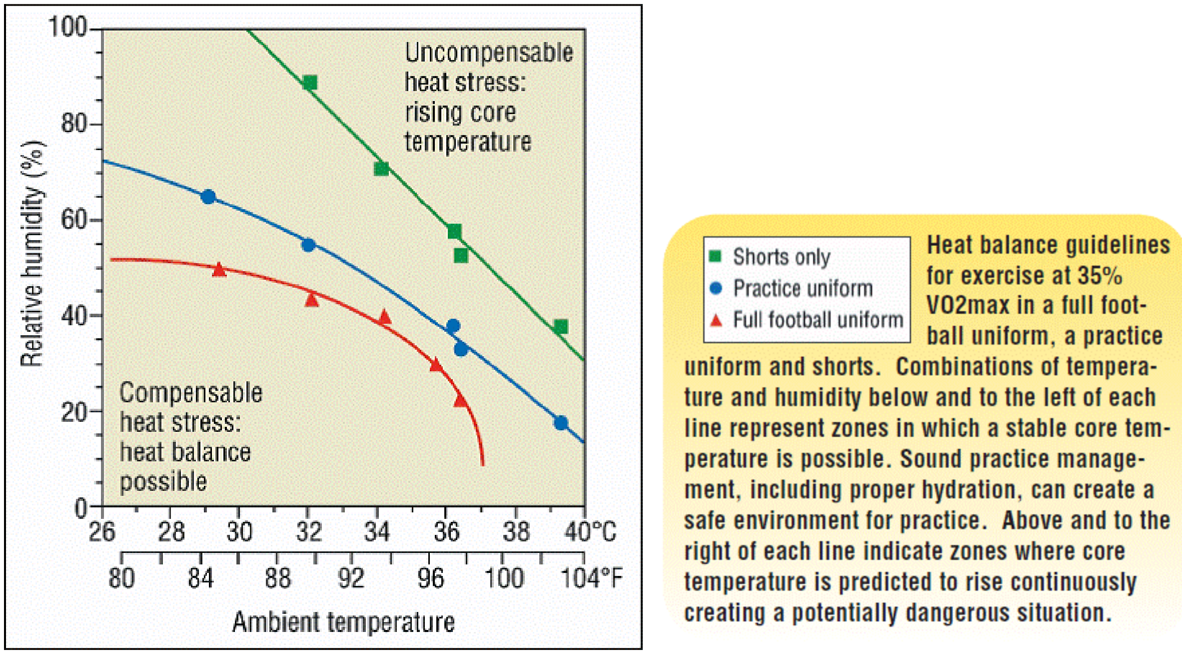

Figure 2.2. Zones of acceptable thresholds for football activities by uniform, based on Temperature and Relative Humidity, from Kulka and Kenney (2002).

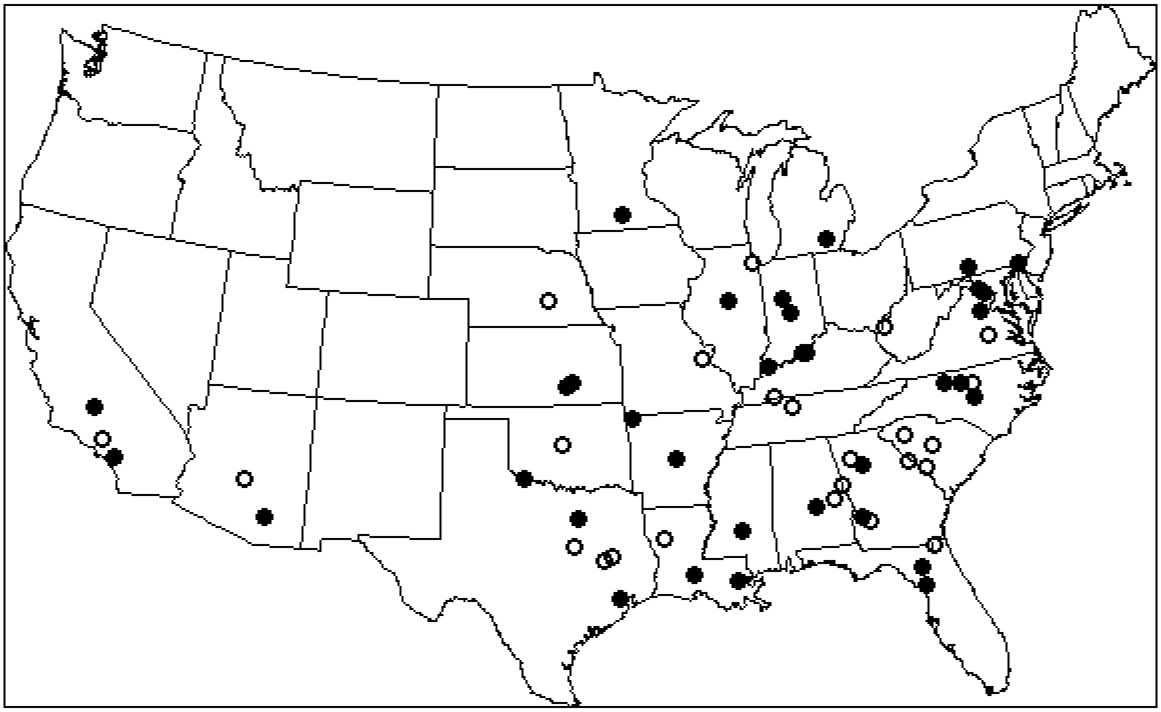

Figure 2.3. Football hyperthermia deaths, 1980–2009. Filled circles are deaths that occurred in locations with meteorological observing stations within 50 km, from Grundstein et al. (2010).

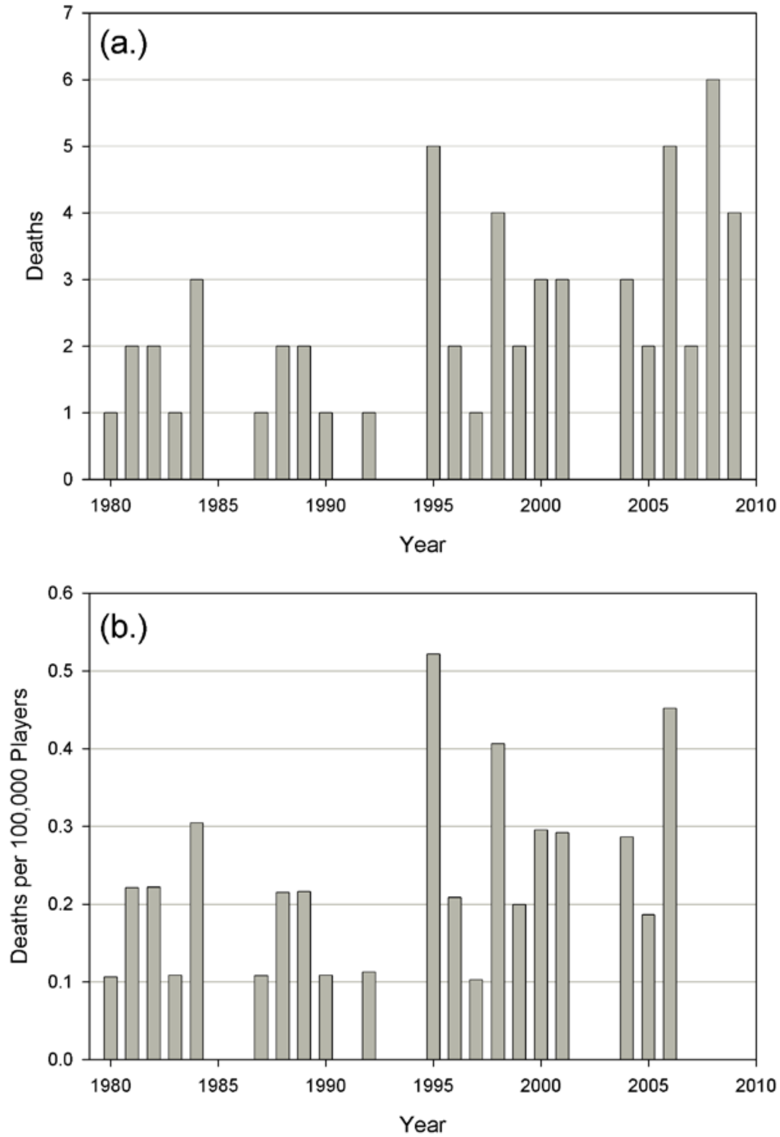

Figure 2.4. Time series of a) total football hyperthermia deaths and b) deaths per 100,000 players. Deaths were normalized using data on the number of high school football players from the period 1980–2006, from Grundstein et al. (2010)

CHAPTER 3

RESEARCH DESIGN AND METHODS

3.1 Data

3.1.1 National Center for Catastrophic Sports Injury Research

The National Center for Catastrophic Sports Injury Research (NCCSIR), located at the University of North Carolina-Chapel Hill, collects and analyses data on severe high school and college sports injuries. The center was initiated during the 1982-1983 school year, and recommends rule changes, improved equipment, and safer coaching techniques based on its research and analysis. The primary data source for this study is the data set collected and maintained by Dr. Frederick Mueller at the NCCSIR, which includes causes of deaths/injuries as both a direct and indirect result of participation in athletics. Data are compiled with the assistance of coaches, athletic trainers, athletic directors, executive officers of state and national organizations, online news reports, and professional associates of the researchers with additional support provided by the National Collegiate Athletic Association (NCAA), National Federation of State High School Associations (NFHS) and the American Football Coaches Association (AFCA) (Sports Digest 2010). The main portion of the dataset used in this research documents all deaths attributed to hyperthermia, across all sports (predominantly football) since 1955. Grundstein et al. (2010) made significant updates to the dataset by analyzing news reports for each player's death, incorporating exposure date and time, equipment worn, activities taking place etc. as available. This updated version of the dataset will be used in this study.

3.1.2 Temperature Data

The daily temperature data used in calculating heat wave percentiles for each site are obtained from NWS daily climate summaries, via the Midwest Regional Climate Center (MRCC), from the station nearest the exposure site (NCDC 2010). High temperature is the only parameter needed in making the percentile threshold calculations for each site in question to determine if a heat wave is present, so it is the only variable retrieved. The upgrade to Automated Surface Observing Stations (ASOS) in the late 1980's through the early 1990's at sites across the country, including those in this study, changed the instrumentation used to measure temperature. The ASOS upgrade, in addition to any prior instrumentation changes and site movements that occurred during the period 1949-2008, are noted as possible limitations with the datasets. Instrumentation differences can also have an impact on the measurement of extremes, including temperatures. These limitations are known and the dataset used for this portion of the study is assumed to be an accurate representation of the conditions present at each site during the period 1949-2008.

3.1.3 NSRDB Dataset

The hourly data needed to run the energy balance model were retrieved using the National Solar Radiation Database (NSRDB; NREL 2011). The NSRDB data is very comprehensive and includes hourly solar data in addition to climate data. Data is available from the NSRDB from the period 1991-2005, thus cases are identified for modeling from this time period. Hourly variables taken from the NSRDB dataset and used to run BioKlima (Błażejczyk 2011) include: modeled global solar radiation, kglob (w/m^2), modeled direct solar radiation, kdir (w/m^2), modeled diffuse solar radiation, kdif (w/m^2), dry-bulb or air temperature, t (°C), relative humidity, f (%), cloud cover, N (%), pressure, p (hPa), and wind speed, v (m/s). Wind speed is corrected logarithmically from a height of 10 meters (the height of the anemometer) to two meters to represent wind speeds on the field.

3.1.4. Climatological Data

The data needed to create a climatological, or average, day used to run the model for a comparison is obtained from Local Climatological Data publications from the National Climatic Data Center (NCDC) for the years 2001-2010 (NCDC 2011). Hourly variables taken from these datasets and used to run BioKlima include dry-bulb temperature, t (°C), relative humidity, f (%), cloud cover, N (%), pressure, p (hPa), and wind speed, v (m/s). Wind speed is corrected logarithmically from a height of 10 meters (the height of the anemometer) to two meters to represent wind speeds on the field.

3.2 Methodology

3.2.1 Late-Summer Heat Waves in Georgia

As stated previously, there are many methods and criteria that can be used in defining a heat wave. A heat-wave definition that contained few complex and difficult-to-obtain variables, unlike the Heat Index equation, was optimal. Also important was having a method that was not location-specific, so that the method and results of this research could be applied and compared to other parts of the country and even the world. The methods used by Meehl and Tebaldi (2004) satisfied both of these requirements. This approach uses only daily maximum temperatures, and percentiles from the entire data set to establish its thresholds, in an effort to capture only true heat wave events. Sites were selected that maximized spatial coverage across the state and also had an almost complete data record. After consulting with Pam Knox, Assistant State Climatologist for the State of Georgia, it was decided to obtain the data record for six first-order ASOS sites: Atlanta, Athens, Augusta, Columbus, Macon, and Savannah. The period spans 1 January 1949 through 31 December 2008, giving a 60-year climatology. Daily maximum temperature, minimum temperature, and precipitation values were obtained, courtesy of Pam Knox, from the MRCC (NCDC 2010). As an added bonus, this approach by design takes into account local effects of topography and land cover on temperatures at the site because of the fact that a multi-decadal climatology is used in its calculation.

The percentile thresholds are calculated for each site using only daily maximum high temperatures from the summer months (May-September) instead of the entire year (it is not clear how Meehl and Tebaldi applied their approach to the climatology, whether all months or only months that define the summer period are used). For this study, high temperature data from the months May-September for all years are used to calculate the thresholds used to define a heat wave. The use of summer temperatures capture’s the truly intense heat events as well as allowing for some physiological adaptation of higher heat during the summer months. The criteria established by Meehl and Tebaldi (2004) are then applied to the dataset to identify heat waves that occurred during the period (Figure 3.1).

3.2.2 Heat Waves Affecting Football Players

In determining the potential impact of heat waves on the exposure date for players in this study, the same method of identifying heat waves for the state of Georgia is applied. The primary outcome of this determines if a heat wave was the cause of extreme heat that resulted in the death of a football player. This evaluation creates a heat wave climatology for each site in question for the period 1949-2008. First-order ASOS sites closest to the site of exposure for each player were located using a nearest neighbor analysis through ArcGIS by Grundstein et al. (2010). Sites identified with an incomplete data record were examined manually in an attempt to find a useful site within reasonable proximity of the exposure site of the player.

3.2.3 Biometeorological Modeling of Players

In an effort to discern what conditions caused heat stroke in these players, five cases have been modeled using BioKlima, a biometeorological modeling package (Błażejczyk 2011). BioKlima allows for the evaluation of bioclimatic conditions as well as the human heat balance. The model uses the net heat balance of man in combination with meteorological variables to solve for various indices related to the thermal environment under which activities are taking place. In this research, it evaluates the conditions football players experienced when they developed hyperthermia on the field. The five cases have been identified from the NCCSIR dataset amended by Grundstein et al. (2010) as having the most complete information on a player's height, weight, age, date and time of exposure and clothing and equipment worn. Four different simulations were run for each player (Table 3.1).

Table 3.1 Possible Model Simulation Combinations

	Full Uniform clo factor	Shorts/T-shirt clo factor
Actual Conditions	X	X
Climatology Conditions	X	X

3.2.3.1 Modeling Simulations

To find the effects of the specific conditions experienced when players initially fell ill, the first simulation was run using the conditions recorded by the nearest NSRDB station for the timeframe established by the NCCSIR dataset. The second simulation was run using the average conditions established by the climatology for the site of that day, obtained from the same first-order ASOS station used for the heat wave climatology. This comparison is done to see how abnormal conditions were during the days that players suffered hyperthermia. These two simulations are computed with two different clothing insulation (clo) factors. The first uses a clo factor for a full football uniform (Table 2.2), including a helmet, shoulder pads and padded pants (full ensemble listed in Table 2.1, under G1 Game Uniform) while the second clo factor assumes a player wearing only shorts and a t-shirt (Table 2.2). These two different clo factors are used to show the effect of a full uniform on the heat balance of a player, especially early in the football season when players are more vulnerable to heat illness due to their lack of acclimatization to the conditions they are experiencing.

3.2.3.2 Input Variables

Sun altitude angle is calculated within BioKlima given latitude of the site, month, day of the month, and hours of the day (in question). The meteorological input variables include those mentioned in section 3.1.3. All meteorological variables are interpolated linearly at five-minute increments between hourly NSRDB observations for the given time period with respect to each player. It is assumed that these variables increase and decrease linearly from hour to hour in order to increase the temporal resolution of the model. The two variables that are held constant through each time step are clothing insolation factor (Icl) and metabolic heat production (M).

Values for Icl are determined by the type of uniform the player is assumed to be wearing, with a value of 0.9clo for the t-shirt and shorts ensemble, and a value of 1.28clo for the full football uniform. The full G1 game uniform for warm weather ensemble (McCullough and Kenney 2003) is used here to establish the Icl value in place of the P1 practice ensemble under the assumption that players are fully participating in live contact drills and plays, consequently wearing all protective leg pads as opposed to only a padded girdle. A description of how metabolic heat production is calculated is given in the following section.

3.2.3.3 Calculating Metabolic Heat Production

The calculation of an athletes metabolic heat production begins with establishing their base metabolic rate (BMR). BMR is the number of calories burned by a person if they remained at rest all day (Ainsworth 2000). The Harris-Benedict equation (Equation 3.1) uses an athlete's height, weight, and age to make this calculation (Spodaryk and Kobylarz 2004).

$$BMR(kcal) = 66.5 + 13.75 * weight(kg) + 5.003 * height(cm) - 6.775 * age(years) \quad (1)$$

The value, in kilocalories (kcal), is divided by 24, giving the BMR per hour for an athlete. The BMR/hr is multiplied by a MET value of 9, which is specific to the activities undertaken while participating in the sport of football (Ainsworth 2000). The BMR/hr for football, in units of kcal/hr, is then converted in terms of surface area of the player. This is done by dividing the BMR/hr for football by the players surface area, calculated using the Mosteller (1987) formula for body surface area (BSA) (Equation 3.2). This formula approximates a person's BSA based on a person's height and weight without physically measuring their BSA.

$$BSA(m^2) = \sqrt{\frac{(height(cm) * weight(kg))}{3600}} \quad (2)$$

The resulting value, with units of kcal/hr*m^2, is converted to W/m^2 by multiplying by 1.1622. One kcal is equal to 4184 joules. Since kcal are expressed per hour, 4184 joules are divided by 3600 seconds, the number of seconds within an hour, giving 1.1622 J/s, equivalent to 1.1622 watts. The final calculated value for metabolic heat production is representative of the athlete's characteristics (height, weight, age) and the energy expended by participating in football activities.

3.2.3.4 Calculating Climatological Conditions

For each site, the date that a player fell ill from hyperthermia is the same date for which average conditions are calculated. This is done using Local Climatological Data Publications for each of the five sites from the years 2001-2010 (NCDC 2011). So if a player fell ill on August 1st, the conditions from August 1st for each year from 2001-2010 are averaged to establish the average conditions for that day. A ten-year climatology was used to calculate the average conditions based on data availability as well as being more representative of the climate of the area during the time surrounding a players death. Hourly data is interpolated in the same method as the NSRDB data used to establish the actual conditions the player faced on that day. The players Metabolic Heat Production is held constant through both climatology runs, with Icl being the only variable that changes, based on the uniform it is assumed the player is wearing. Metabolic Heat Production is held constant because it is assumed the player is participating at his fullest capacity during practice. This produces two climatology runs to be compared to the two runs using NSRDB data. The climatology runs are produced as a reference to see how extreme the actual conditions the players faced they day they fell ill were, and if more average conditions would have kept them safer during practice.

3.2.3.5 Output Variables

The model output is analyzed both individually and across all five cases with respect to the variables in question. Humidex, Wet Bulb Globe Temperature (WBGT, in °C), and Universal Thermal Climate Index, with their respective thresholds for acceptable activity, give insight as to whether or not the actual conditions each player faced, the equipment they were wearing, or a combination of both led to heat stroke.

WBGT was invented and first used in the 1950's by the United States Marine Corps to control serious outbreaks of heat illness in training camps (Budd 2008). It was developed as a convenient substitute for effective temperature including a radiation component (ETR) and can be obtained using three thermometers; a wet-bulb thermometer (Tw), a globe thermometer (Tg, which measures effects of solar radiation) and a dry-bulb thermometer (Td). WBGT is calculated using the following equation (3.3):

$$WBGT\ (°C) = 0.7\ Tw + 0.2\ Tg + 0.1\ Td \ (3)$$

This produces a perceived temperature that combines the effects of solar radiation, humidity and air temperature and their effects on a person. Sports Medicine Australia, The American College of Sports Medicine, and the American Academy of Pediatrics have developed safety thresholds using the WBGT for outdoor participation in sports activities (Grundstein et al. 2010).

The Humidex is a bivariate index that combines the health impacts of temperature and humidity (Weir 2002). It is used by Environment Canada in the same manner as the Heat Index is used by the National Weather Service. The current formula for determining the Humidex was developed by Canada's Atmospheric Environment Service in 1979.

The UTCI was developed by the International Society of Biometeorology as a method of assessing the thermo-physiological effects of the atmospheric environment on a person (Jendritzky 2001). UTCI is valid across all climates, seasons and scales, and independent of a person’s own characteristics (height, weight, age, gender, specific activities, etc.), and takes into account all mechanisms of heat exchange by a person. UTCI always has the same thermo-physiological meaning, so it can be used anywhere to assess dangerous conditions, especially in the issuance of daily weather forecasts to the public (Jendritzky 2001).

In addition, sweat loss index (SW, in g/hr), minutes to hyperthermia (Oh_H, in min), and heat stress index (HSI, in %) are shown to establish the severity of the conditions the players were experiencing, and if more average conditions or limited exposure could have prevented hyperthermia. SW indicates how dehydrated players are becoming while on the field. It is calculated based on the potential values of evaporative heat loss. The limit values, that should not be exceeded, depend on the activity and a subject’s level of acclimation. Oh_H indicates the amount of time it would take with the given meteorological and physical conditions for a player’s core body temperature could rise above 40°C and begin to suffer from the effects of hyperthermia. This variable is not calculated cumulatively with time; rather, it portrays the amount of time it would take the player to potentially experience hyperthermia given the current meteorological conditions at each time step. HSI is a ratio that determines how much evaporation is necessary for a person to remain at heat equilibrium given the maximum amount of evaporation possible under environmental conditions.

Results are also shown across all five cases under the actual conditions the players experienced the day they suffered from hyperthermia. Despite occurring in different regions of the U.S. under different conditions, exceedance of indices relating to the body's ability for thermoregulation is the common link between all of these cases. The loss of this ability over the course of practice is shown through: SW, HSI, Oh_H, heat load index (HL), and acceptable level of physical activity (MHR, in w/m^2). Each of these indices is calculated based on the uniform the player was, or is assumed to be, wearing at the time of falling ill due to hyperthermia. HL combines all physical and meteorological variables in determining the body's ability to maintain its own internal heat load. The heat load of a player is calculated based on net heat storage, absorbed solar radiation and evaporative heat loss, and illustrates the load on the central thermoregulation system due to the player's adaptive processes. MHR gives the upper limit of activity under given meteorological conditions that will not provoke a heart rate over 90 beats per minute. A further explanation of how each of these indices is calculated, as well as threshold values, can be found in Appendix A.

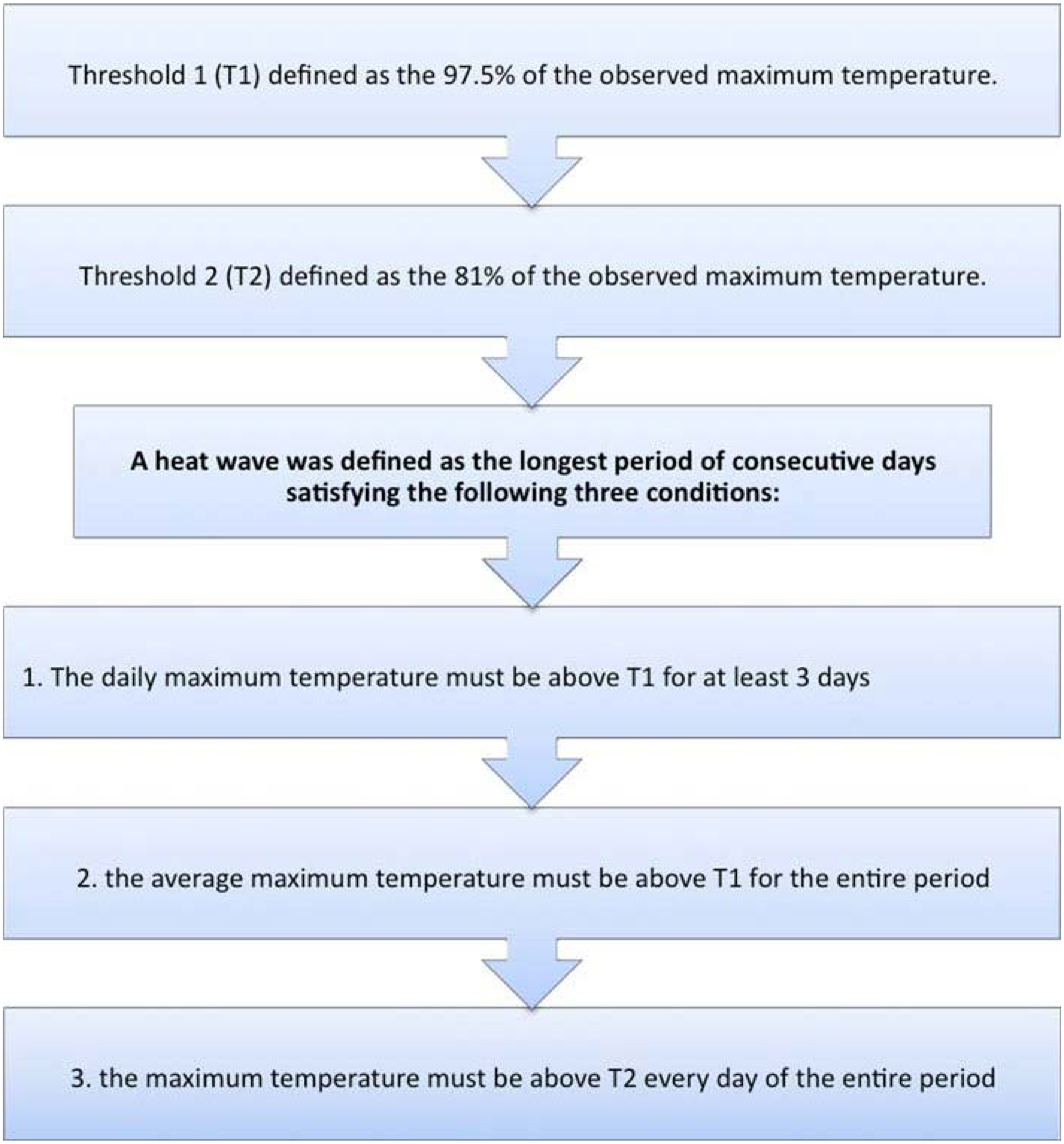

Figure 3.1. Flow chart depicting method of how a heat wave is defined (from Zhou and Shepherd 2010)

CHAPTER 4

RESULTS

4.1 Late-Summer Heat Waves in Georgia

Percentile thresholds calculated for each site can be seen in Table 4.1. Thresholds are calculated for each site based on summer months (May-September) to capture truly intense heat wave events. On average, the 97.5th percentile summer thresholds are 2°F higher than those calculated for the entire year, with the exception being Columbus at 1°F higher. Overall, each site saw the greatest number of heat waves, in terms of decade, from 1979-1988 (Table 4.2 and Figure 4.1). Multiple periods of drought in the Southeast during this time period were a large contributing factor to the sharp rise in the number of heat waves recorded (Ross and Lott 2003). As precipitation deficits increase, daytime high temperatures increase because of the increase in the sensible heat fluxes as a result of the depletion of soil moisture and the reduction of evapotranspiration from vegetation (Chen and Konrad 2006).

Table 4.1. Temperature Percentiles, in degrees Fahrenheit

Percentile	Athens KAHN	Atlanta KATL	Augusta KAGS	Columbus KCSG	Macon KMAC	Savannah KSAV
97.5th Summer	98	96	100	98	100	98
81st Summer	92	91	94	94	95	93
97.5th Full Year	96	94	98	97	98	96
81st Full Year	88	87	90	90	91	90

Table 4.2. Number of heat wave events, per decade, by site

	Athens	Atlanta	Augusta	Columbus	Macon	Savannah
1949-1958	**7**	**9**	**5**	**5**	**7**	**8**
1959-1968	**3**	**2**	**1**	**2**	**3**	**6**
1969-1978	**2**	**1**	**3**	**6**	**5**	**3**
1979-1988	**14**	**15**	**6**	**10**	**9**	**11**
1989-1998	**7**	**9**	**4**	**13**	**5**	**5**
1999-2008	**8**	**9**	**3**	**8**	**6**	**4**
Average Per Decade	**6.83**	**7.5**	**3.67**	**7.33**	**5.83**	**6.17**

As expected, Georgia sees the majority of its heat waves during the months of June and July across all sites (Table 4.3). However, August and September, normally thought of as cooler, transitional months from summer to fall, produce a surprising percentage of all heat waves. For every site, at least 20% of heat waves from the period occurred in the late-summer period of August and September (Table 4.4). In Atlanta, a startling 40% of heat waves occur during the late-summer period.

Table 4.3. Number of heat wave events, by month, for the entire period

	Athens	Atlanta	Augusta	Columbus	Macon	Savannah
May	0	0	0	0	0	1
June	13	9	7	15	12	12
July	18	18	10	18	16	16
August	**9**	**16**	**5**	**8**	**7**	**8**
September	**1**	**2**	**0**	**3**	**0**	**0**

Table 4.4. Percent of total number of heat wave events occurring during August-September

Athens	**24.3%**	**Atlanta**	**40%**	**Augusta**	**22.7%**
Columbus	**25%**	**Macon**	**20%**	**Savannah**	**21.6%**

Late-summer heat waves that occur in Athens and Augusta average a longer duration than the average duration for all heat wave events occurring from 1949-2008 (Table 4.5). The average duration of late-summer heat waves that occur at the other four sites (Atlanta, Columbus, Macon, and Savannah) is slightly less than the average duration for all events, but late-summer heat waves persist on average at least 5 days.

The heat waves of longest duration were also found for each site (Table 4.6). Four sites have the longest heat wave from this period occurring entirely during the late summer season (Athens), or lasting into the beginning of August (Atlanta, Augusta, and Savannah). These heat waves also lasted longer than the longest heat waves on record for Macon and Columbus, which both lasted 18 days and occurred entirely in the month of July.

This analysis of late-summer heat waves in Georgia establishes that heat is a potential and recurrent hazard in August and September. Football practices at the high school and collegiate levels generally start at the beginning of August, coinciding with the start of the fall semester. The coincidental timing of late-summer heat waves and the start of the fall practice season warrants further investigation to ascertain if these heat waves are causing players to succumb to hyperthermia. Heat waves are events that do not only occur in Georgia, making it important to see the impact heat waves have in other regions of the United States.

Table 4.5. Average duration for all events and for August-September (Late-Summer) Events

	All Events	Aug-Sept Events			All Events	Aug-Sept Events
Athens	**7 days**	**7.3 days**		**Columbus**	**7 days**	**5.18 days**
Atlanta	**7.3 days**	**6.27 days**		**Macon**	**6.2 days**	**5.71 days**
Augusta	**8.63 days**	**8.8 days**		**Savannah**	**6.84 days**	**5 days**

Table 4.6. Longest Duration Heat Waves, State of Georgia

Athens	**22 days, 5 August 2007- 26 August 2007**
Atlanta	**21 days, 16 July 1986- 5 August 1986**
Augusta	**32 days, 3 July 1993-3 August 1993**
Columbus	**18 days, 5 July 2000-22 July 2000**
Macon	**18 days, 8 July 1986-25 July 1986**
Savannah	**33 days, 7 July 1993- 4 August 1993**

4.2 Late-Summer Heat Waves and Football Players

4.2.1 Late-Summer Heat Waves at Hyperthermia Death Locations in the U.S.

Of the 58 cases of death due to hyperthermia in football in the U.S. from 1980-2009, 10 had to be omitted due to either incomplete data records of ASOS sites closest to the exposure site of the players, or else not being able to locate the site accurately. From the remaining 48 cases, only three sites were experiencing a heat wave on the exposure date of players that later died due to hyperthermia (Table 4.7). The characteristics of heat waves at these sites are examined to establish any similarities between them and those that occur in Georgia.

Table 4.7. Players Who Died Due to Hyperthermia During a Heat Wave

Player	School	State	Exposure Date	Heat Wave Dates	Heat Wave Duration
Greg Pratt	Auburn University	Alabama	8/20/1983	8/20/1983 – 8/24/1983	5 Days
Damon Terrell	University of Arizona	Arizona	8/10/1995	7/25/1995 – 8/10/1995	17 Days
Lonnie Magee	Mount Olive High School	Mississippi	8/8/2007	8/2/2007 – 8/25/2007	24 Days

The percentile thresholds calculated for each site are shown in Table 4.8. Despite being further west, the thresholds for Laurel, MS are exactly the same as those for Columbus, GA. However, heat waves occurring in Laurel differ in both duration, and timing vs. Columbus. For all heat wave events, those occurring in Laurel, MS last on average 1.6 days longer than those occurring in Columbus, GA (Table 4.9). The percentage of late-summer heat waves that occur in Laurel, MS is almost 15% higher than that of Columbus, GA (Table 4.10). Magee fell ill during the longest heat wave in the climatology for Laurel, MS, during which the average temperature for those 24 days was 102.3°F, over four degrees greater than the 97.5th percentile summertime threshold for extreme heat.

It makes sense that the thresholds for Tucson, AZ are considerably higher than any other station in this study, since Tucson is located in the middle of a desert region. Tucson only experienced one late-summer heat wave from 1949-2008, with one other that began in July and continued into August. This differs considerably from the trends observed with the Georgia sites, as well as Laurel, MS. With regard to average duration for heat waves in Tucson, no real conclusions can be drawn between the difference in late-summer heat waves and all events, because late-summer heat waves are not a recurring event for Tucson, making up only 3.8% of all events (Table 4.10) However, it should be noted that the heat wave occurring when Terrell fell ill from hyperthermia was the second-longest heat wave occurring in the climatology, the longest being 24 days.

Table 4.8 Temperature Percentiles, in degrees Fahrenheit (degrees Celsius)

Percentiles	Columbus, GA	Tucson, AZ	Laurel, MS
97.5th Summer	98	108	98
81st Summer	94	102	94
97.5th Full Year	97	106	97
81st Full Year	90	98	90

Table 4.9 Average duration in days for all events and for August-September (Late-Summer) events

	All Events	Aug-Sept Events
Columbus, GA	**7**	**5.18**
Tucson, AZ	**6.34**	**6 (1 event)**
Laurel, MS	**8.60**	**9.54**

Table 4.10 Percent of total number of heat wave events occurring during August-September

Columbus, GA	**25%**	**Tucson, AZ**	**3.8%**	**Laurel, MS**	**39.39%**

4.2.2 Connection Between Late-Summer Heat Waves and Hyperthermia

Approximately 94% of players in the NCCSIR dataset did not succumb to hyperthermia due to a heat wave, as defined in this study. This leads to the conclusion that extreme heat is not the only factor that leads to a player's inability to regulate their own internal temperature. Heat waves, as synoptic-level events, do not capture processes and conditions occurring at the mesoscale, or even microscale, causing players to overheat and suffer from hyperthermia. Understanding these conditions on a small spatial and temporal scale is necessary to prevent these deaths from occurring in the future. Below, five cases are modeled to observe how hyperthermia occurs in football players at these small scales.

4.3 Modeling Using BioKlima

4.3.1 Individual Results

The five players selected for examination in the modeling portion of this study had the most complete records within the NCCSIR dataset of time of day when they were practicing and subsequently fell ill, the activities they were participating in, as well as the clothing they were wearing. They also coincided with the period of data availability from the NSRDB dataset. It should also be noted that according to news accounts, none of these five players had any pre-existing conditions that could have contributed to their death. All of these conditions were necessary for a fine-grained temporal analysis of the conditions that cause hyperthermia in football players. The time of practice for each player is in local standard time (LST).

4.3.1.1 Damon Terrell

Damon Terrell fell ill from hyperthermia while participating in morning conditioning drills at the University of Arizona on August 10, 1995 (NCCSIR 2010). A comparison between the actual conditions Terrell was experiencing, and the 10-year climatological averages of the same day can be seen in Table 4.11. News reports cited that Terrell was participating in morning conditioning drills and may have become dehydrated at the end of a training run (NCCSIR 2010).

Table 4.11 Actual versus average conditions for Damon Terrell (Tucson, AZ), 10 August

	Temperature (°C)	**Relative Humidity (%)**	**Wind Speed (kts)**	**Pressure (hPa)**	**Cloud Cover (%)**
Actual Conditions					
8:00 AM	32.2	41	3.00	917	30
9:00 AM	33.8	37	0.58	917	20
10:00 AM	35.5	33	1.18	918	30
11:00 AM	37.2	29	0.88	918	20
12:00 PM	38.3	27	0.88	917	30
Average Conditions					
8:00 AM	27.22	56.4	1.32	927.69	9.4
9:00 AM	29.13	49.9	1.12	927.73	7.5
10:00 AM	30.48	45.5	1.14	927.66	9.4
11:00 AM	31.88	41.5	1.31	927.46	14.4
12:00 PM	33.13	37.6	1.31	926.88	15.0

Humidex values are calculated independent of clothing insulation factor (clo), so results are displayed as actual versus average conditions (Figure 4.2). Even under average conditions, Terrell would have been above the Extreme Caution threshold throughout the duration of practice. Under actual conditions, Terrell crossed over into the danger threshold approximately 100 minutes into practice, in which case activity is recommended to be suspended, with possible heat stroke given continued exposure.

Wet Bulb Globe Temperature (WBGT) values are calculated independent of clothing insulation factor (clo), so results are displayed as actual versus average conditions (Figure 4.3). Under average conditions, Terrell would have still been at extreme risk, crossing into the threshold under which cancelling practice is recommended by both the American College of

Sports Medicine and Sports Medicine Australia approximately 45 minutes into practice. Under the actual conditions of the day, this threshold was exceeded throughout the duration of practice.

Universal Thermal Climate Index (UTCI) values are calculated independent of clothing insulation factor (clo), so results are displayed as actual versus average conditions (Figure 4.4). Practicing under average conditions would have given Terrell only approximately 25 more minutes of practice before experiencing very strong heat stress. Given the actual conditions, this threshold was crossed approximately 130 minutes into practice.

Sweat Loss Index (SW) values are dependent on the clothing insulation factor (clo), so results for all four model runs are shown in Figure 4.5. Had practice taken place during an average day, Terrell's sweat loss would have remained below the hazardous threshold for an unacclimatized person, despite the type of uniform present, throughout the duration of practice. Assuming a shorts and t-shirt clothing ensemble, given that Terrell was participating in a training run (NCCSIR 2010), puts him above the hazardous threshold for an unacclimatized person approximately 105 minutes into practice under the conditions of that day.

Hyperthermia risk (in minutes) is dependent on the clothing insulation factor (clo), so values for all four model runs are shown in Figure 4.6. This value is not cumulative over time; rather it depicts the amount of time it would take the player to potentially experience hyperthermia given the current meteorological conditions at each time step. Unless the value increases above the remaining time of practice, the player is assumed to be at risk. Terrell would have likely experienced hyperthermia more quickly under average conditions, despite which uniform he would have been wearing. This is attributed to the average relative humidity being higher than the actual relative humidity of that day. Given actual conditions, minutes to hyperthermia increase during the course of practice, indicating some improvement of conditions, but not enough to decrease the risk of hyperthermia.

Heat Stress Index (HSI) values are dependent on the clothing insulation factor (clo), so values for all four model runs are shown in Figure 4.7. HSI values are similar with regard to the conditions present, despite the differences in clo factor between the two uniform ensembles. Actual conditions exceed the hazard of overheating threshold approximately 25 minutes into practice, and stay well above this threshold under the average conditions of the day. Despite the average conditions remaining above the threshold throughout the duration of practice, the HSI under actual conditions has a much higher magnitude overall.

4.3.1.2 Robert Barrett

Robert Barrett fell ill from hyperthermia while participating in practice at Southeast High School in Wichita, KS on August 17, 1998 (NCCSIR 2010). A comparison between the actual conditions Barrett was experiencing, and the averages of the same day can be seen in Table 4.12. News reports cited that the HI reached 105°F during practice and that coaches usually give players water every 15 minutes, plus a 5-minute break, during hot weather. Since Barrett's death, coaches have ensured that all players drink enough water to avoid dehydration (NCCSIR 2010).

Table 4.12 Actual versus average conditions for Robert Barrett (Wichita, KS), 17 August

	Temperature (°C)	Relative Humidity (%)	Wind Speed (kts)	Pressure (hPa)	Cloud Cover (%)
Actual Conditions					
8:00 AM	28	22	3.65	966	0
9:00 AM	31	46	3.65	966	0
10:00 AM	33	41	3.82	965	0
11:00 AM	34	39	3.94	965	100
12:00 PM	36	33	3.65	965	100
Climatological Conditions					
8:00 AM	22.66	82.5	2.5	968.73	64.7
9:00 AM	23.72	79.4	2.55	969.04	71.3
10:00 AM	24.42	75.3	3.05	969.01	72.3
11:00 AM	25.35	71.9	3.18	968.90	75.3
12:00 PM	26.55	67.6	2.97	968.77	76.3

Humidex values under average conditions remain above the extreme caution threshold for the majority of practice, but are reasonable given adequate precautions (Figure 4.8). Average conditions also depict a steady increase in the Humidex. The actual conditions of the day however, drive the Humidex above the danger threshold at approximately 180 minutes into practice. Values increase sharply during the first hour of practice, with a more gradual increase throughout the duration of practice.

WBGT remains above the high threshold under both sets of conditions (Figure 4.9). Average conditions reach the WBGT threshold for canceling the event right at the end of the practice. Under the actual conditions, this same threshold is reached just 50 minutes into practice, as the WBGT increases sharply until approximately 65 minutes into practice.

UTCI never reaches the threshold for strong heat stress under average conditions (Figure 4.10). The actual conditions of the day drive the UTCI above the strong heat stress threshold approximately 60 minutes into practice and within 2°C of the very strong heat stress threshold by the end of practice. Almost 75% of the practice that day took place when the UTCI was above the strong heat stress threshold.

SW under average conditions rises steadily for both uniform combinations throughout practice, and remains well below the hazardous level for an acclimatized person (Figure 4.11). The actual conditions that Barrett faced that day were much more dangerous, crossing the hazardous threshold for an acclimatized person at 70 minutes with the practice uniform, and at 110 minutes for the full uniform. The SW values also increase faster further along into practice.

Barrett's time to hyperthermia risk would have been decreased under average conditions because of higher relative humidity values. Both uniform combinations under actual conditions show a sharp decrease in the amount of time to hyperthermia during the first hour of practice (Figure 4.12). Actual conditions gradually improve throughout the rest of practice, as the amount of exposure time required to reach hyperthermia increases.

Surprisingly, the HSI is greater for the average conditions than for the actual conditions of the day, across both uniform combinations. Average conditions keep the HSI above the maximal heat stress threshold for the first 110 minutes of practice, and for the last 30 minutes. The actual conditions show the HSI below this threshold throughout the duration of practice, while crossing the very intensive heat stress threshold at 45 minutes into practice for both uniform combinations. Actual RH values much lower than those under average conditions explain the difference in HSI values.

4.3.1.3 Eraste Austin

Eraste Austin fell ill with hyperthermia while participating in summer workouts at the University of Florida on July 19, 2001 (NCCSIR 2010). A comparison between the actual conditions Austin was experiencing, and the averages of the same day can be seen in Table 4.13. It is important to note here that the actual temperature was lower than the average temperature for that day, unlike the other four cases in this study. However, the Relative Humidity on the exposure day is higher than the average. News reports cited that Austin lifted weights from 2:30 to 3:30 p.m. and participated in a conditioning session from 4 to 4:50 that included a 10-minute warmup (light mobility drills), five minutes of stretching, five minutes each at four agility stations and 15 minutes of sprints. Austin collapsed outside of Ben Hill Griffin Stadium as he and teammates jogged nearly 300 yards from the practice field to the stadium (NCCSIR 2010).

Table 4.13 Actual versus average conditions for Eraste Austin (Gainesville, FL), 19 July

	Temperature (°C)	**Relative Humidity (%)**	**Wind Speed (kts)**	**Pressure (hPa)**	**Cloud Cover (%)**
Actual Conditions					
8:00 AM	30	72	1.53	1012	30
9:00 AM	29.4	75	1.82	1011	60
10:00 AM	31.7	63	2.11	1011	40
11:00 AM	29.4	72	2.71	1010	80
12:00 PM	29.4	75	1.82	1010	20
Climatological Conditions					
8:00 AM	32.37	53.5	1.61	1010.28	24.8
9:00 AM	31.57	56.6	2.04	1010.01	34.3
10:00 AM	30.77	60.4	2.34	1009.67	30.1
11:00 AM	29.88	63.9	2.02	1009.58	29.2
12:00 PM	29.06	67.3	1.61	1009.69	20.3

Humidex values are rather similar between both sets of conditions (Figure 4.14). Under average conditions, the Humidex begins just above the danger threshold, and decreases gradually throughout practice, falling below the threshold at 125 minutes into practice. For the actual conditions, the Humidex values do remain above the danger threshold during the entire practice, but only reach a maximum value of 42.26 at 125 minutes into practice, where the danger threshold is 40.

WBGT under both sets of conditions indicates that practice never should have taken place (Figure 4.15). Average conditions have a WBGT of 32.5°C at the beginning of practice, steadily decreasing to 31°C at the end of the practice time. Under actual conditions, the WBGT reaches a peak of 33.5°C at 125 minutes into practice.

Average conditions begin almost at the threshold for very strong heat stress under the UTCI, but UTCI values gradually fall below the strong heat stress threshold (at 190 minutes) as practice continues (Figure 4.16). Under actual conditions, UTCI values remain below the very strong heat stress threshold, and even fall below the strong heat stress threshold before spiking over a 50 minute period (minutes 175 to 225 of practice) to well above the very strong heat stress threshold. This indicates a relatively quick increase of the severity of conditions that Austin was outside working out in.

For all four model simulations, SW remains below the hazardous threshold for an acclimatized person, but above the hazardous threshold for a non-acclimatized person, throughout the duration of practice (Figure 4.17). Under average conditions, the amount of sweat loss decreases throughout practice for both uniform combinations. Actual conditions show the same trend for both uniform combinations, with a notable sharp increase in SW at 175 minutes into practice.

Average conditions at the beginning of practice have a faster time to hyperthermia when compared to the actual conditions (Figure 4.18), and remain this way until 175 minutes into practice. For actual conditions, the minutes to hyperthermia drops drastically from 50 minutes to less than 10 minutes under the practice uniform ensemble, and 13 minutes under the full uniform. This drop occurs over a period of approximately 40 minutes, showing a severe increase in the harshness of conditions Austin was experiencing.

Across all four model simulations, HSI remains above the hazard of overheating threshold for the entire practice (Figure 4.19). Under average conditions, the HSI decreases from approximately 160 to 125 over the first 125 minutes of practice, and then increases up to 145 by the conclusion of practice. Actual conditions show an almost identical HSI for both uniforms, starting at 180 and decreasing to 115 over the first 3 hours of practice, and then spiking to over 200 by the end of the session.

4.3.1.4 Korey Stringer

Korey Stringer fell ill from hyperthermia during the third day of team training camp while competing for the Minnesota Vikings on July 31, 2001 (NCCSIR 2010). A comparison between the actual conditions Stringer was experiencing, and the averages of the same day can be seen in Table 4.14. News reports cited that Stringer had completed the morning practice session, lasting nearly two and a half hours, with the Minnesota Vikings and walked to an air conditioned shelter after practice (ending at 11:30 am LDT), where he later developed symptoms of hyperthermia (NCCSIR 2010).

Table 4.14 Actual versus average conditions for Korey Stringer (Mankato, MN), 31 July

	Temperature (°C)	Relative Humidity (%)	Wind Speed (kts)	Pressure (hPa)	Cloud Cover (%)
Actual Conditions					
8:00 AM	27.7	85	3.47	976	0
9:00 AM	28	85	3.71	976	0
10:00 AM	30	76	2.12	976	0
11:00 AM	31	77	3.59	976	20
12:00 PM	32	73	4.36	976	10
Climatological Conditions					
8:00 AM	23.85	70.3	1.76	981.6	53.7
9:00 AM	24.88	66.4	2.13	981.94	63.2
10:00 AM	26.05	63	2.09	981.6	56.8
11:00 AM	27.11	59.9	2.75	981.6	48.4
12:00 PM	28.44	53.5	2.84	981.26	50.7

Humidex values show the same trend in a general increase over time for both sets of conditions (Figure 4.20). Under average conditions, the Humidex remains above the extreme caution threshold for all but the first 10 minutes of practice. Actual conditions cause the Humidex to remain above the danger threshold for all but the first 35 minutes of practice.

The same increase over time seen in the Humidex is also observed with the WBGT for both sets of conditions (Figure 4.21). Under average conditions, the WBGT starts almost 3°C above the danger threshold and increases beyond the practice cancellation threshold with 30 minutes left in practice. The actual conditions show the WBGT beginning at 32°C, 4°C above the cancellation threshold, and increasing to almost 36°C by the end of practice.

UTCI remains below the strong heat stress threshold under average conditions for the duration of practice (Figure 4.22). Values range from 27°C at the beginning of practice to 30°C at the end of practice, with a peak of 31°C 220 minutes into practice. Under actual conditions, the UTCI crosses above the strong heat stress threshold 100 minutes into practice, peaking at 34.8°C when practice ends, never going above the very strong heat stress threshold.

For all model simulations, SW values remain well above the hazardous threshold for a non-acclimatized person, but stay below the hazardous threshold for an acclimatized person (Figure 4.23). The trend of increasing over time is extremely similar across all four simulations. The highest SW values are produced by the practice uniform under actual conditions, with the lowest SW values coming from the full uniform under average conditions simulation.

Minutes to Hyperthermia remain, on average, higher under average conditions for both uniform combinations when compared to the actual conditions (Figure 4.24). The full uniform under average conditions posed the least risk of hyperthermia of all four simulations, beginning at 45 minutes and concluding practice at almost 42 minutes, with a lowest value of 38 minutes to hyperthermia at 200 minutes into practice. The practice uniform under actual conditions posed the greatest risk of hyperthermia, beginning at almost 44 minutes, but falling to less than 32 minutes by the end of the practice session.

The trends observed with the HSI differ from the similar trends observed among the other five indices. Each uniform combination is almost identical with respect to the conditions of the simulation (Figure 4.25). Under average conditions, HSI values begin at 110 and decrease to just below 70 at the end of practice, crossing below the hazard of overheating threshold at 140 minutes into practice, and below the maximal heat stress threshold at 225 minutes into practice. Actual conditions show the HSI spiking up to 162 at 125 minutes into practice, then gradually coming back down almost 120 by the end of practice, remaining above the hazard of overheating threshold throughout practice.

4.3.1.5 Eric Brown

Eric Brown fell ill from hyperthermia while participating in practice for D.W. Carter High School in Dallas, TX on August 2, 2004 (NCCSIR 2010). A comparison between the actual conditions Brown was experiencing, and the averages of the same day can be seen in Table 4.15. News reports cited that Brown collapsed at home after the morning practice session and that he had no physical on file with the school (NCCSIR 2010).

Table 4.15. Actual versus average conditions for Eric Brown (Dallas, TX), 2 August

	Temperature (°C)	Relative Humidity (%)	Wind Speed (kts)	Pressure (hPa)	Cloud Cover (%)
Actual Conditions					
8:00 AM	29	79	1.23	992	0
9:00 AM	31	70	1.23	993	0
10:00 AM	32	67	1.23	993	0
11:00 AM	33	59	1.23	993	40
12:00 PM	33	53	0.88	992	30
Climatological Conditions					
8:00 AM	28.74	64.3	2.07	993.99	34.7
9:00 AM	29.38	61.7	2.16	993.99	31.4
10:00 AM	29.77	60.7	2.06	993.89	30.5
11:00 AM	30.28	58.9	1.86	993.82	25.9
12:00 PM	30.88	56.3	1.68	993.65	29.5

Humidex values under average conditions remain above extreme caution, but below danger thresholds during practice (Figure 4.26). They increase gradually from 37 at the start of practice to just over 39 by the end. For actual conditions, the Humidex stays above the danger threshold throughout practice, peaking at 44 approximately 125 minutes into practice.

WBGT remain above the practice cancellation threshold for both average and actual conditions (Figure 4.27). Under average conditions, WBGT values steadily increase from around

30°C to just over 31°C over the course of practice. For actual conditions, the WBGT starts and ends at approximately 33°C, with a peak of 34.5°C at 125 minutes into practice.

UTCI values stay between the thresholds for strong heat stress and very strong heat stress during practice (Figure 4.28). UTCI values under average conditions are less than those for actual conditions, but increase gradually throughout practice, from 32.9°C to 36.5°C. UTCI values for the actual conditions show less variation, ranging from 35.7°C at the beginning of practice to peaking at 36.7°C right at the end of the session.

SW values are clustered together between 550g/hr and 700 g/hr, with all simulations above the hazardous threshold for a non-acclimatized person and below the hazardous threshold for an acclimatized person (Figure 4.29). The practice uniform simulations are higher than those for the full uniform, irrespective of the conditions present. The highest SW values overall are from the practice uniform under average conditions, with SW values ranging from approximately 650g/hr to just over 700g/hr at the end of practice. The lowest SW values overall are from the full uniform under actual conditions, with SW values ranging from 577g/hr to 66g/hr at the end of practice.

Values for Minutes to Hyperthermia gradually decrease for both simulations under average conditions (Figure 4.30). Under actual conditions, the environment improves over time through practice as the minutes to hyperthermia increase gradually and then taper off towards the end of practice for both uniform combinations. The most extreme simulation is the practice uniform under average conditions, decreasing from 33 minutes to 29.7 minutes at the end of practice.

For the HSI, all four model simulations remain above the threshold for hazard of overheating. HSI values are nearly independent of uniform type, depending almost entirely on the conditions present. The HSI under average conditions increases from just below 130 to 150 over the course of practice. Under actual conditions, HSI values remain nearly constant around 225 until 125 minutes into practice, where they decrease to 210 at 185 minutes into practice, and climb back up to approximately 230 at the conclusion of practice.

4.3.2 Collective Player Results

A heat load greater than 1.751 indicates an extreme hot stress on the player's ability for thermoregulation. Figure 4.32 shows the collective heat load for each player over the course of the practice they were participating in. All players began their practice session at a heat load significantly higher than what is considered an extreme hot load in humans. In all players, this heat load continued to increase throughout the duration of practice.

For metabolic heat production greater than 70 W/m^2, which all five players exceed, the accepted limits of SW are listed in Table 4.16. All five players exceed the hazardous limit for a non-acclimated player, while Barrett and Terrell exceed the hazardous limit for an acclimated player (Figure 4.33). This indicates serious dehydration, decreasing the body's ability for thermoregulation.

Table 4.16 Limits of acceptable water loss (g/hr), based on level of acclimatization

	Acclimated Player
Warning SW limit	520
Hazardous SW limit	780
	Non-Acclimated Player
Warning SW limit	260
Hazardous SW limit	390

Players started practice ranging from 29 minutes to 74 minutes until hyperthermia (Figure 4.34). Given that practices lasted between 2.5 and 4 hours, all players became endangered when they walked onto the field, expecting to complete the practice. Stringer's Oh_H steadily declined throughout practice, indicating an increase in severity of the ambient conditions outside. Brown's Oh_H increased slightly over time, from 29 minutes to 35 minutes, showing some improvement in conditions, but still maintaining a dangerous imbalance. Barrett and Terrell had nearly identical trends, decreasing minutes to hyperthermia over the first hour of practice, then slowly improving throughout the practice duration. Austin maintained a level of between 75 and 85 minutes to hyperthermia through the first three hours of practice. During hour three however, Austin's Oh_H dropped drastically, bottoming out at less than 10 minutes, indicating a very sudden worsening of conditions.

For all players but one, Barrett, Heat Stress Index values remained above the threshold for hazard of overheating (Figure 4.35). The most extreme case is Brown, whose HSI values remain at or above 210 throughout practice. Barrett is the least extreme case, in which his HSI values cross the very intensive heat stress threshold at 50 minutes into practice and level off at around 80 for the duration of practice. Terrell exhibits the highest HSI value, peaking at 230 approximately 60 minutes into practice.

The time series for MHR through practice is shown in Figure 4.36. All players far exceed this threshold based on their activity specific metabolic rate (M), with the lowest value for M being that of Terrell at 432.52 W/m^2.

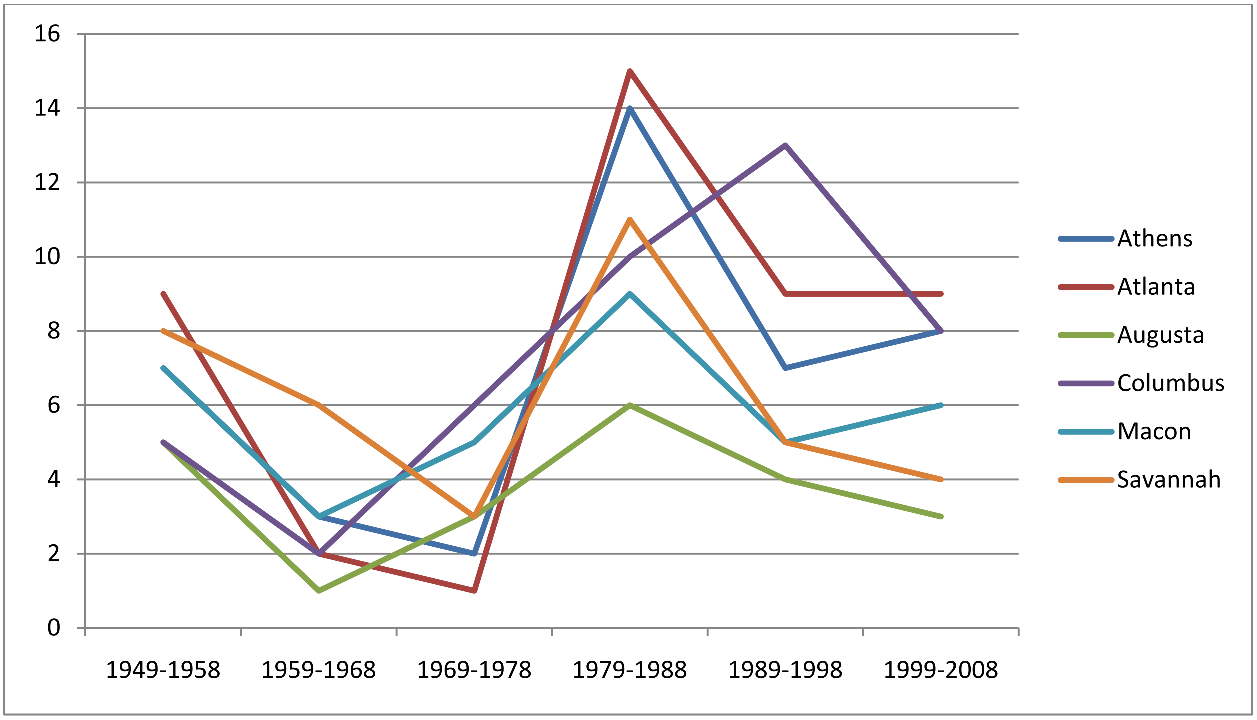

Figure 4.1. Number of heat wave events, per decade, by site in Georgia

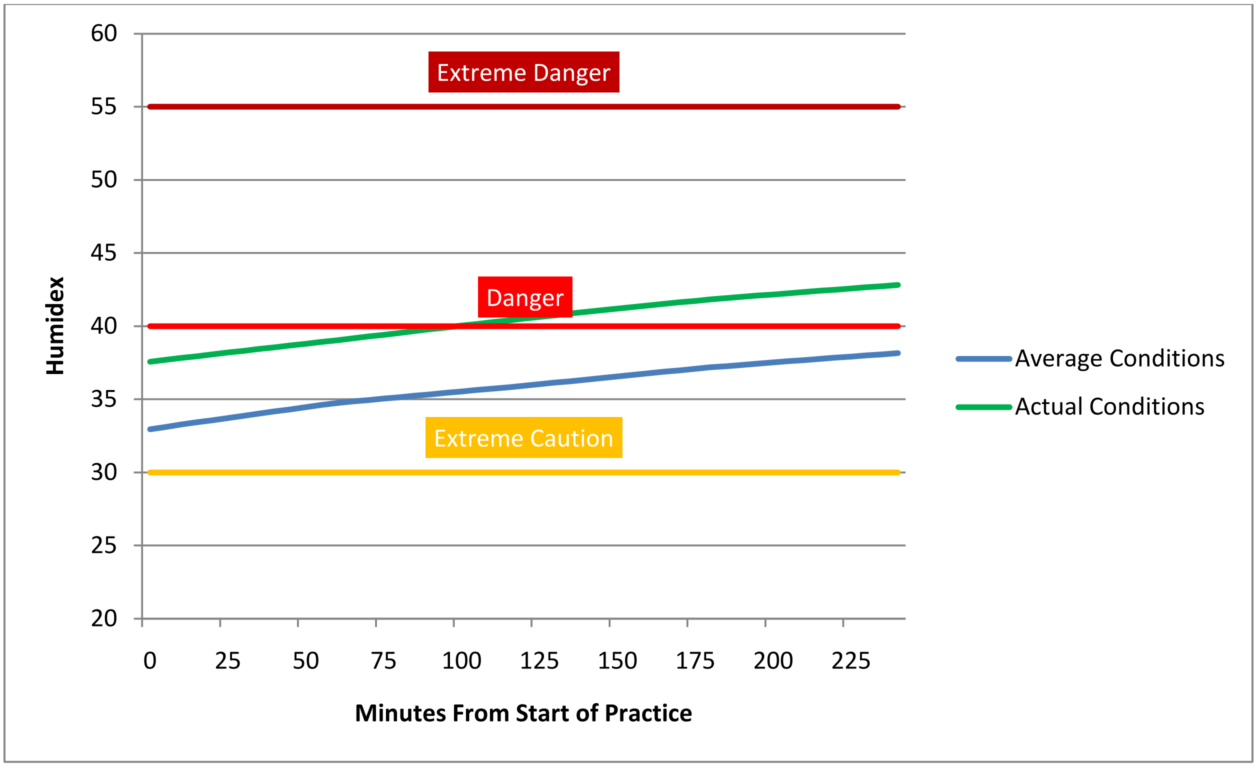

Figure 4.2. Humidex values, including safety thresholds, for Damon Terrell

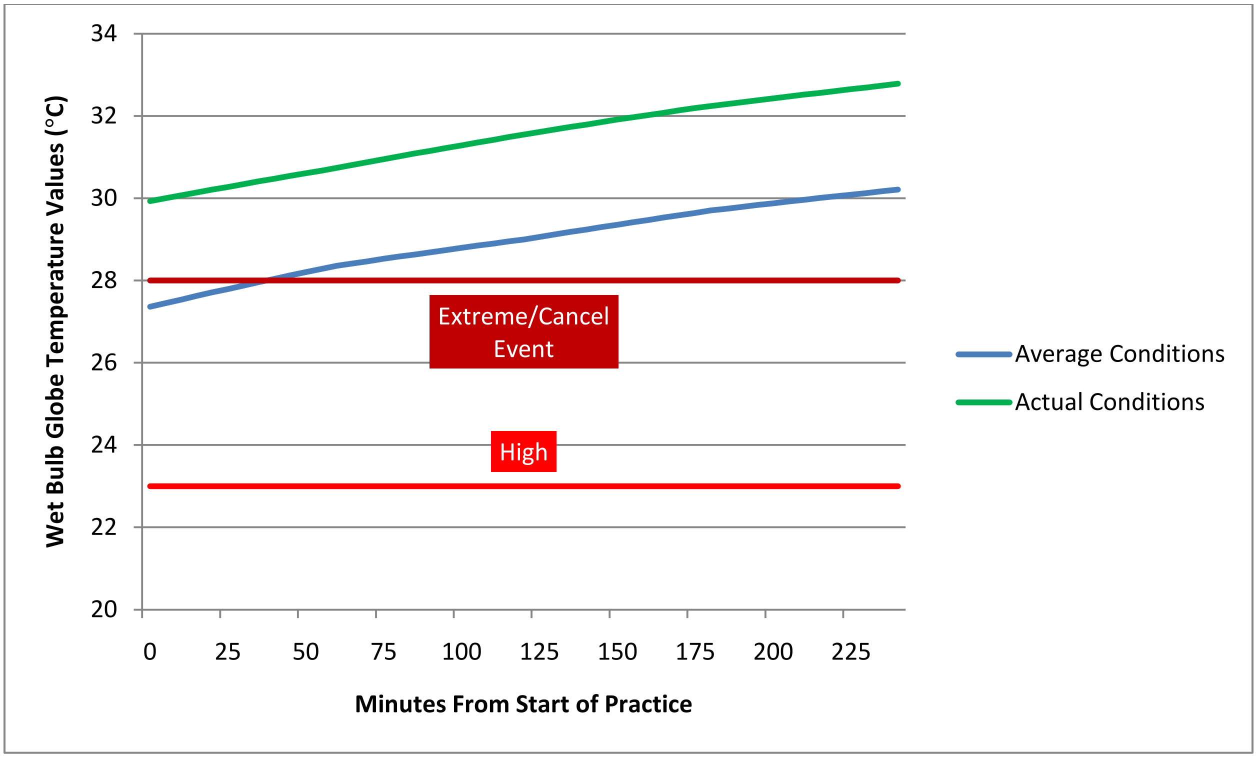

Figure 4.3. Wet Bulb Globe Temperature values, including safety thresholds, for Damon Terrell

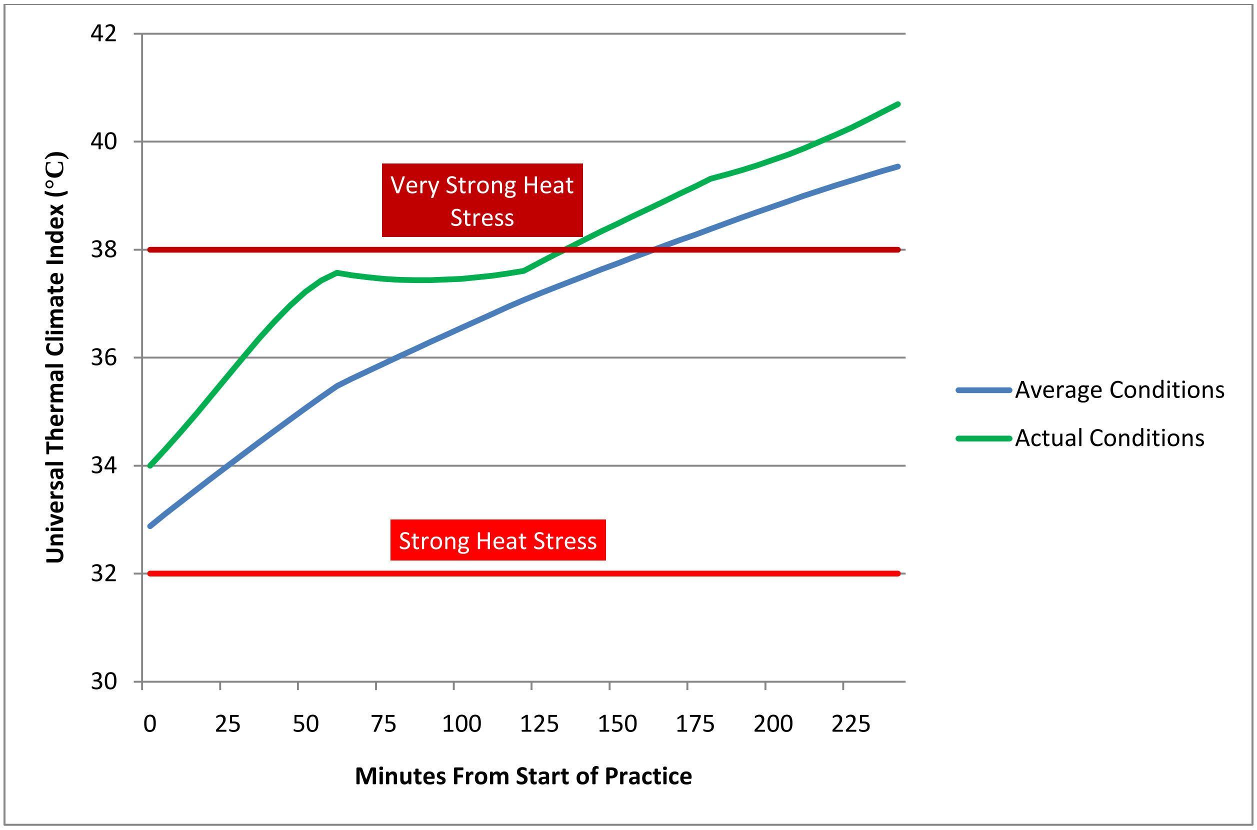

Figure 4.4 Universal Thermal Climate Index values, including safety thresholds, for Damon Terrell

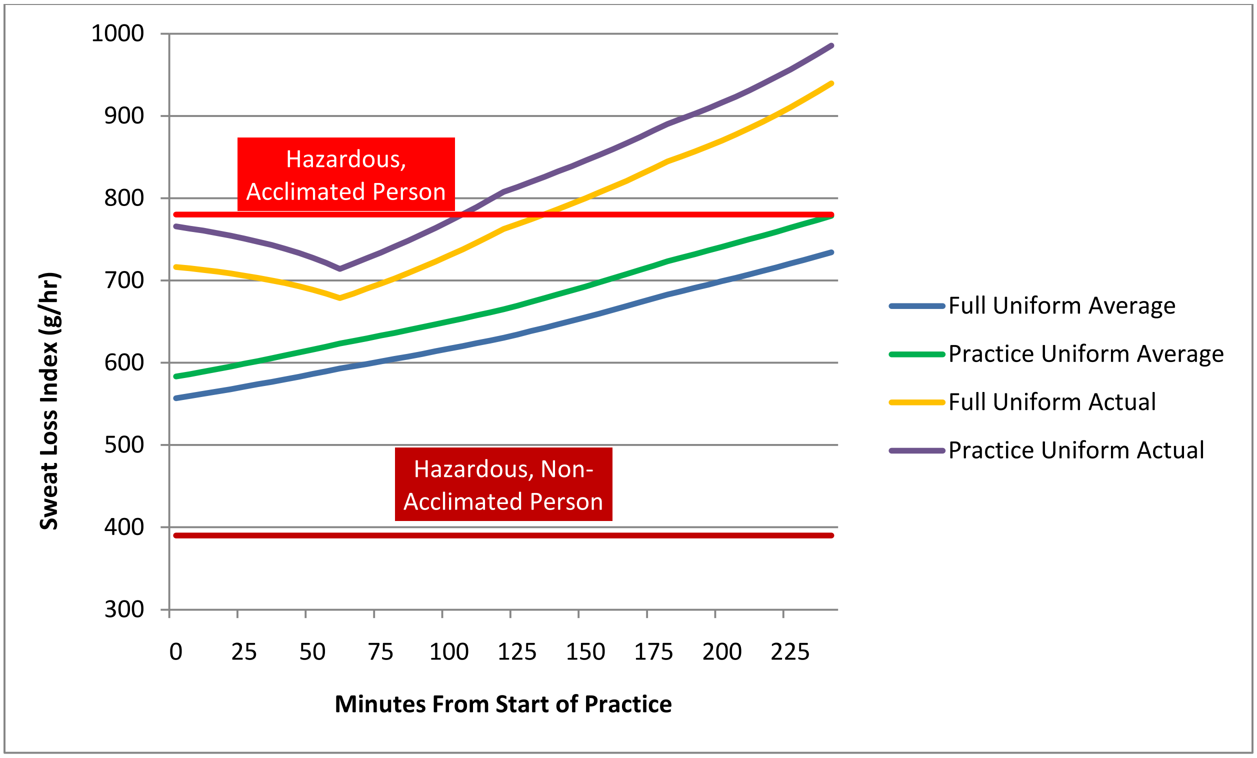

Figure 4.5. Sweat Loss Index, with safety thresholds, for Damon Terrell

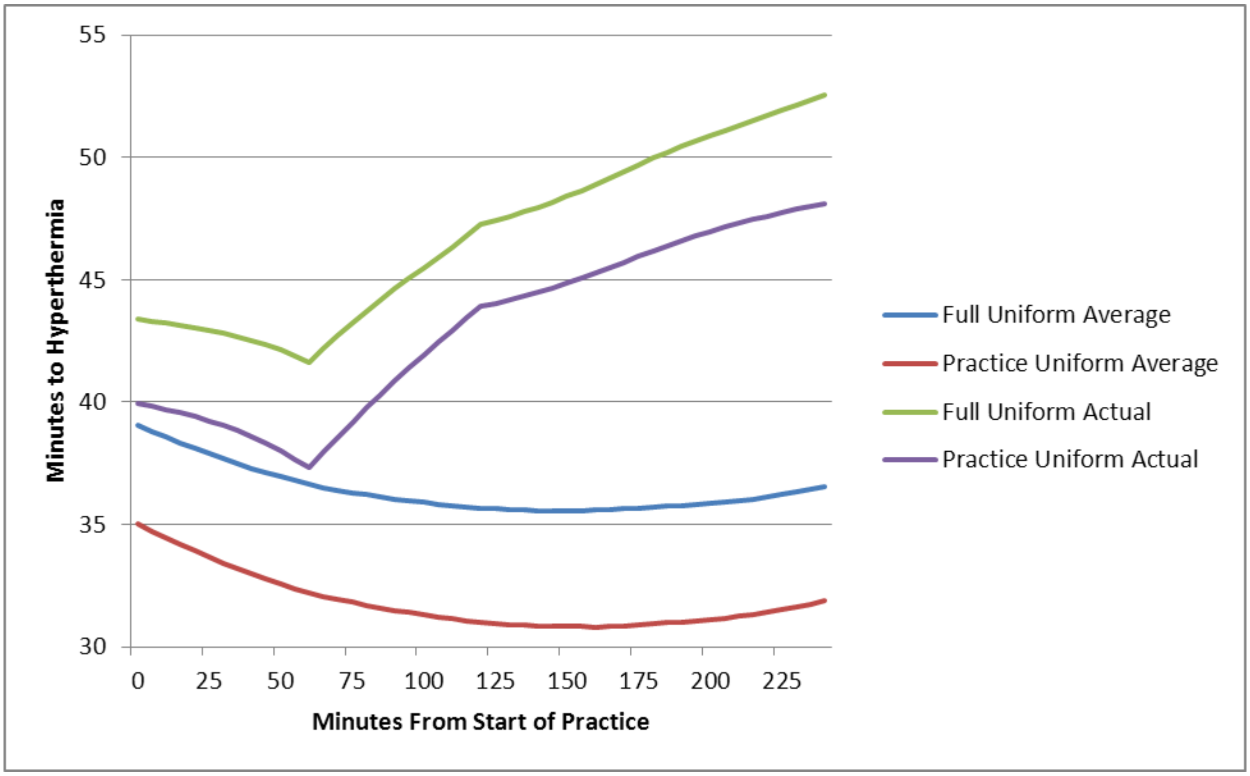

Figure 4.6 Hyperthermia Risk (in minutes), for the duration of practice, for Damon Terrell

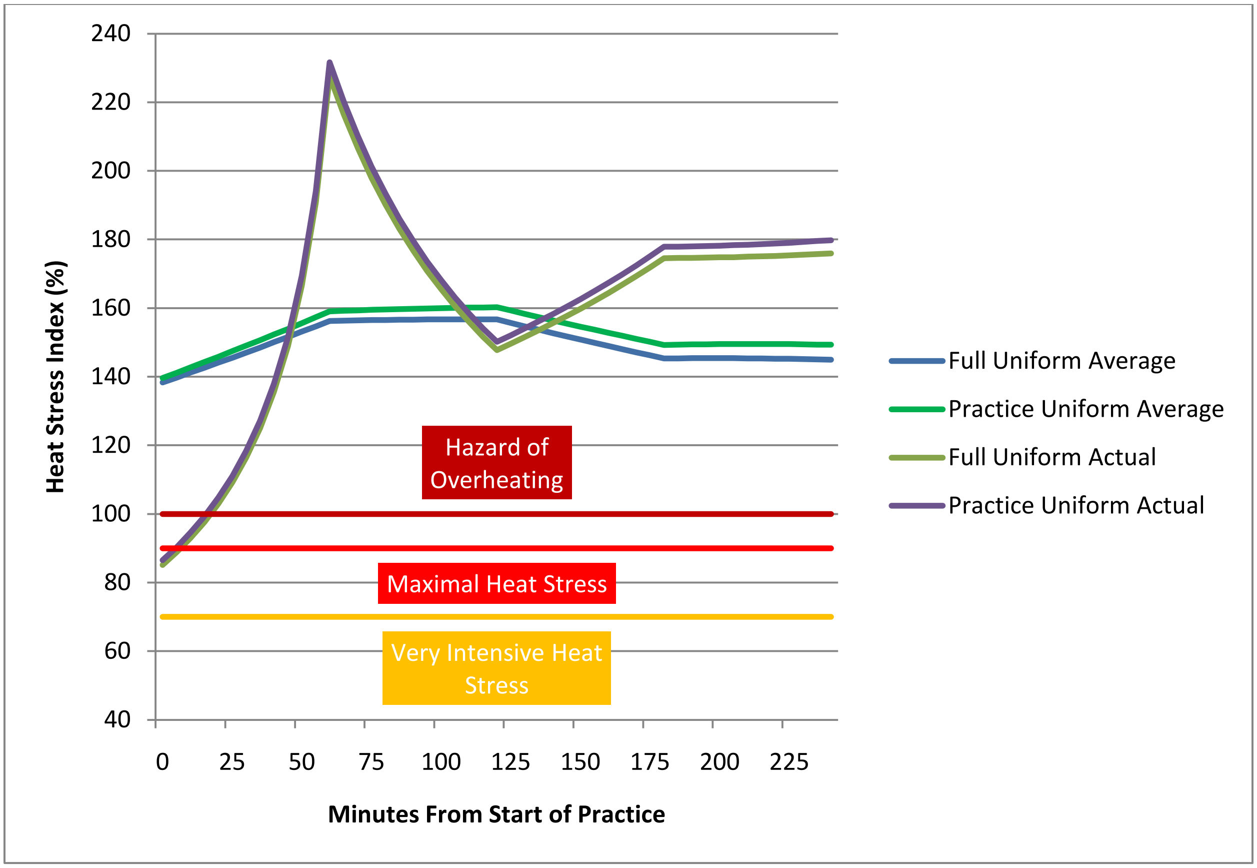

Figure 4.7. Heat Stress Index, with safety thresholds, for Damon Terrell

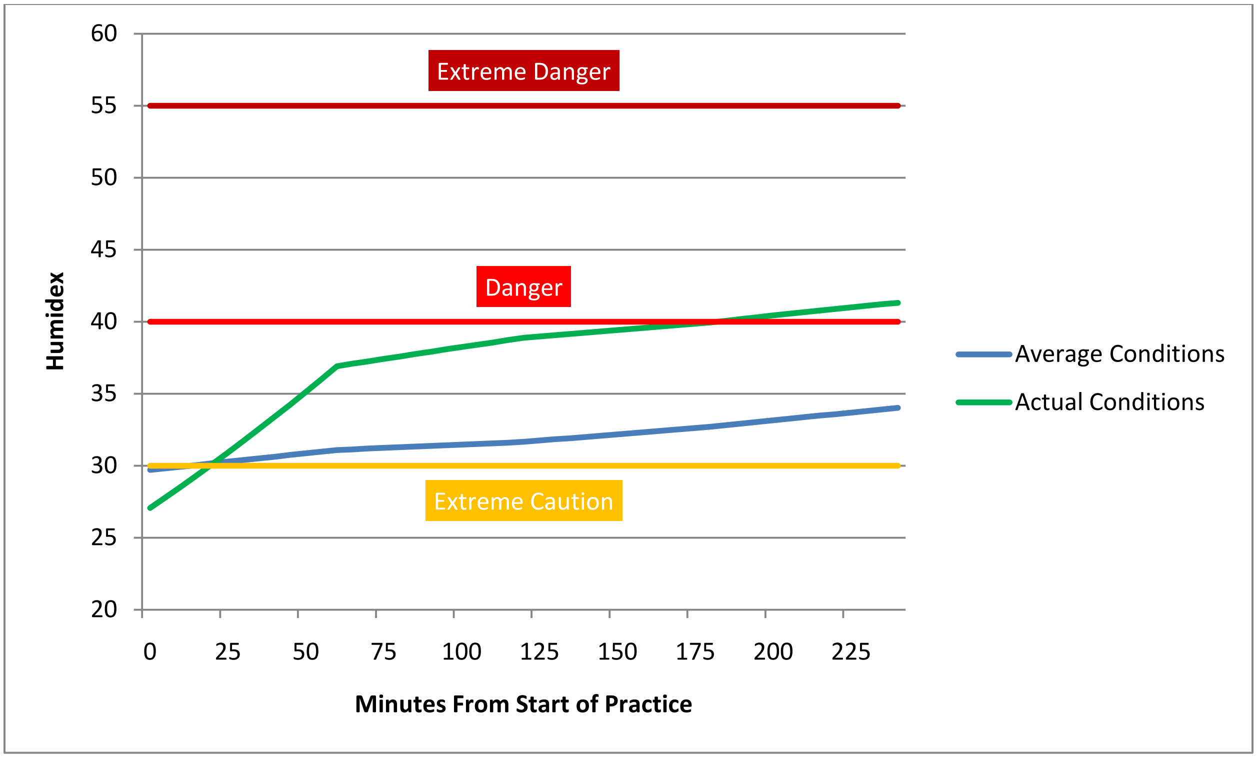

Figure 4.8. Humidex values, including safety thresholds, for Robert Barrett

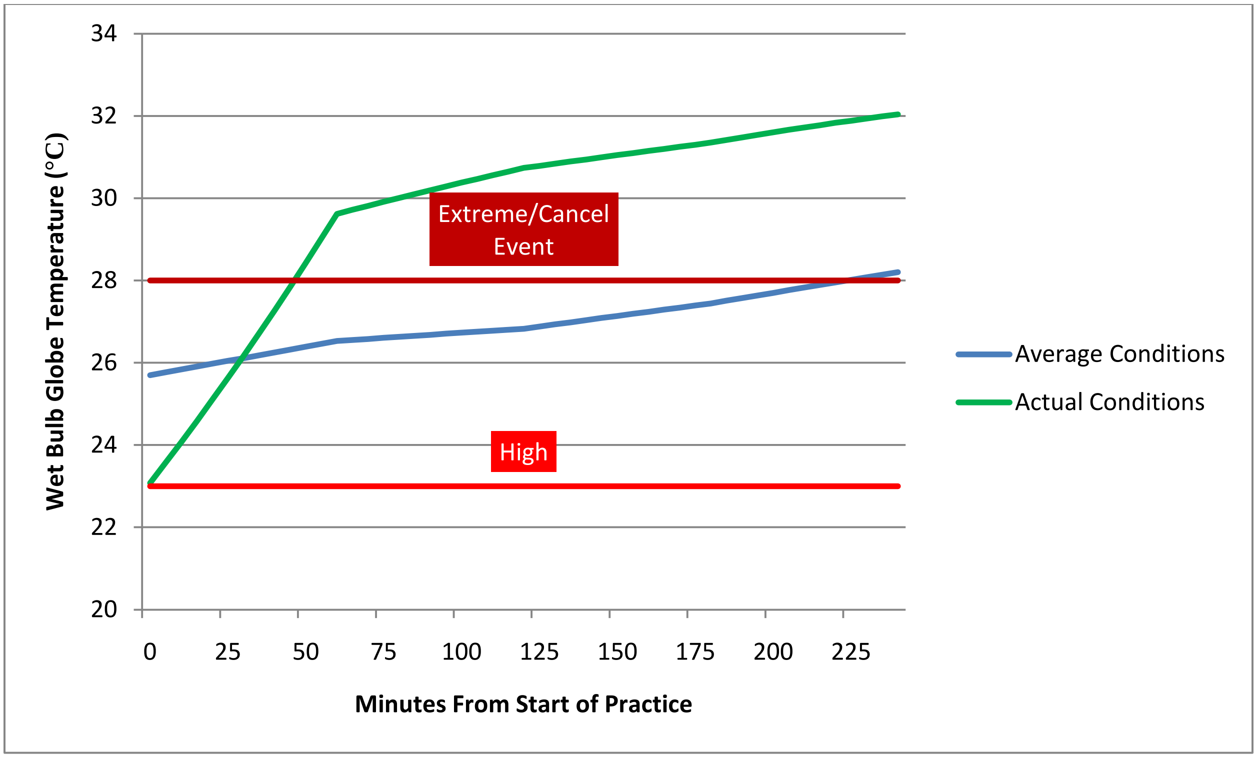

Figure 4.9. Wet Bulb Globe Temperature values, including safety thresholds, for Robert Barrett

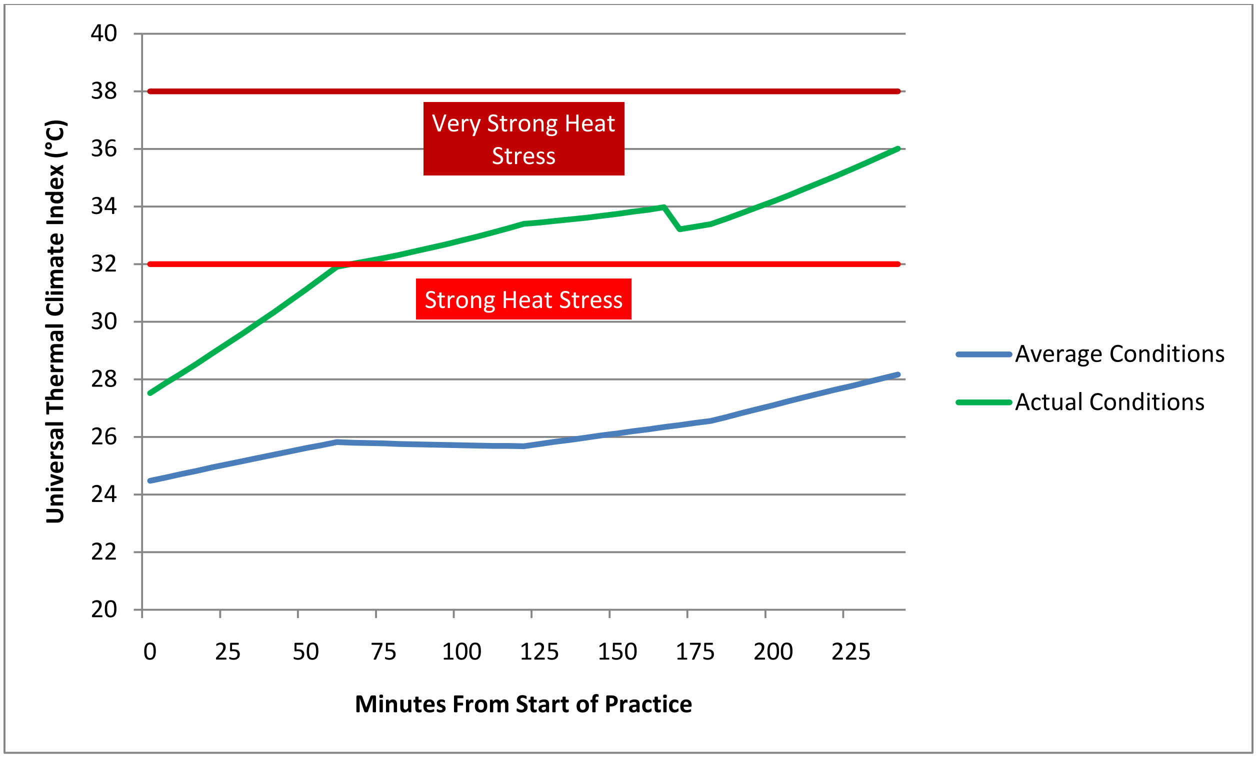

Figure 4.10. Universal Thermal Climate Index values, including safety thresholds, for Robert Barrett

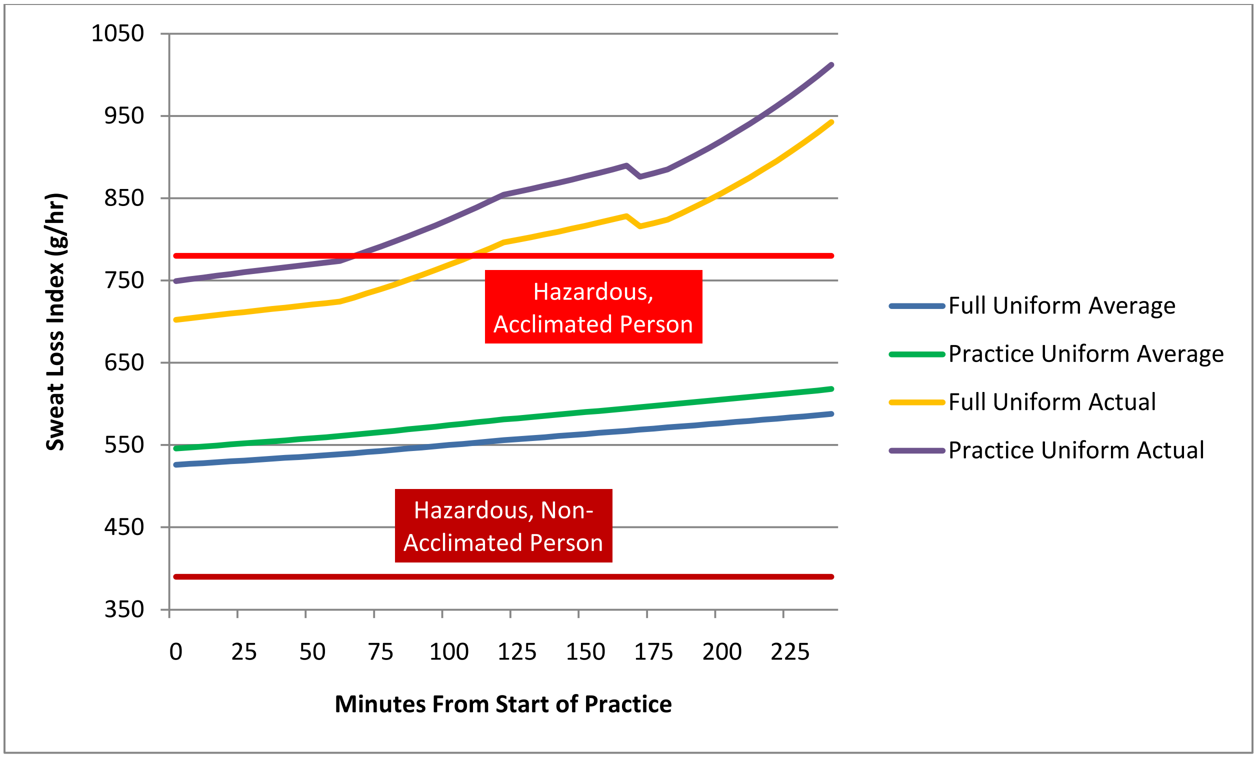

Figure 4.11. Sweat Loss Index, with safety thresholds, for Robert Barrett

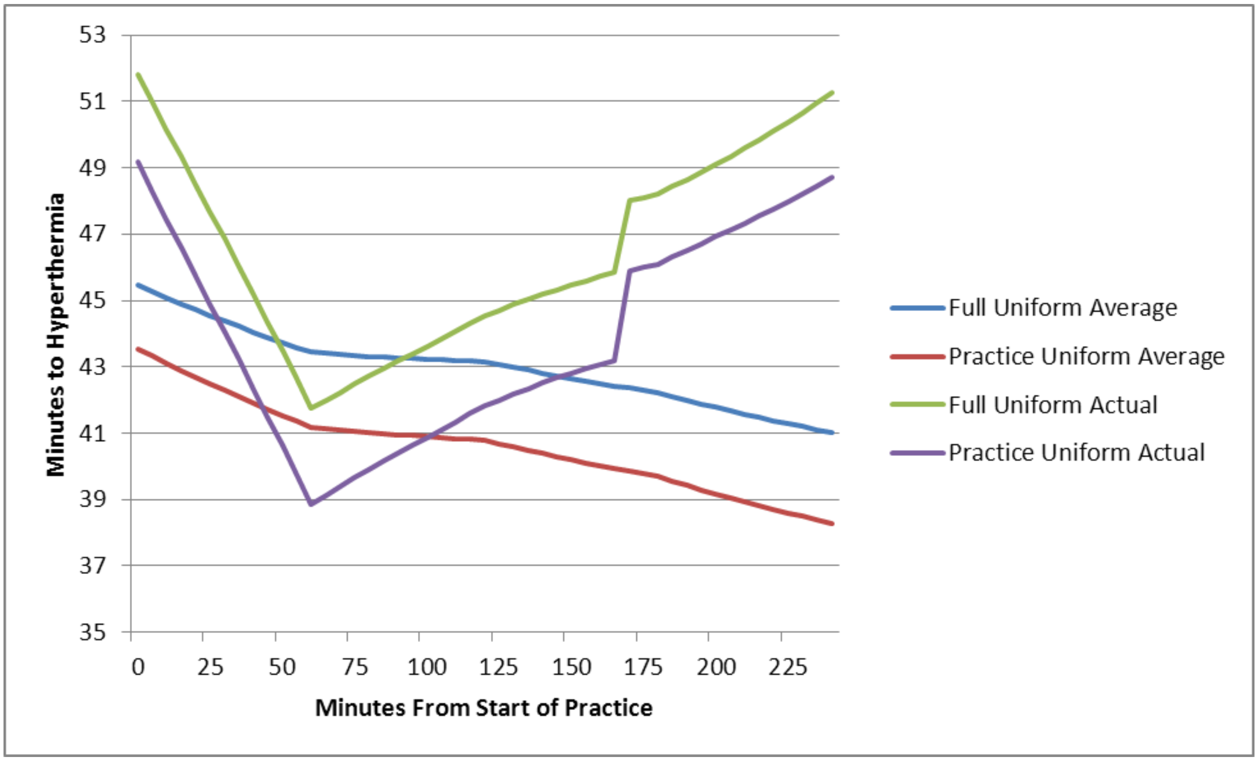

Figure 4.12. Hyperthermia Risk (in minutes), for the duration of practice, for Robert Barrett

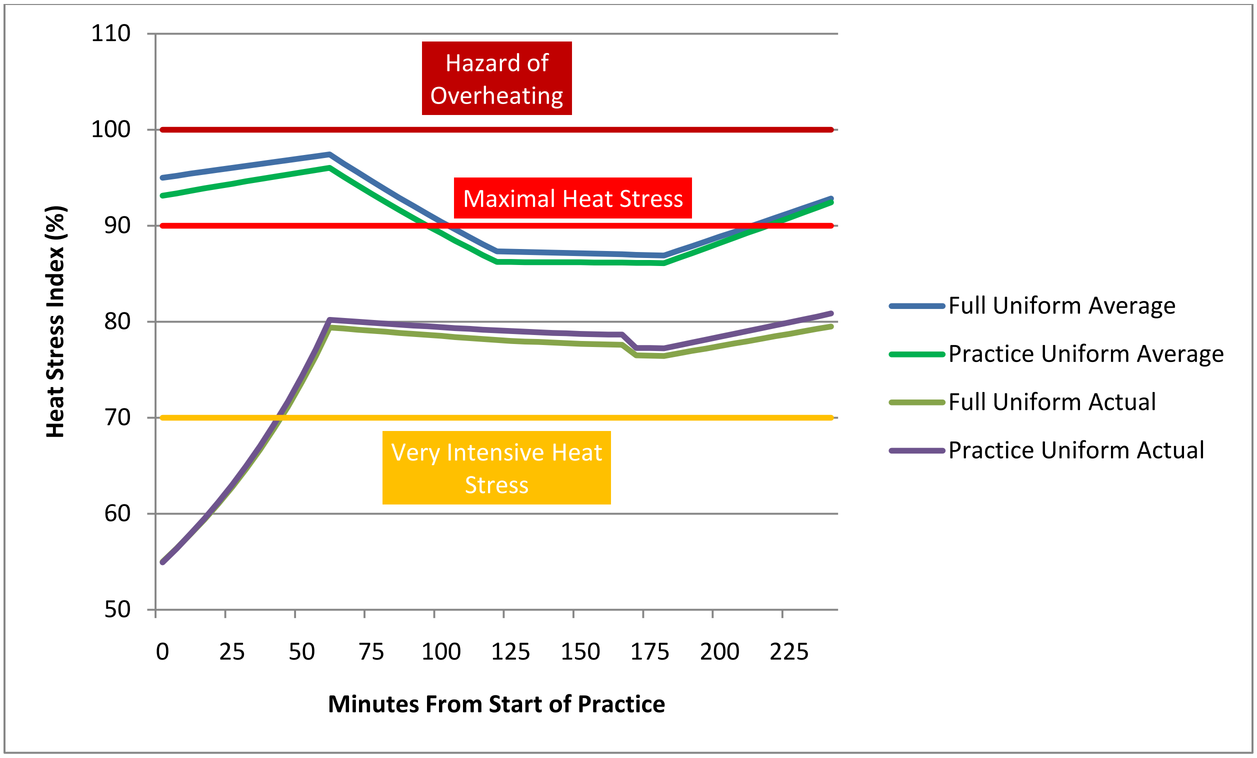

Figure 4.13. Heat Stress Index, with safety thresholds, for Robert Barrett

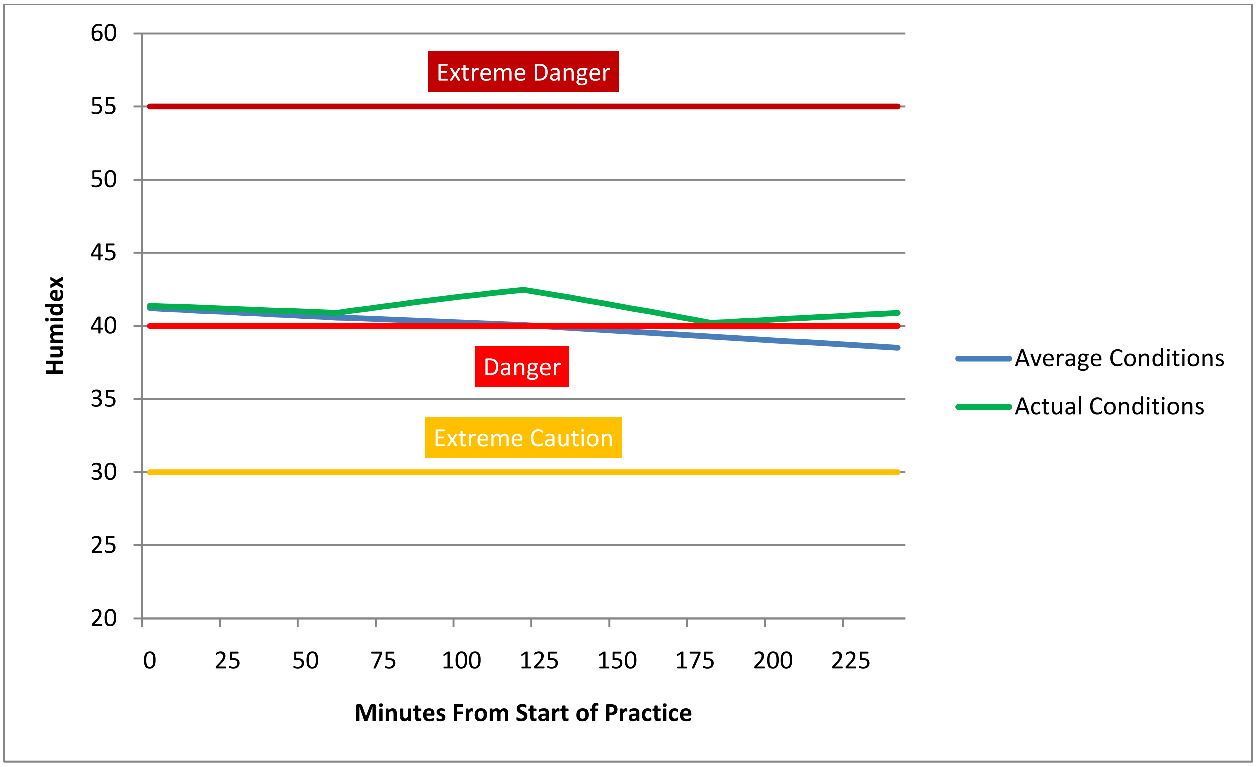

Figure 4.14. Humidex values, including safety thresholds, for Eraste Austin

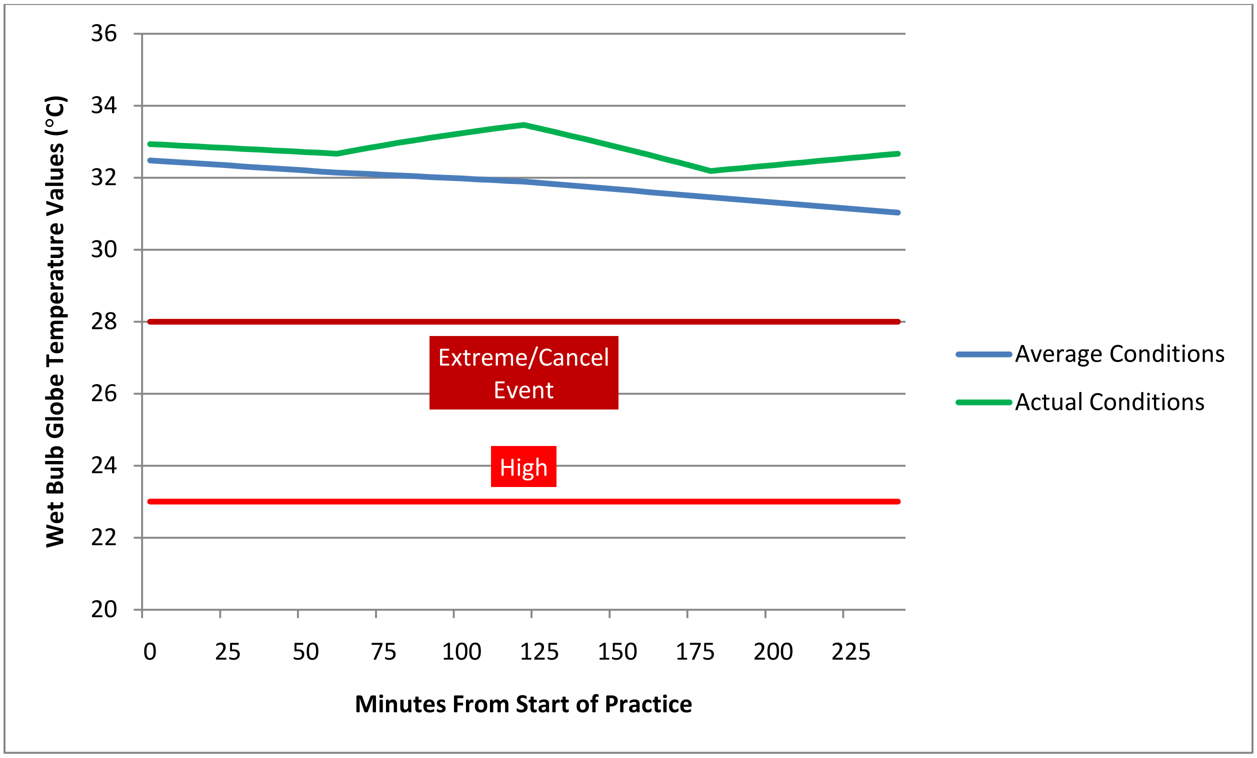

Figure 4.15. Wet Bulb Globe Temperature values, including safety thresholds, for Eraste Austin

Figure 4.16. Universal Thermal Climate Index values, including safety thresholds, for Eraste Austin

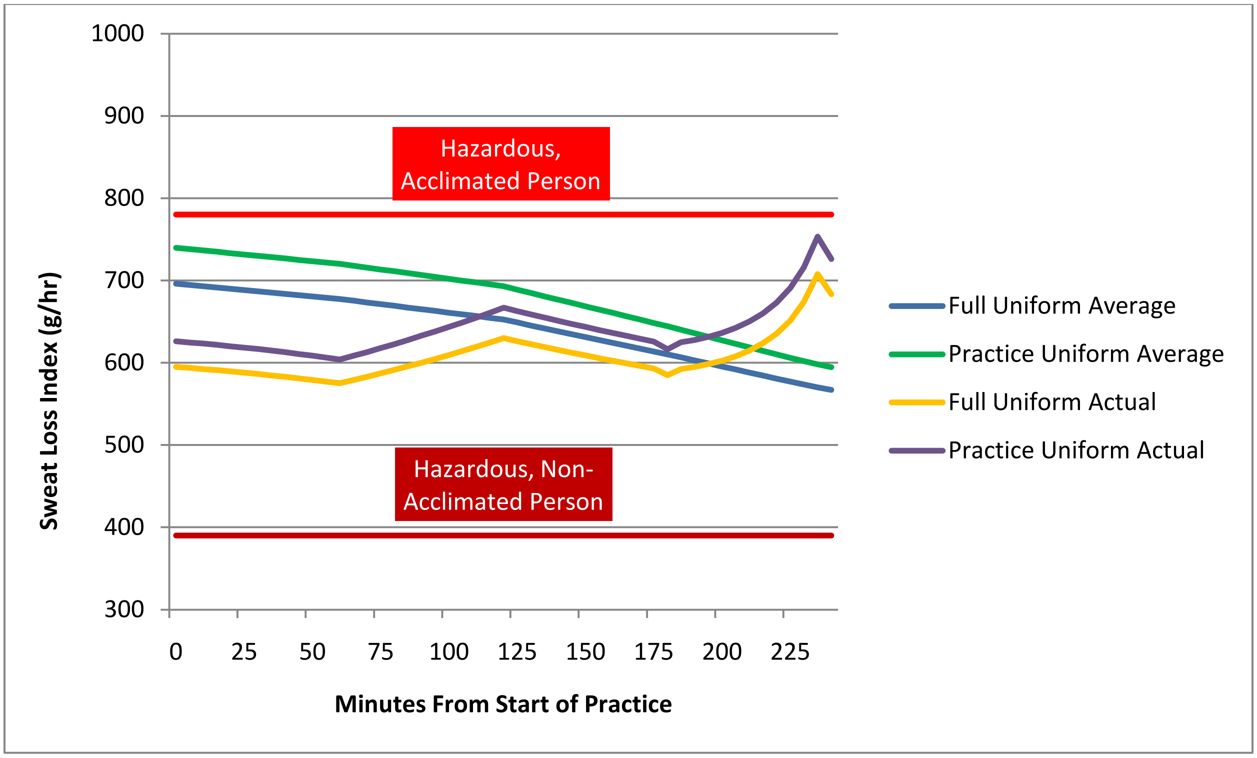

Figure 4.17. Sweat Loss Index, with safety thresholds, for Eraste Austin

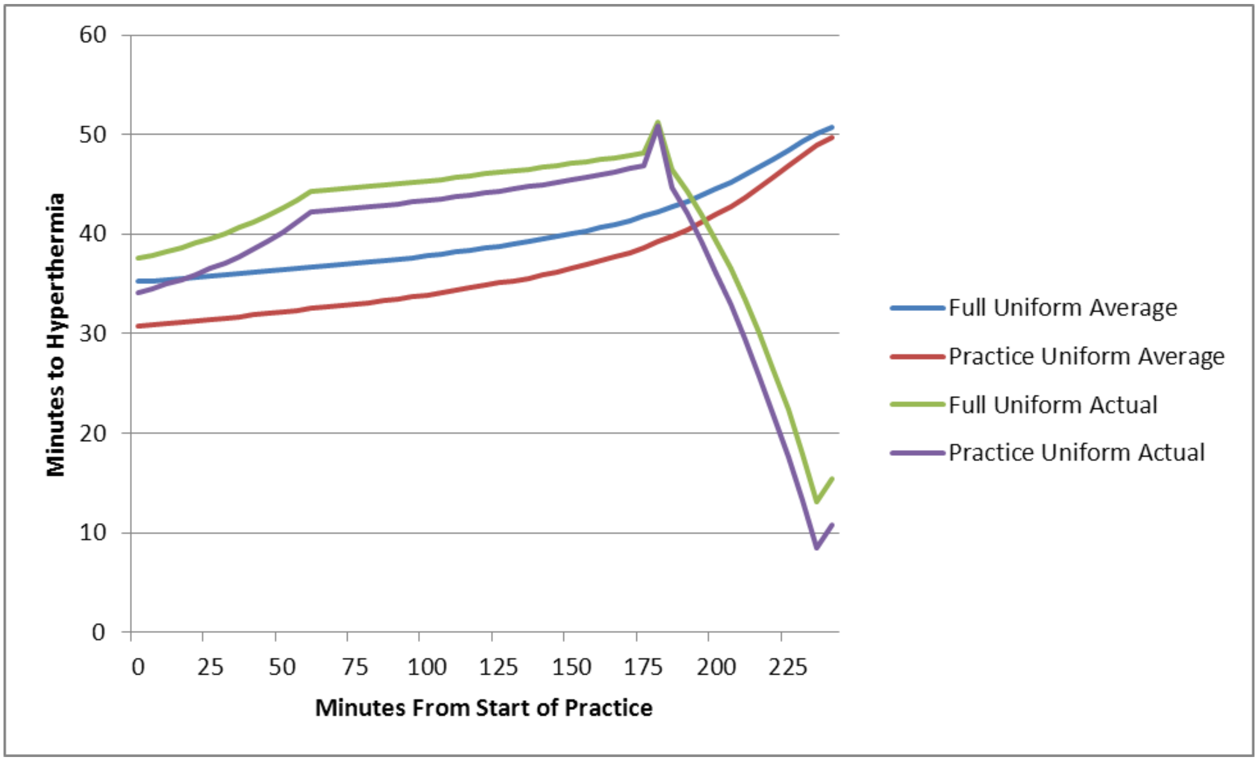

Figure 4.18. Hyperthermia Risk (in minutes), for the duration of practice, for Eraste Austin

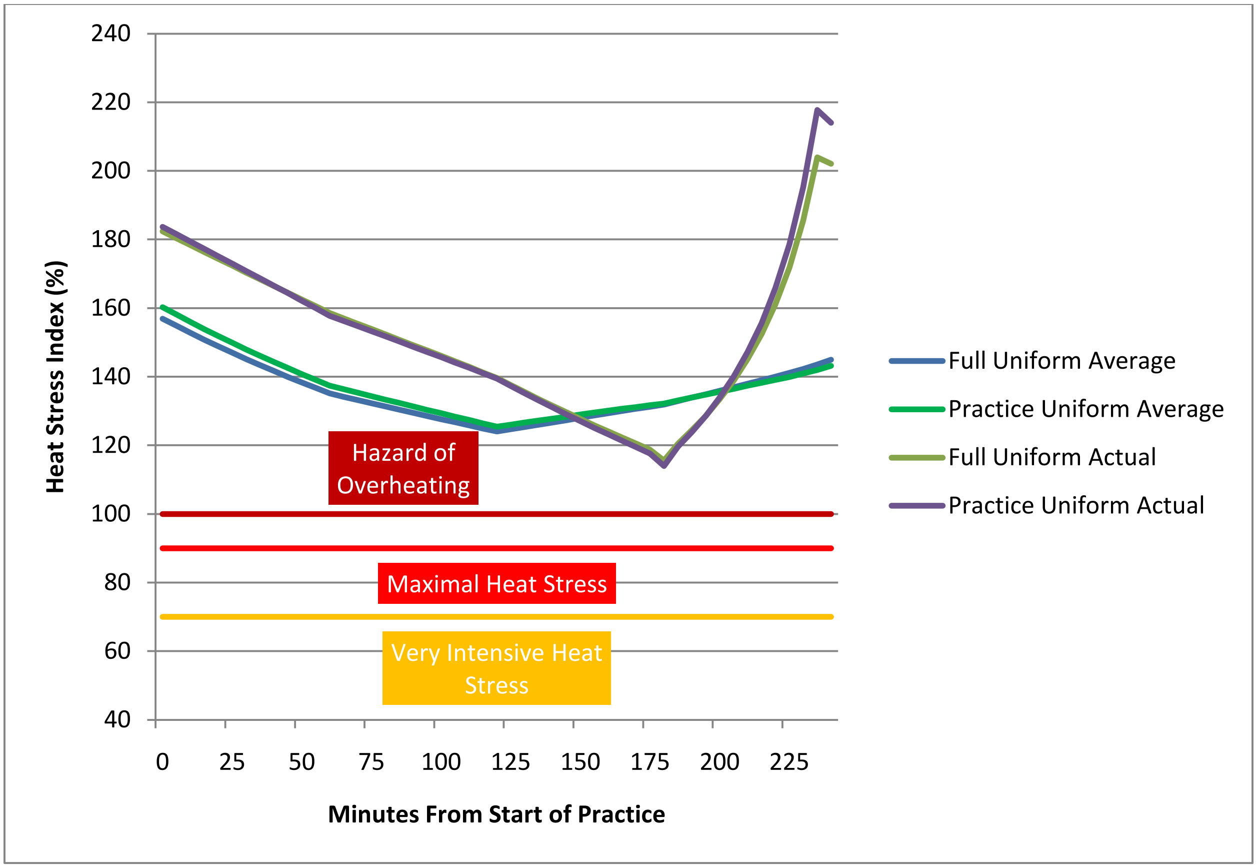

Figure 4.19. Heat Stress Index, with safety thresholds, for Eraste Austin

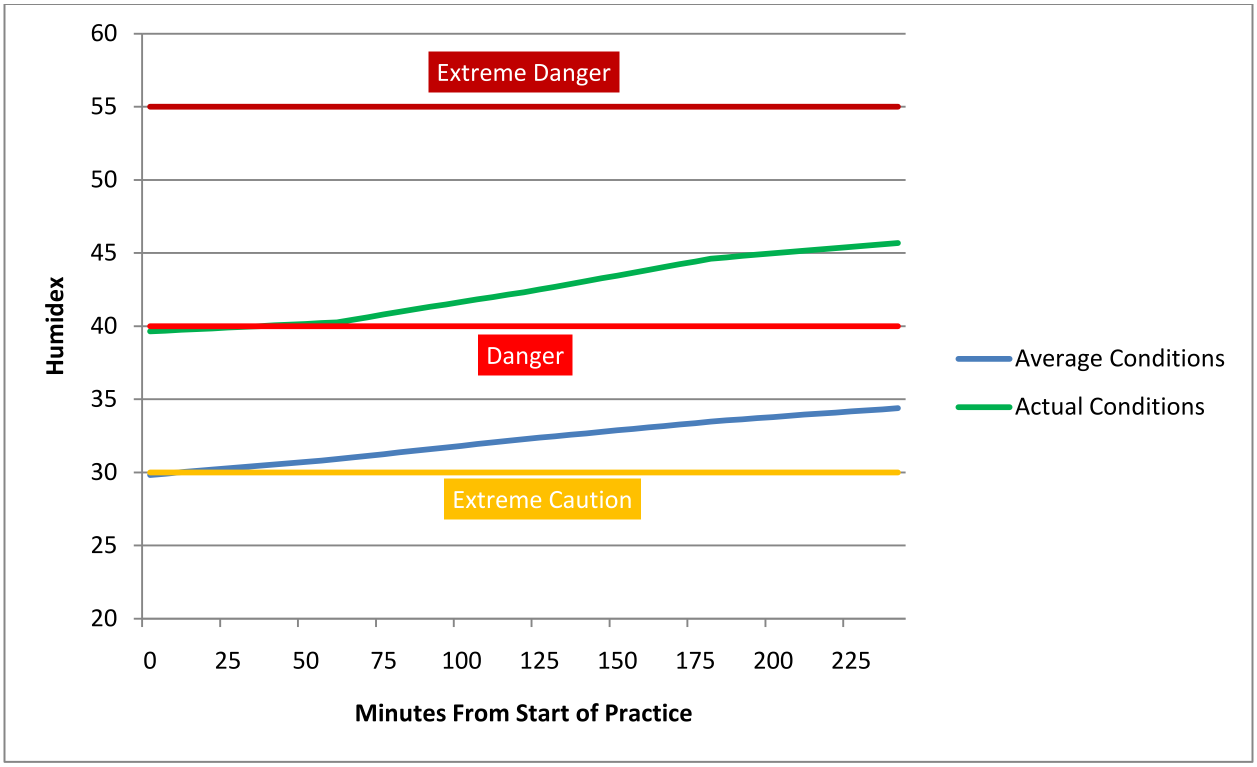

Figure 4.20. Humidex values, including safety thresholds, for Korey Stringer

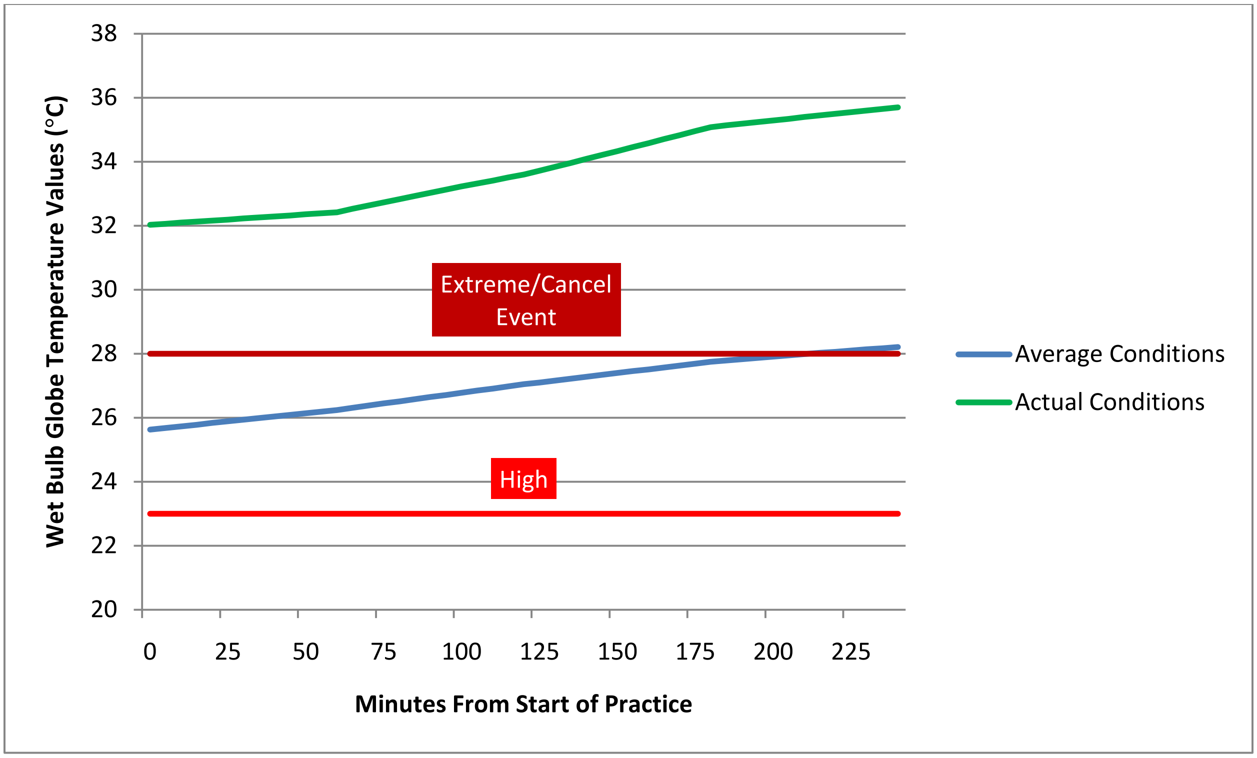

Figure 4.21. Wet Bulb Globe Temperature values, including safety thresholds, for Korey Stringer

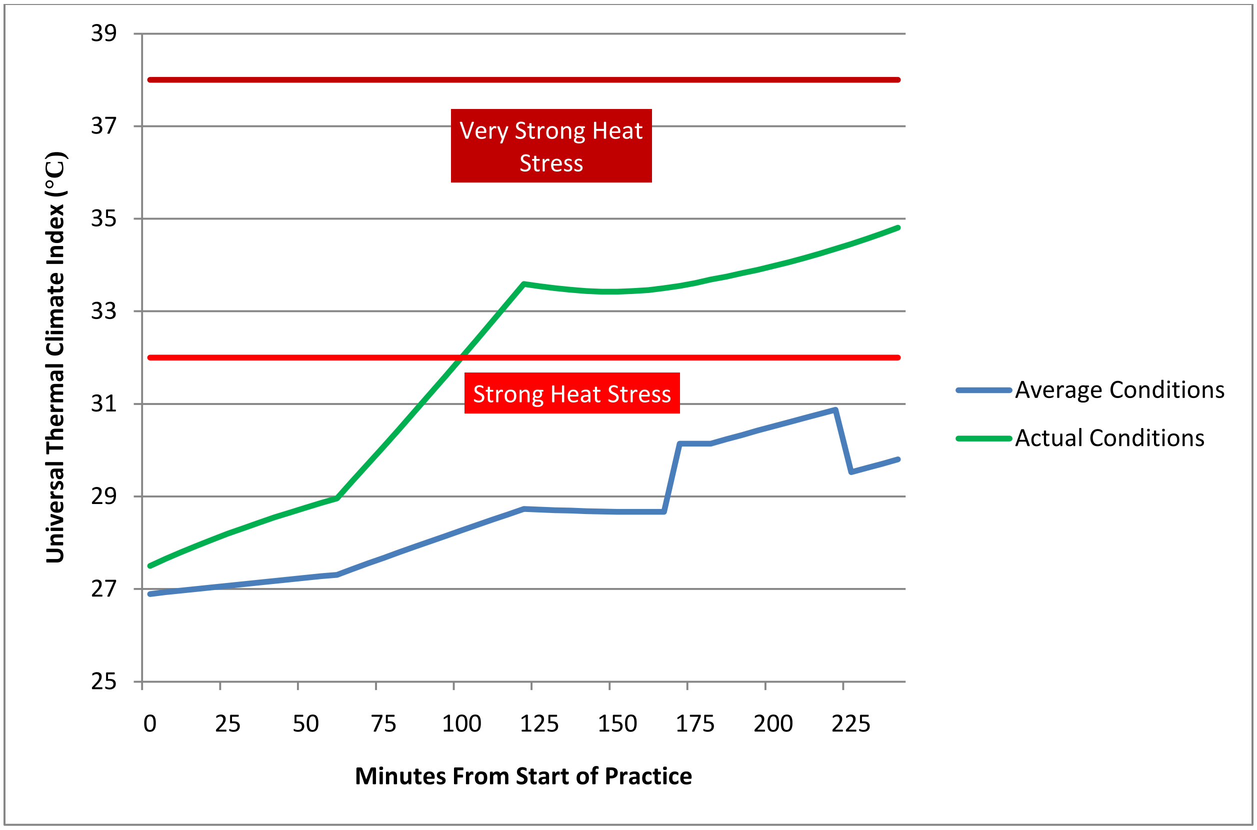

Figure 4.22. Universal Thermal Climate Index values, including safety thresholds, for Korey Stringer

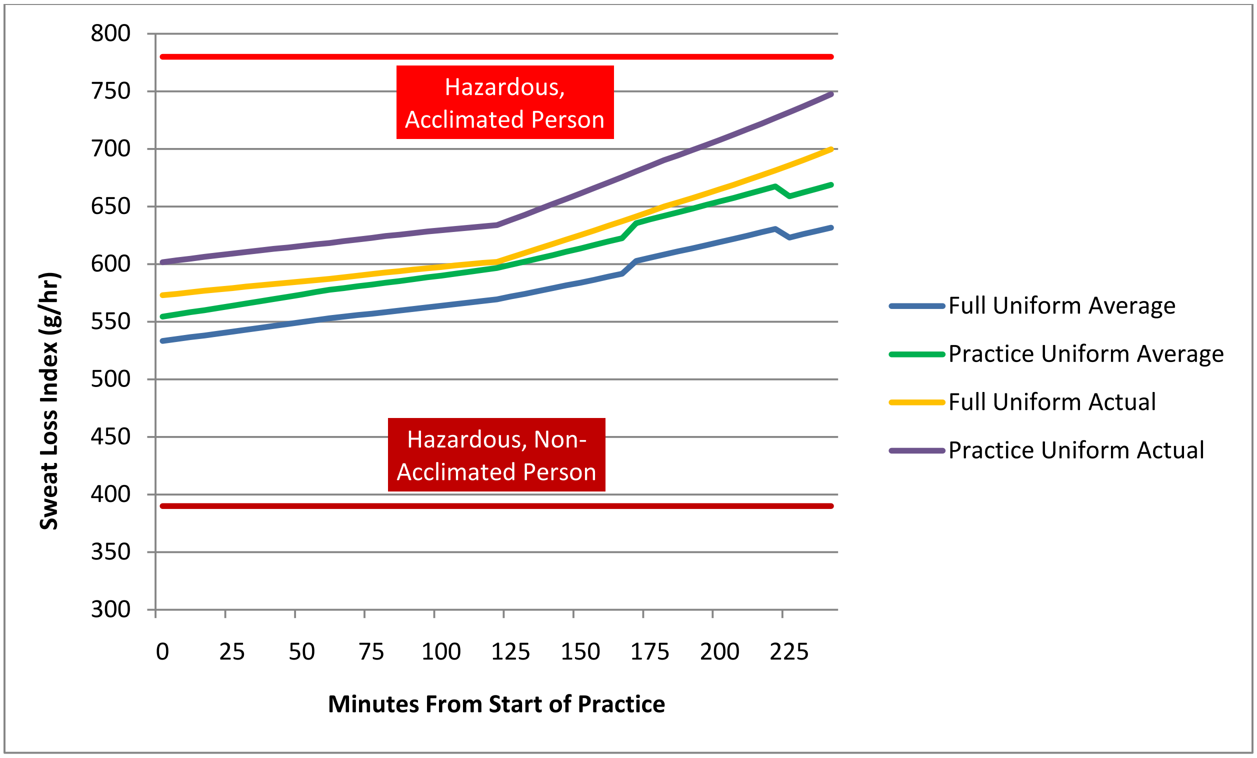

Figure 4.23. Sweat Loss Index, with safety thresholds, for Korey Stringer

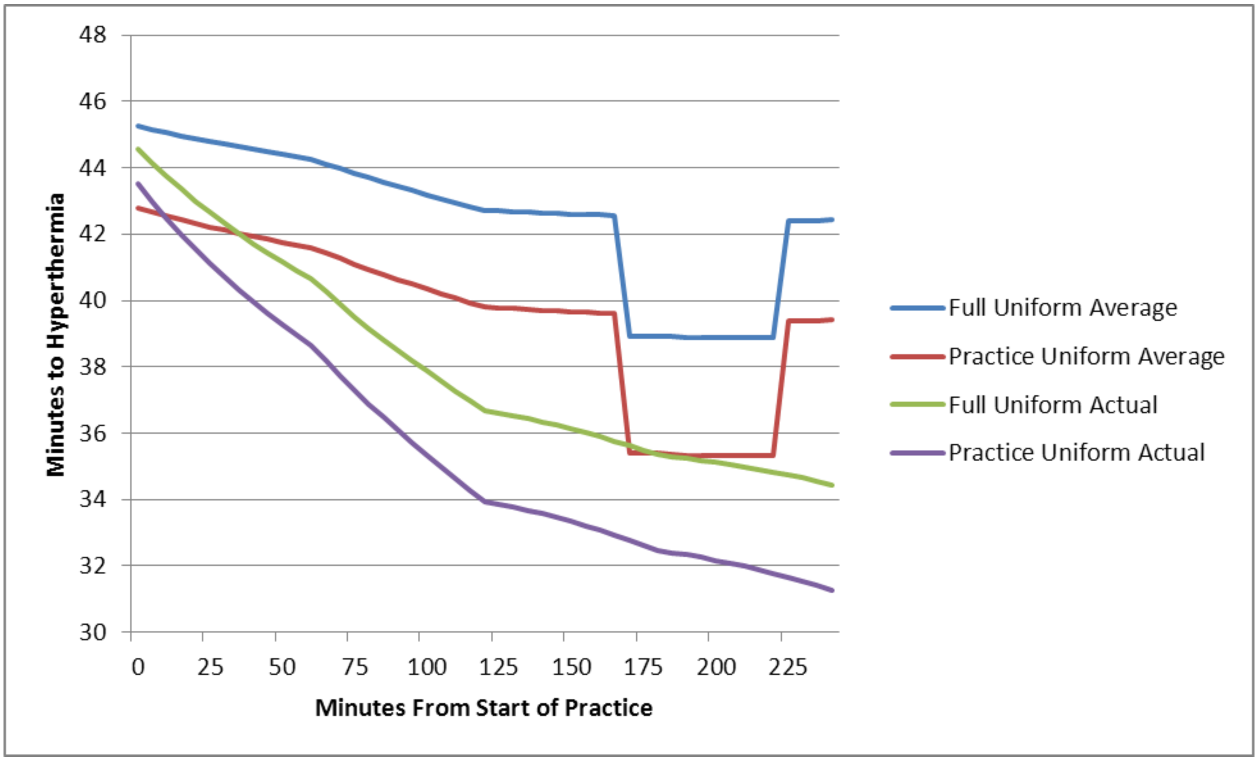

Figure 4.24. Hyperthermia Risk (in minutes), for the duration of practice, for Korey Stringer

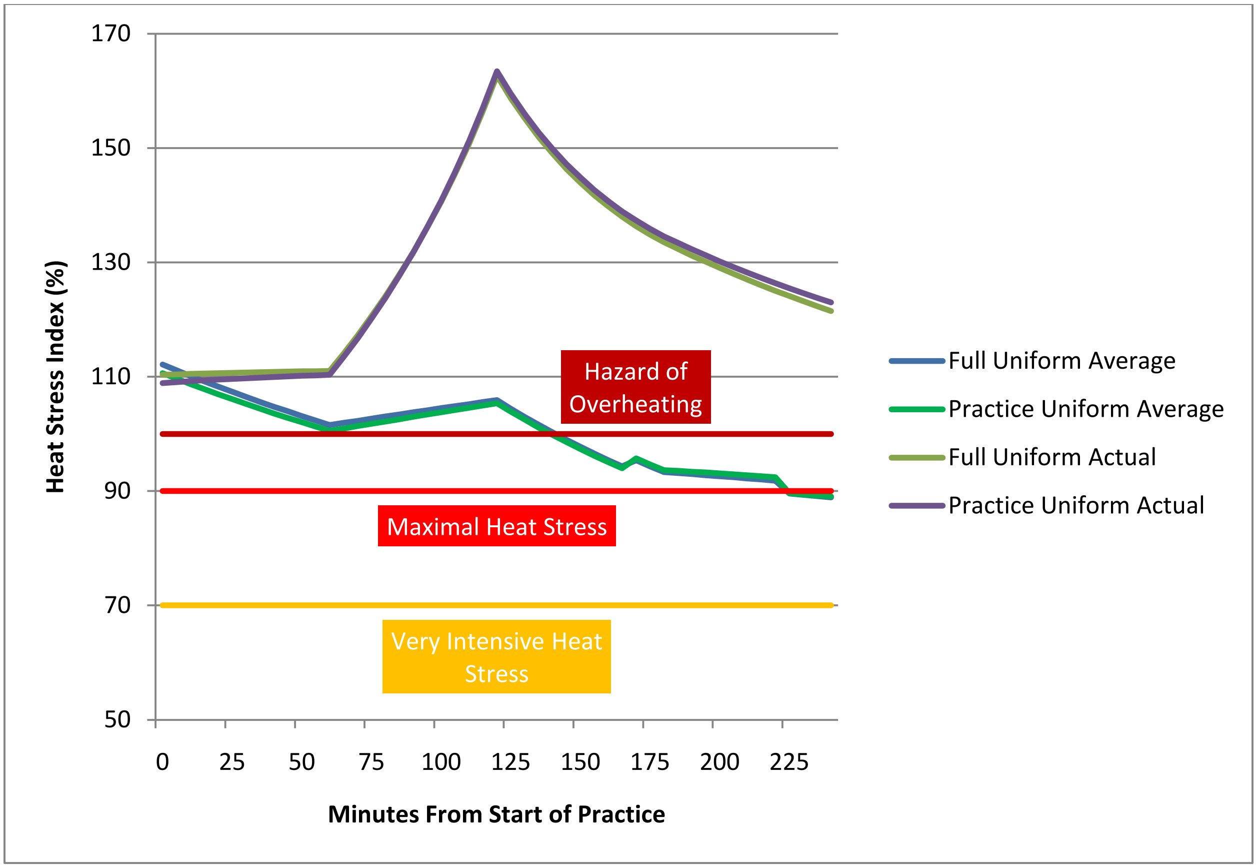

Figure 4.25. Heat Stress Index, with safety thresholds, for Korey Stringer

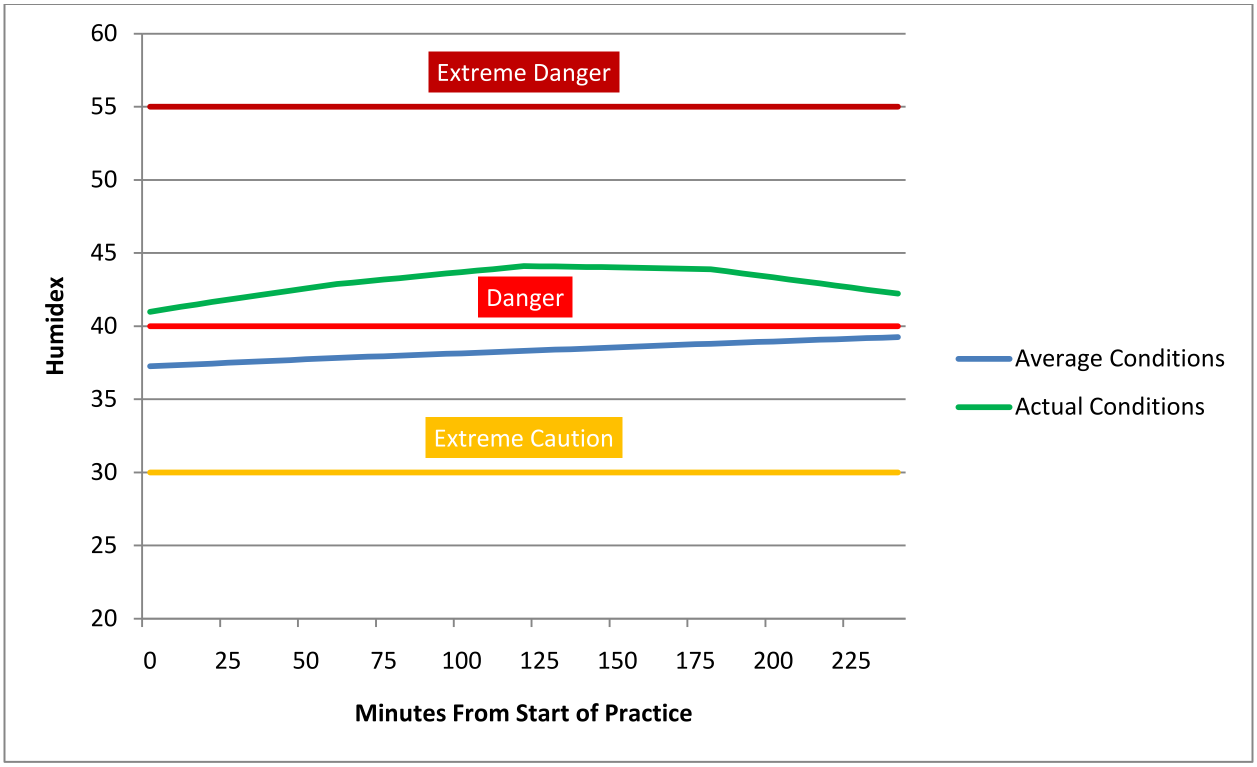

Figure 4.26. Humidex values, including safety thresholds, for Eric Brown

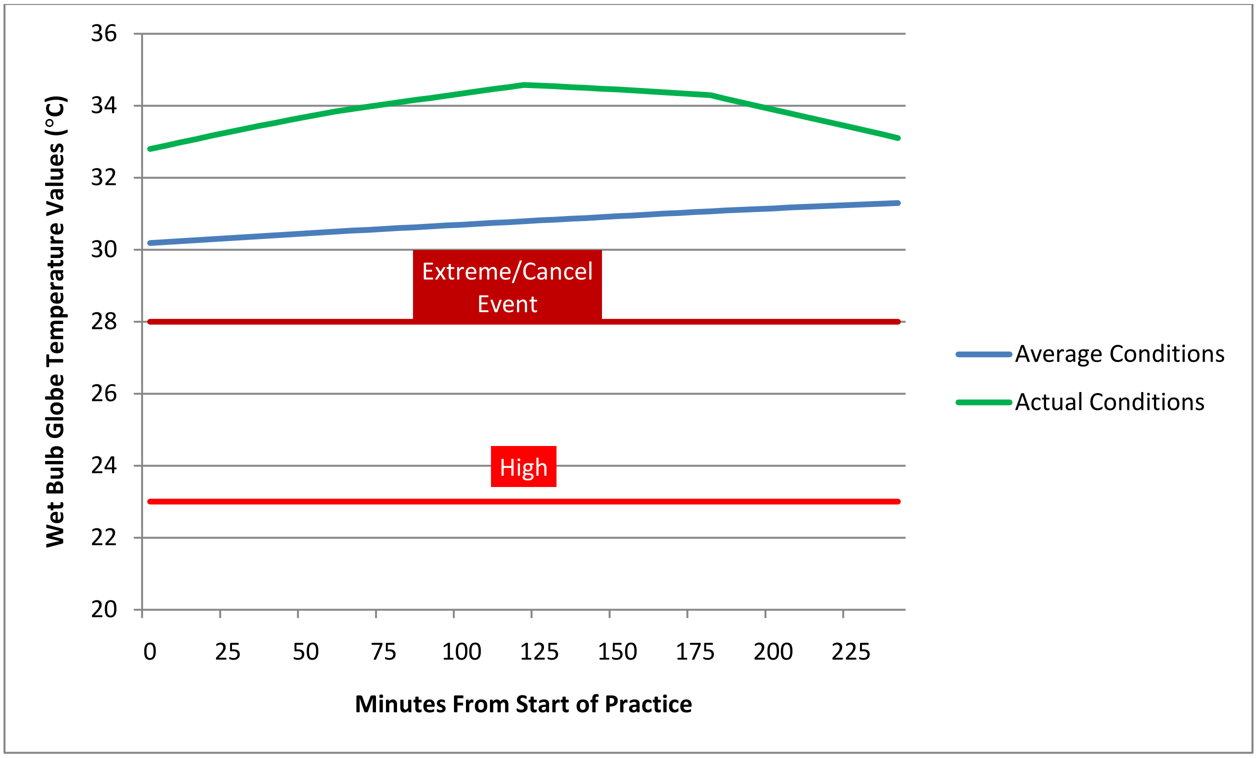

Figure 4.27. Wet Bulb Globe Temperature values, including safety thresholds, for Eric Brown

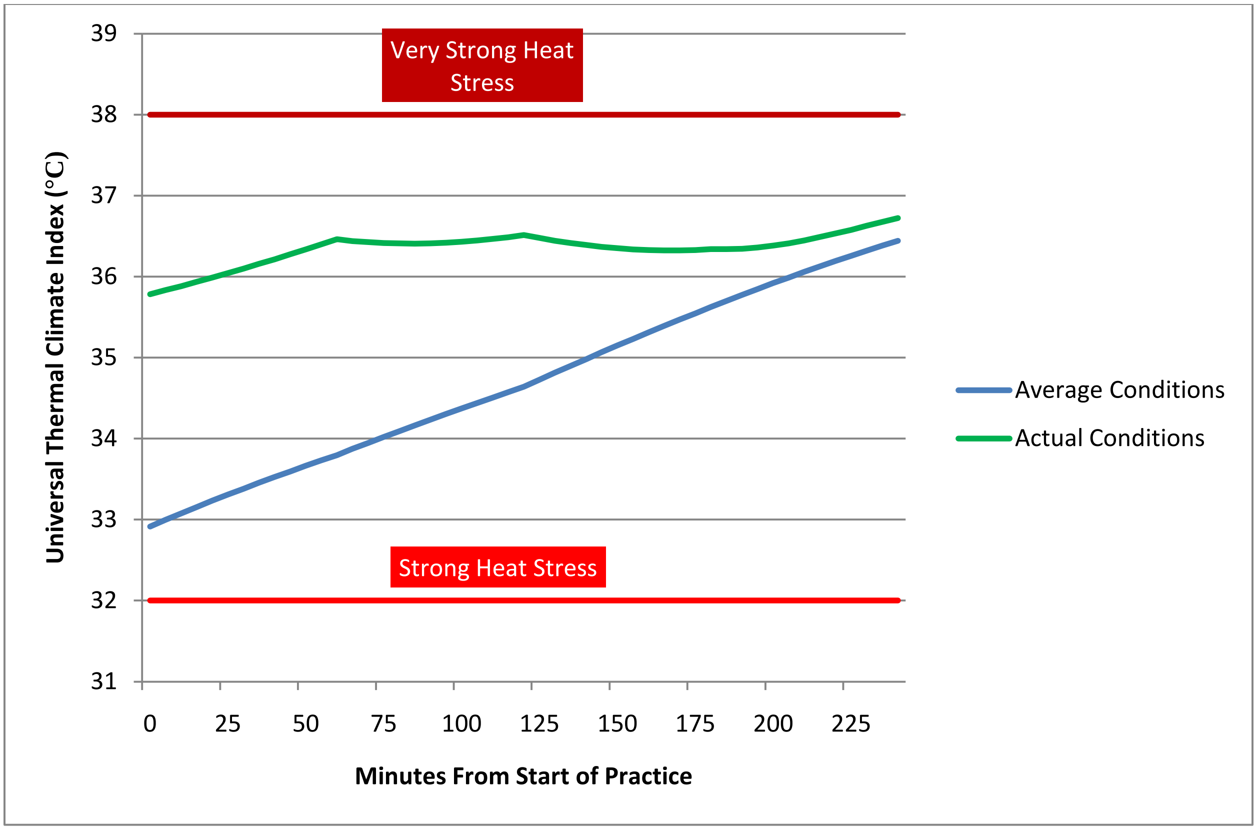

Figure 4.28. Universal Thermal Climate Index values, including safety thresholds, for Eric Brown

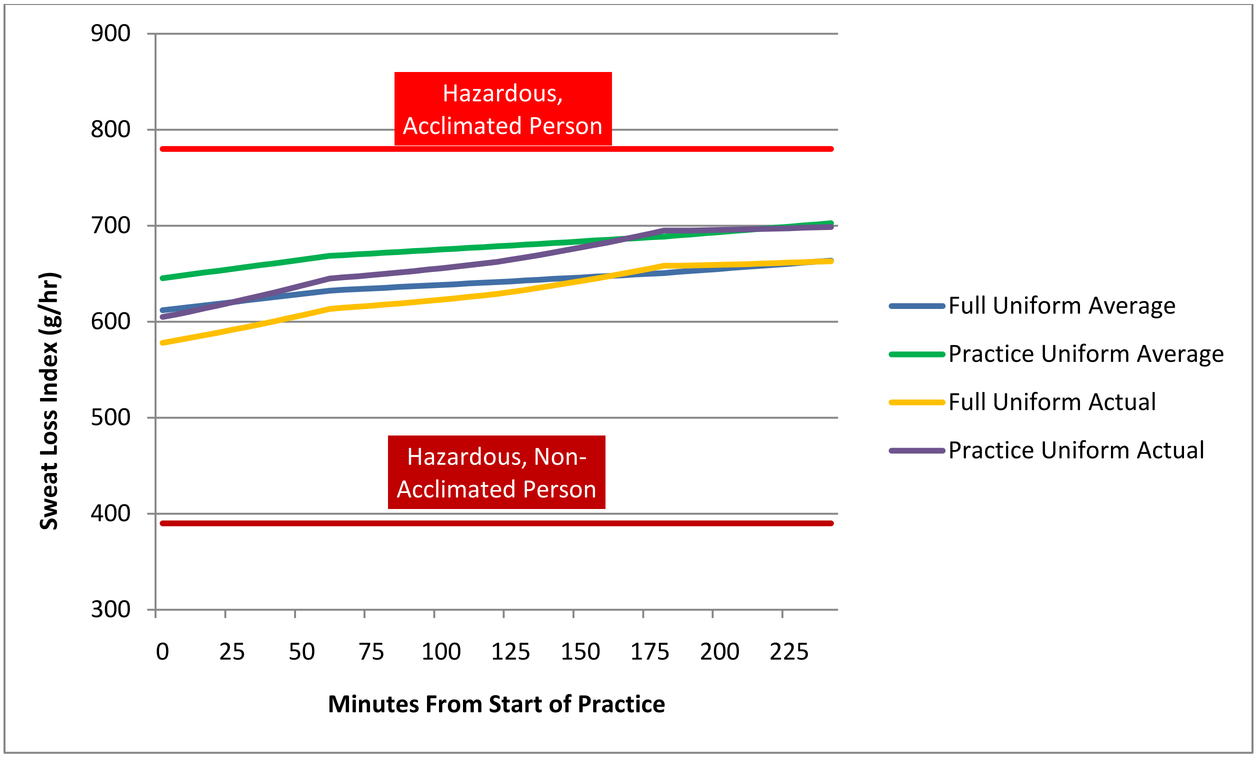

Figure 4.29. Sweat Loss Index, with safety thresholds, for Eric Brown

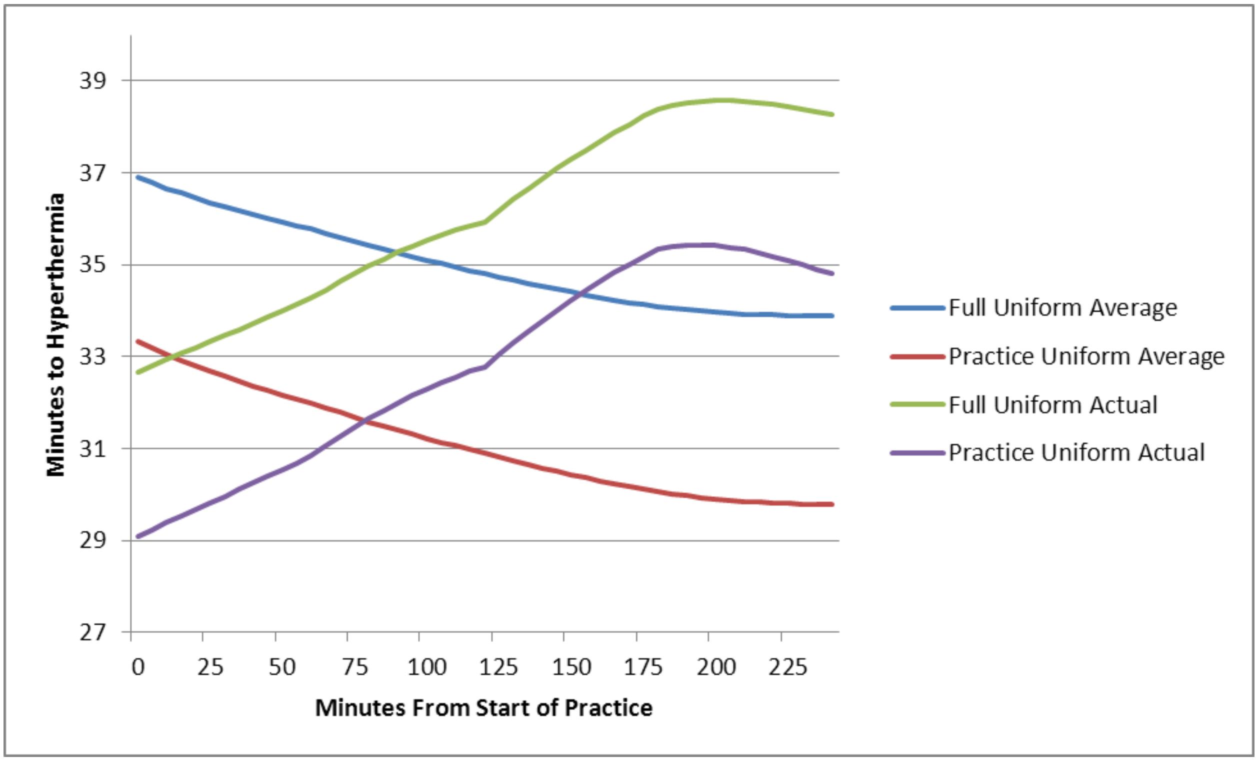

Figure 4.30. Hyperthermia Risk (in minutes), for the duration of practice, for Eric Brown

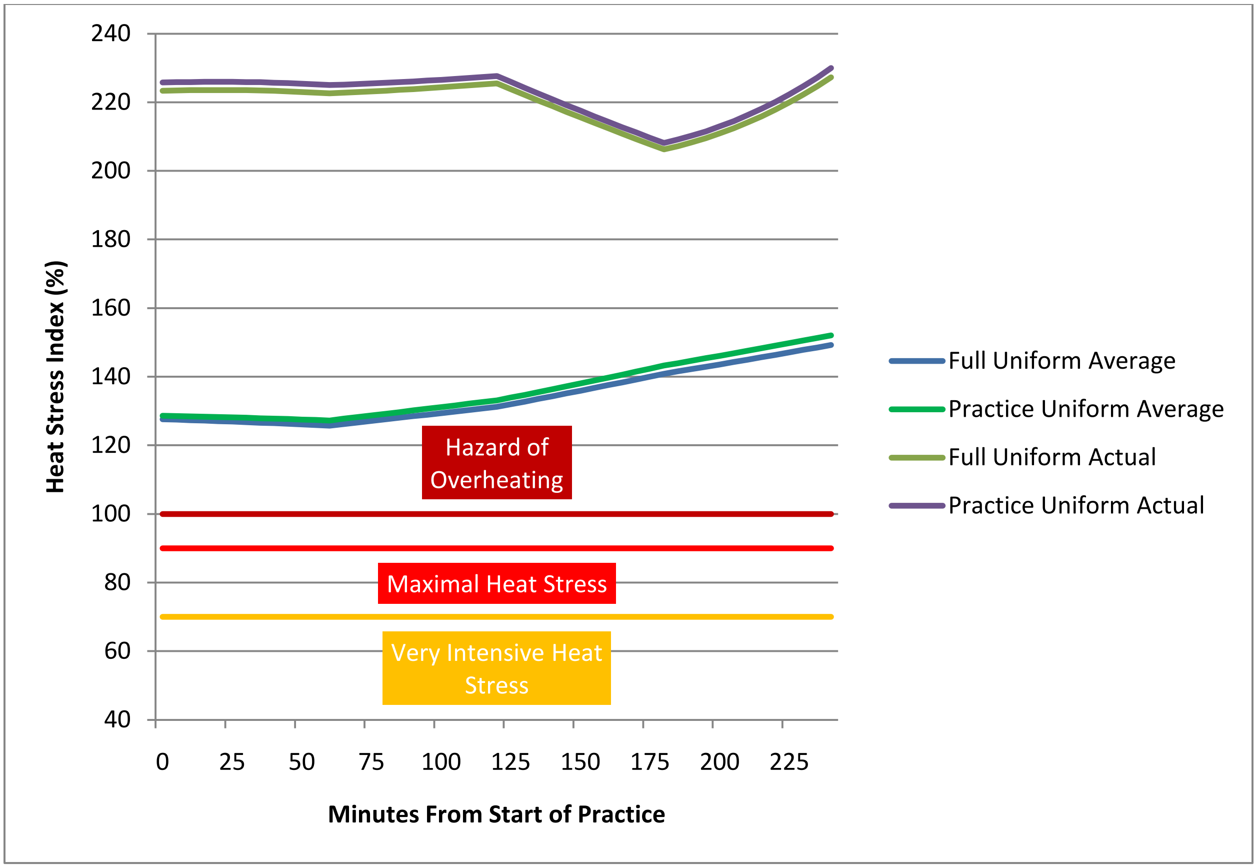

Figure 4.31. Heat Stress Index, with safety thresholds, for Eric Brown

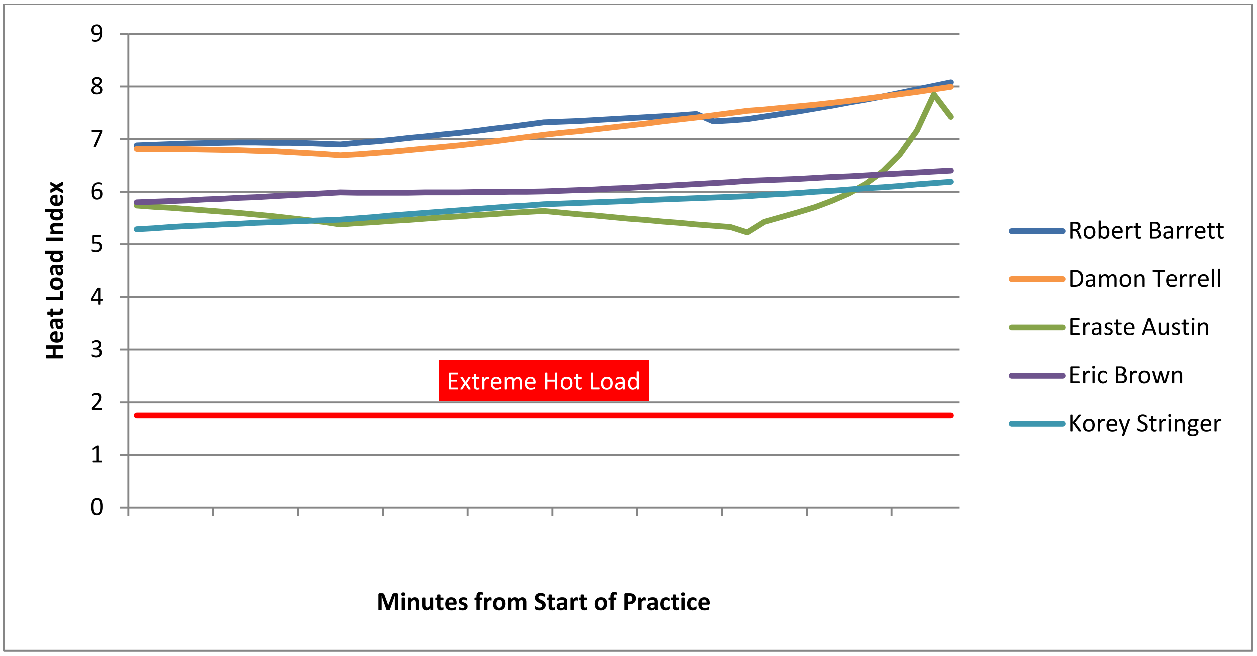

Figure 4.32. Heat Load Index, throughout the duration of practice

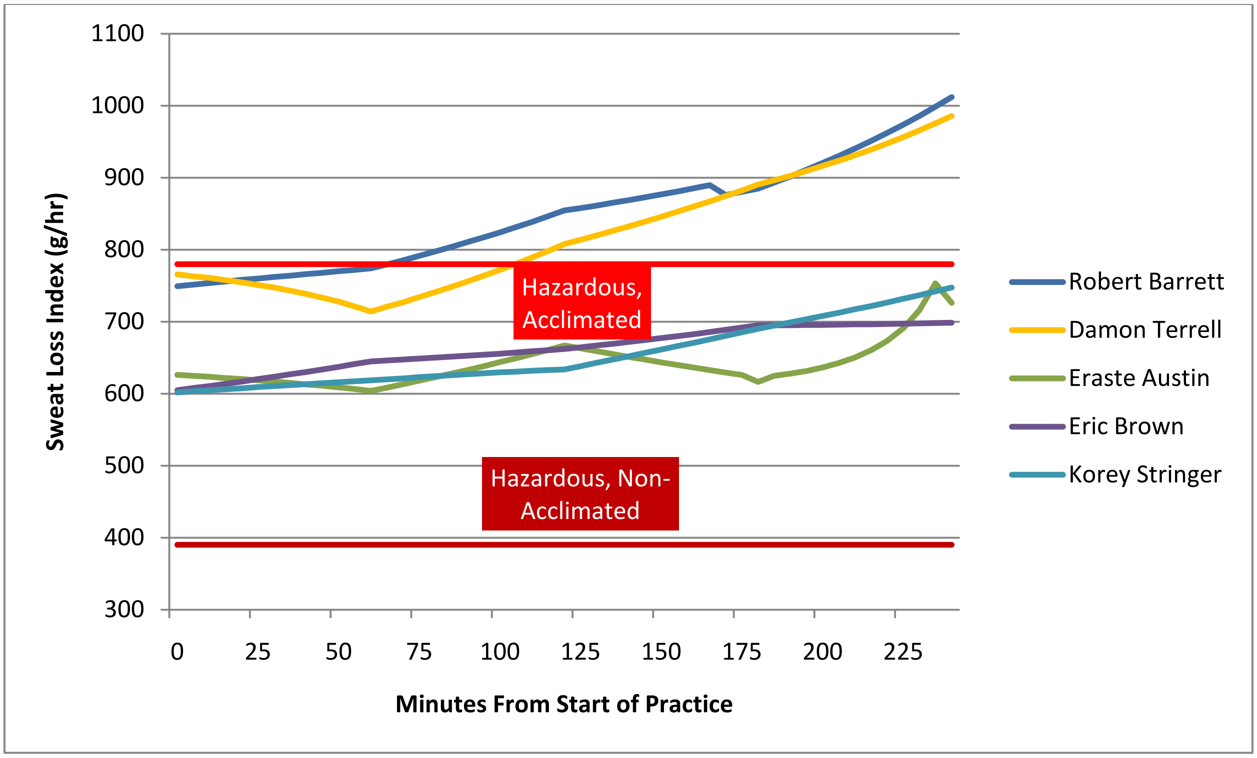

Figure 4.33. Water Loss Index (g/hr), throughout the duration of practice

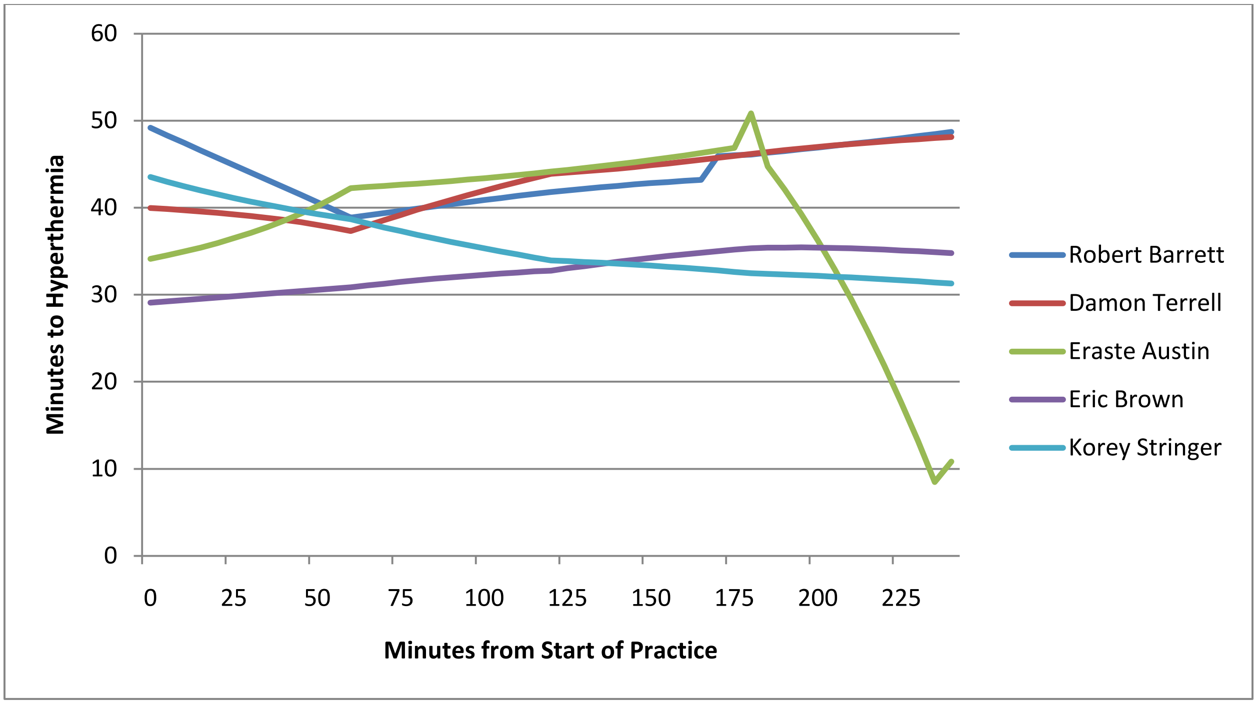

Figure 4.34. Hyperthermia Risk (in minutes), throughout the duration of practice

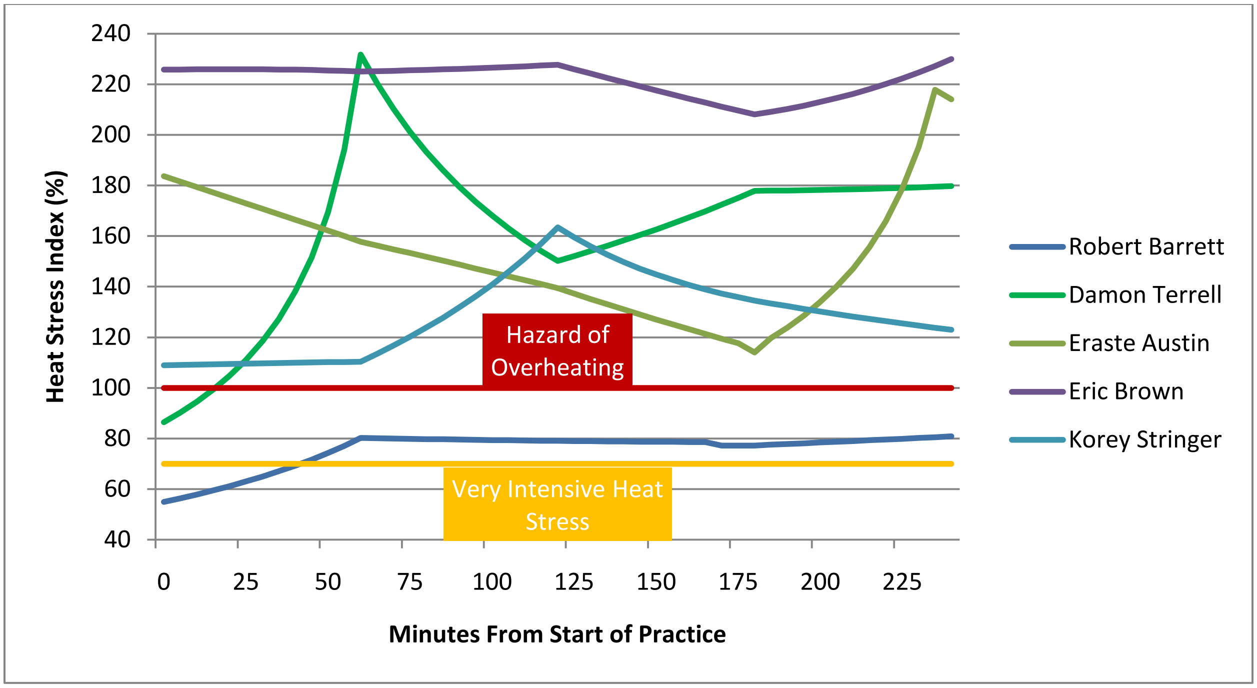

Figure 4.35. Heat Stress Index, throughout the duration of practice

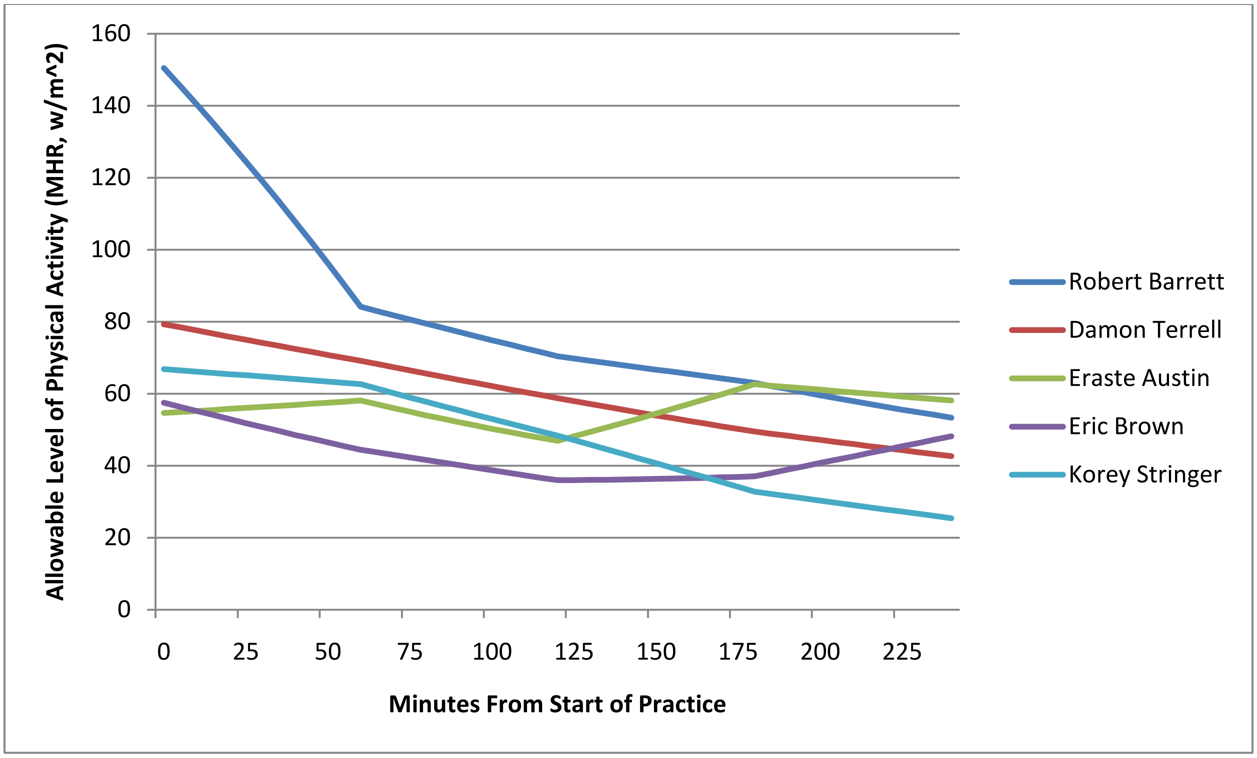

Figure 4.36. Allowable level of physical activity, throughout the duration of practice

CHAPTER 5

CONCLUSIONS

This research has broad implications for the field of heat-related mortality, especially with regard to heat waves and hyperthermia in football players. A warmer climate in the future increases the potential impacts of heat waves, especially in urban areas where populations are increasing. Understanding the current characteristics of late-summer heat waves with regard to their duration and frequency is crucial in being able to mitigate their effects in the future. This study has also been able to highlight in detail the conditions that lead to death from hyperthermia in five athletes participating in the sport of football during the late-summer. The results presented reinforce the need for coaches to carefully monitor conditions on the field to prevent hyperthermia, as well as showing the fact that players are not being exposed to locally extreme heat when hyperthermia occurs. The following is a summary and discussion of the findings of this study.

5.1 Late-Summer Heat Waves in Georgia

Through the creation of heat wave climatologies for six sites in the state of Georgia, the frequency and duration of these events is shown over time. Percentiles calculated during only summer months (May-September) were used to depict truly intense heat wave events as well as allowing for some physiological adaptation to conditions. This is to say that the extreme events in relation to normal summertime conditions are the ones that pose the most significant risk to the general population. The average number of heat waves per decade is similar across all sites, with Augusta being the exception, experiencing almost half as many heat waves per decade as all other sites. The extremely active period from 1979-1988 coincided with extended periods of drought across the entire Southeast. It is reasonable to expect that when Georgia is in an extended period of drought that heat waves are expected to occur during the summer season. The potential for these heat waves increases as the summer season progresses during a drought, given the increasing lack of moisture available for evapotranspiration.

For every site, at least 20% of heat waves occurred during August and September. This is a sizeable percentage considering that June and July are commonly considered to be the hottest months of the summer period. This leads the general population to be often unaware of the impacts of these events late in the summer season. It also shows that late-summer heat wave events are not as uncommon as previously thought. The literature suggests that late-summer heat wave events seem to preferentially target the Southeast and the results found in this study support this claim. Many Georgia public schools also begin classes, and consequently football practices, during this late-summer period, at the beginning of August. Oppressive heat events occurring while classes are in session can be a major health hazard if cooling units fail.

The average duration of late summer events by site is slightly less than the average for all events, but still averages at least 5 days. This suggests that late-summer heat waves behave in the same manner as heat waves that occur earlier in the summer period. Athens and Augusta late summer heat waves last longer on average than those occurring during the rest of the summer. Finally, four of the six sites have their worst heat wave from the record either beginning or ending in August, during the late-summer period.

The results from this study differ slightly from those found by Zhou and Shepherd (2010) for the city of Atlanta. The primary reason for this difference lies in the two different reporting stations used; this research used data obtained from Hartsfield-Jackson International Airport (KATL) located in southern Atlanta where Zhou and Shepherd used Peachtree-Dekalb Airport (KPDK) located on the northeast side of the city. Other factors include the use of a 60-year climatology in this study, versus a 24-year climatology by Zhou and Shepherd, as well as the use of summer-time thresholds to establish a heat wave in this study rather than thresholds taken from the full year.

This study shows that late-summer heat waves do have a large impact on the state of Georgia. Football players are perhaps at the greatest risk of illness during these events, beginning their training regimens during the late-summer period. Understanding the role that heat waves play in deaths due to hyperthermia show if extreme heat is the primary factor in these deaths.

5.2 Late-Summer Heat Waves and Football Players

The next step in this study was applying the method of identifying heat waves used in Georgia to the problem of football players dying from hyperthermia. Of the 48 sites of football-related hyperthermia deaths that a heat wave climatology could be developed for, only three sites were experiencing a heat wave on the day that a player experienced hyperthermia and later died. This shows that extreme or unusual heat, according to the site's climatology, is not what is killing the majority of these players. The common perception of coaches and the public alike is that if a player dies from hyperthermia, extreme heat must be the cause. By demonstrating that this is not the case, it reinforces the need for coaches to monitor not only more than just the temperature, but also just because a period of extreme heat is not forecast does not mean players are not at risk during the early part of the football season.

The final part of this study is an effort to ascertain the conditions that lead to death from hyperthermia in five football players, and in doing so, provide coaches with an accurate metric for assessing potential danger during football practices and games.

5.3 Modeling Using BioKlima

5.3.1 Perceived Temperature Indices

The primary metrics used to assess the danger of the conditions the players were facing when they fell ill were WBGT, Humidex, and UTCI. WBGT appears to be the best index for showing extremely dangerous conditions. All five players experienced conditions at some point during practice where, according to the WBGT, practice and activities should have been cancelled. WBGT was the most consistent method of assessing the danger of conditions on the practice field. UTCI and Humidex were less useful in predicting the combined effects of all meteorological variables used, with some players not appearing to be in an extreme situation, according to these indices. Considering that all five players died, and clearly were in danger during practice, WBGT was the best metric for assessing whether practice should have been modified or continued at all. Other studies have made similar recommendations (Cooper at al. 2006, Luke et al. 2007, Binkley et al. 2002) but not through looking at actual conditions surrounding the deaths of players on the field. These studies primarily reinforced the use of a metric that combines the use of air temperature and humidity (Luke et al. 2007), longer heat acclimatization periods for players (Cooper et al. 2006), and the ability of trainers and coaches to recognize symptoms of heat illness (Binkley et al. 2002). It is the recommendation of this study that all coaches use WBGT with defined safety thresholds in planning and conducting football activities.

5.3.2 Other Bioclimatic Indices

All five players remained above the SW threshold for hazardous conditions for a non-acclimatized player. Even with acclimatization, players can quickly become dehydrated, especially while in a full football uniform, as players do not perceive they are sweating as much as they really are while wearing full pads. Unrestricted access to fluids and mandatory water breaks during practice are absolutely necessary because the body's internal thermoregulation system is dependent upon being adequately hydrated. The further dehydrated a player becomes, the more taxing it is on the body to maintain proper thermal balance. This process is considerably harder under the harsh conditions that these players faced, making even more crucial the need for hydration.

Minutes to hyperthermia for each player ranged from 29 minutes to 49 minutes at the beginning of practice. Given this timeframe, steps can be taken in the scheduling of practices to limit a player's exposure time to conditions, and give their bodies time to recover before hyperthermia sets in. Not all players are at risk, but careful monitoring of all players, especially larger players, is crucial. Many coaches breed a survivalist mentality that dictates restricting breaks and fluids to make their players tougher. Players can be kept out of danger while being able to perform at high levels of expectation, but only with coaches who understand the potential dangers that can arise during practice as a result of high heat and humidity.

Four out of the five players exceeded the HSI threshold of 100%, indicating that they could not possibly cool their bodies through evaporation enough to overcome the conditions they faced during practice. Barrett was the lone exception which is attributed to the low relative humidity present on the day he became ill with hyperthermia. However, the process of the body being able to adequately cool itself by sweat evaporating from the skin is contingent upon the person being adequately hydrated, which SW indicates that Barrett was not. News reports suggest that Barrett had ample access to water, being given water breaks every 15 minutes during practice, but this does not necessarily mean that he was adequately hydrated (NCCSIR 2010).

All five players showed a heat load index much greater than the value considered to be an extreme hot load on man. Given the constant exposure to conditions during practice, these players quickly lost the ability to keep their internal temperature at a reasonable level, at which point their core body temperature began rising until hyperthermia set in. Once again, proper scheduling of practices and breaking up periods during which players are outside and exposed to the elements will limit the cumulative effect of an individual's heat load, allowing them to recover properly and avoid being placed in danger during practice.

5.3.3 Morning Practices Are Safer?

An extremely common practice among coaches is holding morning practice sessions, believing in doing so, they are keeping players safer and out of the dangerous afternoon heat. Four out of the five deaths in this study occurred during a morning practice session. In two of these cases, the RH values of that morning were much higher than the climatological average of the same day. The effects of higher RH were seen in the modeling of these two cases. Higher moisture content in the air prevents players from sweating adequately to cool their bodies. So, despite cooler morning temperatures compared to the afternoon, higher RH values have almost the same effect as practicing during the drier and hotter afternoon period. Temperature alone cannot be used to indicate whether practices are safe or not for players. Once again, this is why using the WBGT is the preferred indicator of whether or not practice should take place because it incorporates relative humidity as well as temperature.

5.4 Future Directions

This study has shown the prevalence of late-summer heat waves in the overall heat wave climatology for six sites in the state of Georgia. The relationship between late-summer heat waves and deaths of football players was also examined. Understanding the past and current effect of heat waves, especially with regard to frequency and duration, is a crucial step in being able to understand the potential impacts of climate change on these events. Future work in developing similar heat wave climatologies for sites all across the U.S. will give insight as to how heat waves behave in different parts of the country. This would also provide a uniform base to analyze future impacts of climate change across the wide variety of projected scenarios, allowing for potential mitigation and public health strategies in cities vulnerable to periods of extreme heat. It is also important to assess the impact that humidity has on heat wave mortality based on current climate change scenarios. In a warmer future climate, the warmer air will inherently have a greater capacity for holding water vapor according to the Clausius Clapeyron relation. Warmer temperatures would lead to higher possible humidity values, significantly increasing mortality during heat wave events above levels that are presently seen.

Future work with regard to late-summer heat waves and hyperthermia deaths in football players lies in educating coaches and administrators that an extremely hot day is not necessary for conditions that result in a player’s death. Heat advisories and other products issued by the

National Weather Service and local media are not enough information to determine whether or not it is safe to hold practice.

The five cases of football players dying due to hyperthermia modeled using BioKlima show that Wet Bulb Globe Temperature is the best metric for determining if conditions are safe for football players. WBGT can be easily calculated using meteorological data (Td, Tw, Tg) from a nearby observing station. Even more prudent would be for all schools to have a handheld environmental monitor, such as the WBGT-103F Heat Stroke Checker, used in the study by Cooper et al. (2002), to constantly monitor conditions on the field. The use of this specific device is advocated by the following organizations for the use of preventing heat stroke; American College of Sports Medicine, The United States Army, Japan Amateur Sports Association, Japan Society for Occupational Health, and the American Conference of Governmental Industrial Hygienists (KEM 2011).

The consensus of the other bio-climatic indices that were calculated showed that these five players experienced dangerous conditions that ultimately led to their deaths from hyperthermia. Future work in developing base levels of these indices across players of different positions as well as locations throughout the country would give coaches a better indication of the temporal scale at which conditions can become hazardous. This would allow for not only optimum scheduling of practices for a day's given meteorological conditions, but also would ultimately keep players safe.

Football is the most popular sport in the U.S., with participation increasing every year. All deaths due to hyperthermia in football players, absent of pre-existing medical conditions, are 100% preventable given proper monitoring and care by responsible coaches. It is hoped that this study will serve as a useful contribution toward educating coaches of the potential danger they face when their teams take the field at the beginning of the season, and that through proper mitigation, they can keep their players safe and continue to foster growth and education in the great sport of football.

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Appendix A

Description of Model Output Variables and Thresholds (from BioKlima Help Section)

Humidex (in °C) is a general heat stress index. It represents outdoor temperature felt by man in hot and humid environment. Humidex is calculated as follows:

Humidex = t + 0.5555 (e - 10)

According to Environment Canada, Humidex-related hazards are as follows:

Humidex (°C):	Danger category:	Heat syndrome:
below 30	Caution	Little discomfort, Fatigue possible with prolonged exposure and activity
from 30 to 40	Extreme caution	Some discomfort, heat stroke, heat exhaustion and heat cramps possible with prolonged exposure and activity
from 40 to 55	Danger	Great discomfort, avoid exercise. Heat cramps or heat exhaustion likely. Heat stroke possible with prolonged exposure and activity.
above 55	Extreme danger	Heat stroke imminent with continued exposure

Wet bulb globe temperature (WBGT, in °C) is an index illustrating thermal and humid impacts on man. WBGT can be measured with the use of special equipment or calculated according to the following formula:

$$WBGT = 0.567\,t + 0.393\,e + 3.94$$

The following ranges of WBGT indicate several recommendations for outdoor activity:

WBGT:	Recommendation:
below 18°C	Unlimited
from 18°C to 24°C	Keep alert for possible increases in the index and for symptoms of heat stress
from 23°C to 28°C	Active exercise for unacclimatised persons should be curtailed.
from 28°C to 30°C	Active exercise for all but the well acclimatised should be curtailed.
above 30°C	All activity should be stopped

Universal Thermal Climate Index (UTCI) is defined as the air temperature (t) of the reference condition causing the same physiological response as the actual condition. Thus, UTCI is the air temperature which would produce under reference conditions the same thermal strain as in the actual thermal environment. The multi-node Fiala model of the human heat balance was applied to assess physiological response of an organism.

Both meteorological and non-meteorological (metabolic rate and thermal resistance of clothing) reference conditions were defined:

- Wind speed (v) of 0.5 m/s at 10 m height (approximately 0.3 m/s at 1.1 m).
- Mean radiant temperature (Mrt) equal to air temperature.
- Vapour pressure (e) that represent relative humidity of 50%; at high air temperatures (29ºC) the reference humidity was taken constant at 20 hPa.
- Representative activity (M) of a person walking with a speed of 4 km/h (vprim = 1.1 m/s). This provides a metabolic rate of 135 W m-2.

The adjustment of clothing insulation is a powerful behavioral response to changing climatic conditions. The overall intrinsic clothing insulation (Icl) is a function of the ambient air temperature.

The UTCI is calculated as polynomial regression function up to 6th order of: t, v10m, e and Mrt-t. If v10m is absent, it is estimated from the regular wind speed: v10m = v / 0.667.

UTCI is categorized in terms of thermal stress in man as follows:

UTCI range (°C)	Stress Category	Physiological responses
above +46	extreme heat stress	Increase in rectal temperature (Tre) time gradient. Steep decrease in total net heat loss.Averaged sweat rate >650 g/h, steep increase.
+38 to +46	very strong heat stress	Core to skin temperature gradient < 1K (at 30 min).Increase in Tre at 30 min.
+32 to +38	strong heat stress	Dynamic Thermal Sensation (DTS) at 120 min >+2. Averaged sweat rate > 200 g/h. Increase in Tre at 120 min.Latent heat loss >40 W at 30 min. Instantaneous change in skin temperature > 0 K/min.
+26 to +32	moderate heat stress	Change of slopes in sweat rate, Tre and skin temperature: mean (Tskm), face (Tskfc), hand (Tskhn).Occurrence of sweating at 30 min. Steep increase in skin wettedness.
+9 to +26	no thermal stress	Averaged sweat rate > 100 g/h. DTS at 120 min < 1. DTS between -0.5 and +0.5 (averaged value).Latent heat loss >40 W, averaged over time.Plateau in Tre time gradient.

Water loss index (SW, in g/hour) is calculated based on the potential values of evaporative heat loss (Epot). Epot is derived from Blazejczyk's man-environment heat exchange model MENEX_2002 taking into accout 5% level of relative humidity of air (f):

SW = -2,6 Epot

where Epot is calculated the same way as mE but with e replaced by e'. e' is vapour pressure calculated using f always equal to 5%, regardless of the f value provided in the source data table.

Limit values of SW depend on human activity and subject acclimation levels as follows:

	Activity level	
	M <= 70 W/m2	M > 70 W/m2
acclimated subject:		
warning SW limit	520	780
hazardous SW limit	780	1040
non-acclimated subject:		
warning SW limit	260	520
hazardous SW limit	390	650

During prolonged stay at extreme ambient conditions physiological processes of thermoregulation can be insufficient to keep homeothermy. According to Hardy (1965) at core temperature (Tc) of about 40°C (that correspond to heat accumulation of about 900 kJ) thermoregulation disorders are observed and at Tc of 43°C (change in body heat content of +1800 kJ) hyperthermia and heat stroke arises.

Hyperthermia Risk (Oh_H) is a time (in min) that due to great increase in body heat content hyperthermia can occur. (Oh_H) is calculated as follows:

- for SR >= 0 W/m2:

$$Oh\_H = 2\ [(900000 - 1.6\ 1200\ |mS|) / (1.6\ |SR|)] / 60$$

For both Oc_W and Oc_H, when SR < 0, there is no overheating risk and hence no time limit.

SR is the resultant value of net heat storage. In actual ambient environment, the physiological and physical processes continuously fluctuate to keep the equilibrium between heat gains and heat losses. The most intensive adaptation occurs during first 15-20 minutes after the sudden change of environment. The Resultant net heat storage (SR) represents the level of heat exchange after this adaptation time.

The resultant value of net heat storage ($SR = M + mQ^* + mE^* + mC^* + mRes$) is calculated taking into consideration Tsk^* value that is an effect of a cooling of skin surface due to intensive sweat evaporation. The particular heat exchange components are calculated as follows:

$$mQ^* = mR + mL^*$$

$$mL^* = (0.5\ Lg + 0.5\ La - Ls^*)\ Irc$$

$$Ls^* = 0.95\ 5.667\ 10^{-8}\ (273 + Tsk^*)^4$$

$$mE^* = he\ d\ (ie - esk^*)\ w^*\ Ie - [0.42\ (M - 58) - 5.04]$$

$$mC^* = hc\ (iMrt - Tsk)\ Irc$$

$$ie = 6.112\ 10^{[7.5\ iMrt / (237.7 + iMrt)]}\ (f / 100)$$

$$esk^* = \mathrm{EXP}(0.058\ Tsk^* + 2.003)$$

$w^* = 0.002$ for $Tsk^* < 22$ °C

$w^* = 1.0$ for $Tsk^* > 36.5$ °C

$w^* = 1.031 / (37.5 - Tsk^*) - 0.065$ for Tsk^* between 22 °C and 36.5 °C

where iMrt is the inner (i.e. under clothing) mean radiant temperature:

$$iMrt = \{[mR + (0.5\ Lg + 0.5\ La)\ Irc + 0.5\ Ls^*] / (0.95\ 5.667\ 10^{-8})\}^{0.25} - 273$$

and where the remaining components (e.g. Lg, he, d) are calculated as in formulas for mL, mE and mC.

Belding-Hatch's Heat Stress Index (HSI, in %) expresses the ratio of evaporation required for keeping heat equilibrium of an organism to maximal evaporation in actual environmental conditions. 390 W/m2 is a limit of evaporative heat loss and it is equal to water loss of 1 litre per hour. HSI is calculated as follows:

$$HSI = 100\ Ereq / Emax$$

where:

$$Ereq = M + mQ + mC + mRes$$

$$Emax = k\ v^{0.6} (56 - e)$$

k is 7.0 for clothed man ($Icl \geq 0.5$) and 11.7 for nude man ($Icl < 0.5$).

There are the following physiological responses of an organism observed at particular HSI values:

below 0	- Slight cool stress
from 0 to +10	- Thermoneutral conditions
from more then 10 to 30	- Slight and moderate heat stress
from more then 30 to 70	- Intensive heat stress; health hazard for unacclimated persons
from more then 70 to 90	- Very intensive heat stress; water and minerals supply necessary
from more then 90 to 100	- Maximal heat stress tolerated by young, acclimated persons
above 100	- Hazard of an organism overheating; exposure time must be controlled.

Heat Load of an organism (HL, dimensionless) is calculated basing on net heat storage (mS), absorbed solar radiation (mR), and evaporative heat loss (mE), derived from Blazejczyk's man-environment heat exchange model MENEX_2002. HL is calculated as follows

- for $mS < 0$ W/m2 and $mE >= -50$ W/m2

$$HL = [\{mS + 1000) / 1000]^{[5 / (1 + mR)]}$$

- for $mS >= 0$ W/m2 and $mE >= -50$ W/m2

$$HL = [(mS + 1000) / 1000]^{[2 - 1 / (1 + mR)]}$$

- for $mS < 0$ W/m2 and $mE < -50$ W/m2

$$HL = (mE / -50) [\{mS + 1000) / 1000]^{[5 / (1 + mR)]}$$

- for $mS >= 0$ W/m2 and $mE < -50$ W/m2

$$HL = (mE / -50) [(mS + 1000) / 1000]^{[2 - 1 / (1 + mR)]}$$

Note that if mS is less than -1000 W/m2, BioKlima uses the value of -1000.

The intensity of heat load can be assessed as follows:

below 0.25	- extreme - cold stress
from 0.25 to 0.82	- great - cold stress
from 0.82 to 0.975	- slight - cool stress
from 0.975 to 1.025	- thermoneutral
from 1.025 to 1.18	- slight - warm stress
from 1.18 to 1.75	- great - hot stress
above 1.75	- extreme - hot stress

Maximal activity level (MHR, in W/m2) indicates the limit value of activity which does not provoke the rise of heart rate (HR) above 90 beats per minute in given meteorological conditions. MHR is calculated as follows:

$$MHR = [90 - 22.4 - 0.25 (5\ t + 2.66\ e)] / 0.18$$