Portable WBGT Tracker for Outdoor Athletes in the Heat

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Abstract

WBGT Tracker is a portable device that can find and display the local Web Bulb Globe Temperature (WBGT), which indicates heat stress on the human body in direct sunlight. This device allows outdoor athletes to be aware of the environmental conditions for their activities and warn them early to take precautions. It is built with a Raspberry Pi computer to run Python code that downloads WBGT forecasts from the National Oceanic and Atmospheric Administration (NOAA) and shows them on an e-paper display.

X.1 Introduction

Heat-related illnesses are a critical threat for outdoor athletes in the summer months. They impact athletes' conditions, performance, careers and even lives. At the 2021 Tokyo Olympics, which was the hottest Olympic Games on record with temperatures of 93°F (34°C) and humidity of 70%, Tennis player Daniil Medvedev (the Games' number two seed) spoke of "dying on court" during the heat of a match [1]. In the Rings of Fire report, published by the British Association for Sustainable Sport, Olympic bronze medal tennis player Marcus Daniell describes the heat as "true risk – the type of risk that could potentially be fatal" [2].

This project builds a portable device, called WBGT Tracker, which can find and display the Web Bulb Globe Temperature (WBGT) at an area of athletic activity. WBGT is a numerical indicator of heat stress on the human body in direct sunlight. WBGT Tracker allows athletes to be aware of the environmental conditions for their activities and warn them early to take precautions, for example taking breaks frequently in the shade and keeping hydrated.

WBGT Tracker is implemented with a small (credit-card sized) computer called Raspberry Pi. A Python program runs on Raspberry Pi to determine the current location of the device (latitude and longitude) through IP geolocation and download WBGT forecast for that location from National Oceanic and Atmospheric Administration (NOAA). It shows the forecast and heat safety alert on an e-paper display. WBGT tracker can be activated via iOS Siri.

Figs. 1 and 2 show how WBGT Tracker looks like. Since WBGT Tracker uses an e-paper display, it can hold the information displayed even if it is turned off. It can be activated at home, in a car, or at a clubhouse, and then brought to a practice or a match without a power source.

Fig. 1: WBGT Tracker attached to a Tennis Bag (1)

Fig. 2: WBGT Tracker attached to a Tennis Bag (2)

X.2 Background

This section overviews heat-related illnesses, describes Wet Bulb Globe Temperature (WBGT), and summarizes WBGT-based heat safety policies for high school athletes.

X.2.1 Heat-related Illnesses

Heat-related illnesses such as heat cramps, heat exhaustion and heat stroke should be taken into concern when doing sports and other outdoor activities in the summer months. Heat stroke is the most serious heat-related illness and a top cause of preventable death for high school athletes [3, 4, 5]. Symptoms of heat stroke include high body temperature, sweating profusely, dizziness, confusion, headache, losing consciousness, and seizures.

Heat stroke occurs when the body is too overheating to regulate its temperature. High air temperature and direct sunlight exposure increase body temperature. Exercise (muscle contraction) also causes an increase in body temperature. During intense exercise, heat production is 15 to 20 times greater than at rest and can raise body core temperature 1°C (1.8°F) every 5 minutes unless heat is removed [6].

The body strives to regulate its temperature by releasing heat from the skin via evaporation of sweat. Wind accelerates the loss of heat. However, when dehydrated, the sweating mechanism does not work properly. It is also impaired as humidity increases. No extra heat loss can be expected when there is no wind. Due to these factors, the body fails to cool down and cause heat stroke. When heat stroke occurs, the body temperature can rise to 105°F (40.5°C) or higher in 10 to 15 minutes [7].

X.2.2 Wet Bulb Globe Temperature (WBGT)

Wet Bulb Globe Temperature (WBGT) is the most effective method to estimate the threat of heat-related illness. It integrates the influences of sun exposure, air temperature, humidity and wind movement. It is an “apparent temperature,” or “feels-like temperature,” which indicates the human perception of temperature.

WBGT is measured with three different thermometers: dry-bulb, wet-bulb and black-globe thermometers [8]. A dry-bulb thermometer measures the actual air temperature. A wet-bulb thermometer is a thermometer wrapped in a water-moisturized cloth. It behaves differently from a dry-bulb thermometer by taking humidity and wind into account. The less humid the air is, the faster the water will evaporate. The faster water evaporates, the lower the thermometer's temperature will be relative to air temperature. A black globe thermometer is a thermometer inside a black globe. The black surface absorbs solar heat, and the surface temperature is affected by wind.

WBGT is calculated as a weighted mean of the data inputs from these thermometers: dry-bulb temperature (T_d), wet-bulb temperature (T_w) and black-globe temperature (T_g):

$$WBGT = 0.7 * T_w + 0.2 * T_g + 0.1 * T_d$$

If T_d, T_w and T_g are measured in Fahrenheit (F), WBGT is computed in F. If they are in Celsius (C), WBGT is computed in C.

As this equation shows, WBGT places a very high weight for wet-bulb temperature (T_w), compared to dry-bulb temperature (T_d), because it is intended to emphasize the large impact humidity has on the body's ability to sweat and release heat. Although many people look at air temperature and determine the safety of being active outside, this can be misleading. Even when air temperature is on the lower side, it can still be dangerous if humidity is extremely high and there is no wind. WBGT can quantify this risk effectively.

WBGT is similar to the heat index because both are apparent temperatures calculated with air temperature and humidity. However, the heat index uses air temperature in the shade. This is not a reasonable assumption for outdoor athletes. In contrast, WBGT places a higher weight for black-globe temperature (T_g) than dry-bulb temperature (T_d) to emphasize the impacts of direct sunlight on body temperature.

As a result, professional, national and state athletic associations have accepted WBGT as the primary means of determining the appropriate temperatures for hot weather activities. For example, the United States Tennis Association sets WBGT-based heat policies for junior singles, wheelchair singles, women's open singles and men's open singles matches in the US Open Championships [9]. The United States Soccer Federation's player health and safety program, called Recognize to Recover, provides WBGT-based heat safety guidelines [10].

X.2.3 WBGT-based Heat Policies for High School Athletes

The National Athletic Trainers' Association (NATA), which organizes the largest community of high school athletic trainers in the US, released a position statement about heat-related illnesses in 2015 [11]. It uses WBGT as a means of measuring environmental risk factors and offers an example WBGT-based safety policy. It also points out that a "one size fits all" heat policy does not work across different geographical regions in the US.

By analyzing regional variations in acclimatization to heat based on climatology research findings, Grundstein et al. define three regions in the US (Fig. 3) and propose a WBGT-based heat policy for each region (Fig. 4) [12]. As shown in Fig. 4, northern regions (Category 1) have lower WBGT thresholds for activity modification than other regions (Categories 2 and 3) because athletes in the North are less acclimatized to heat than in other regions.

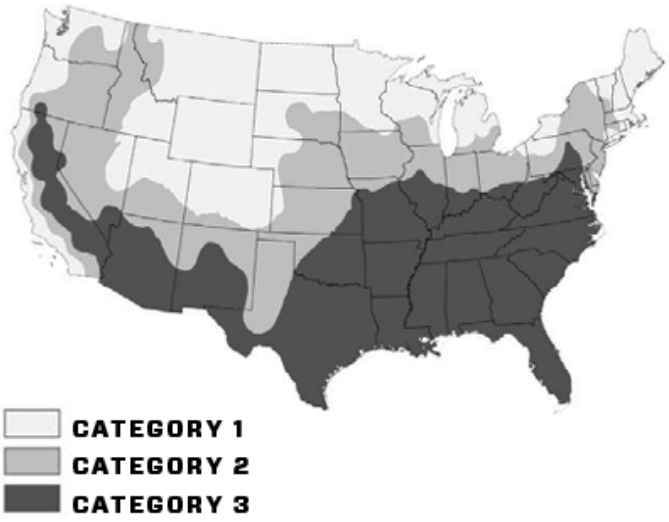

Fig. 3: Regional Categories based on Acclimatization to Heat. Determined with the 90th Percentile Warm Season Maximum Daily WBGT. Excerpt from [10].

ALERT LEVEL	WBGT BY REGION (°F)			EVENT CONDITIONS	RECOMMENDED WORK TO REST RATIOS (ACTIONS & BREAKS)
	CAT 1	CAT 2	CAT 3		
BLACK	>86.2°	>89.8°	>92.0°	Extreme Conditions	No Outdoor Training, delay training until cooler, or Cancel Training.
RED	84.2-86.1°	87.8-89.7°	90.1-91.9°	High Risk for Heat Related Illness	Maximum of 1 hour of training with 4 by 4 minute breaks within the hour. No additional conditioning allowed.
ORANGE	81.1-84.1°	84.7-87.7°	87.1-90.0°	Moderate Risk for Heat Related Illness	Maximum of 2 hours of training with 4 by 4 minute breaks each hour, OR a 10 minute break every 30 minutes of training.
YELLOW	76.3-81.0°	79.9-84.6°	82.2-87.0°	Less than Ideal Conditions	3 Separate 4 minute breaks each hour, OR a 12 minute break every 40 minutes of training
GREEN	<76.1°	<79.8°	<82.1°	Good Conditions	Normal Activities. 3 Separate 3 minute breaks each hour of training, OR a 10 minute break every 40 minutes

Fig. 4: WBGT Thresholds for Heat Alert Levels in each Regional Category. Excerpt from [10].

Currently, this is the most widely-used heat policy for high school athletes. It is recommended by the National Federation of State High School Associations (NFHS), which writes the rules of competition for most high school sports and activities in the US [13, 14]. Most high schools in the US (more than 18,000 high schools) belong to NFHS through their state's high school associations. For example, the Massachusetts Interscholastic Athletic Association (MIAA) is a member of NFHS, and it consists of more than 370 high schools in Massachusetts. Following NFHS' recommendation, MIAA sponsors activities and competitions in 33 sports based on the Category 1 WBGT thresholds in [12] [15, 16].

In this project, WBGT Tracker downloads the local WBGT forecast from NOAA and identifies one of five alert levels based on the forecast and regional category.

X.3 Hardware Setup

WBGT Tracker is built with a Raspberry Pi and an e-paper display.

- Raspberry Pi Zero 2 WH (1x): Purchase a MicroSD card separately. It does not come with a Raspberry Pi. Amazon Standard Identification Number (ASIN): B09LTDQY2Z. This project uses the Version 2 of Raspberry Pi Zero (Zero 2 WH), but its Version 1 works too (Zero WH; ASIN: B0CG99MR5W).

- Pimoroni Inky pHAT (1x): This is a 2.13” e-paper display that can use black, white and red colors. It has 2x20 GPIO sockets (holes); it can sit directly on top of Raspberry Pi’s GPIO header. Its display dimension (48.5mm width x 23.8mm height) perfectly fits with the footprint of Raspberry Pi Zero. This display is designed to be clearly visible even in bright sunlight. Adafruit Product ID: 3743. Pimoroni’s product Web page: [17].

- Flirc Aluminum Case for Raspberry Pi Zero (1x): It is highly recommended to place a Raspberry Pi in a case because WBGT Tracker is intended to be a portable device that is attached to a sports bag and used outdoors. ASIN: B08837L144. Adafruit product ID: 4822.

ASINs can be used for product searches at **`https://www.amazon.com`**, and Adafruit product IDs can be used at **`https://www.adafruit.com`**.

Fig. 5 shows how WBGT Tracker is assembled with the required components.

Fig. 5: Fully assembled WBGT Tracker

X.4 Software Setup

WBGT Tracker runs Python code in Raspberry Pi to determine the current location of the device (latitude and longitude) through IP geolocation and download WBGT forecast for that location from the National Digital Forecast Database (NDFD). NDFD is developed by the National Oceanic and Atmospheric Administration (NOAA) for the National Weather Service [18]. Then, the Python code displays the downloaded forecast and heat safety alert. This section describes how to set up and run the Python code with the Inky.

X.4.1 Setting up an Inky pHAT

First, turn on the Raspberry Pi and update its operating system by running the following commands one by one on a Terminal.

- `sudo apt update -y`
- `sudo apt full-upgrade -y`

Then, enable I2C and SPI communication with the Raspberry Pi Configuration settings. To install a driver for the Inky pHAT e-display, run the following command on a Terminal.

- `curl https://get.pimoroni.com/inky | bash`

See [19] for the reference manual of Inky pHAT.

X.4.2 Setting up the Required Python Modules

NDFD provides a REST API that returns XML data in the Digital Weather Markup Language (DWML). To convert the downloaded XML data to a Python dictionary, you need the **`xmltodict`** module. Install it by running the following command on a Terminal:

- `sudo pip3 install xmltodict`

The next step is to download **`noaa_wbgt.py`** from the **`code`** folder at [20] and run it to confirm REST API access to NDFD. Data downloading is successful if you see an output that contains WBGT data.

WBGT Tracker also requires the **`geocoder`** module, which implements IP geolocation [20]. This feature locates a geographical area where an IP address is used and returns the latitude and longitude of the area's center. Install the module by running the following command on a Terminal:

- **`sudo pip3 install geocoder`**

Run the following code to test IP geolocation:

```
import geocoder
geoInfo = geocoder.ip("me")
lat = geoInfo.lat
lon = geoInfo.lng
print(lat, lon)
```

X. 4.2 Python Code

WBGT Tracker runs the following Python code, which is available as **`wbgt.py`** in the **`code`** folder at [21]. Make sure to place this code and **`noaa_wbgt.py`** in the same folder.

```
import geocoder
from noaa_wbgt import getWbgt
from inky import InkyPHAT
from PIL import Image, ImageFont, ImageDraw

regionCategory = 1

fontBig =     ImageFont.truetype("JetBrainsMono-Regular.ttf", 35)
fontSmall =   ImageFont.truetype("JetBrainsMono-Regular.ttf", 25)
fontSmaller = ImageFont.truetype("JetBrainsMono-Regular.ttf", 20)

def getLatLon():
    geoInfo = geocoder.ip("me")
    return (geoInfo.lat, geoInfo.lng)

def getAlertCondition(wbgt, regionCategory):
    assert regionCategory in [1, 2, 3], "Invalid region number: " +\
           str(regionCategory) + "." + " It must be 1, 2 or 3."

    if regionCategory == 1:
        if   wbgt > 86.1: condition = "Extreme"
        elif wbgt > 84.1: condition = "High Risk"
        elif wbgt > 81.0: condition = "Moderate Risk"
        elif wbgt > 76.1: condition = "Less than Ideal"
        else:             condition = "Good conditions"
    elif regionCategory == 2:
        if   wbgt > 89.7: condition = "Extreme"
        elif wbgt > 87.7: condition = "High Risk"
        elif wbgt > 84.6: condition = "Moderate Risk"
        elif wbgt > 79.8: condition = "Less than Ideal"
        else:             condition = "Good conditions"
    elif regionCategory == 3:
        if   wbgt > 91.9: condition = "Extreme"
        elif wbgt > 90.0: condition = "High Risk"
        elif wbgt > 87.0: condition = "Moderate Risk"
        elif wbgt > 82.1: condition = "Less than Ideal"
        else:             condition = "Good conditions"
    return condition
```

```
def maxWbgtHrToHrDuration(maxWbgt):
    maxTime = []
    for key, value in timeToWbgtDictToday.items():
        if value == maxWbgt:
            maxTime.append(key)

    date = maxTime[0]
    shortDate = date[5:10]

    maxTimeHr = []
    for item in maxTime:
        Hr = int(item[11:13])
        if    Hr > 12: Hr = str(Hr - 12) + "PM"
        else:          Hr = str(Hr)      + "AM"
       maxTimeHr.append(Hr)

    maxTimeHrStr = ""
    if len(maxTimeHr) == 1:
        maxTimeHrStr = maxTimeHr[0]
    else:
        maxTimeHrStr = maxTimeHr[0] + " ~ " + maxTimeHr[-1]
    return (shortDate, maxTimeHrStr)

def displayWbgtInfo(date, maxWbgt, maxWbgtHrToHrDuration, alertCondition):
    display = InkyPHAT("red")
    image = Image.new("P", (display.WIDTH, display.HEIGHT), display.WHITE)
    draw = ImageDraw.Draw(image)

    draw.text((0,0),    "WBGT" + " " + date,   display.BLACK, font=fontSmaller)
    draw.text((0, 25),  str(maxWbgt) + "F ",   display.RED,   font=fontBig)
    draw.text((70, 30), maxWbgtHrToHrDuration, display.BLACK, font=fontSmall)
    draw.text((0, 70),  alertCondition,        display.RED,   font=fontSmaller)
    display.set_image(image)
    display.show()


lat, lon = getLatLon()
currentWbgt, timeToWbgtDictToday, timeToWbgtDictTomorrow, timeToWbgtDictWeek = getWbgt(lat, lon)

maxWbgt = max(timeToWbgtDictToday.values())
todayDate, hrToHr = maxWbgtHrToHrDuration(maxWbgt)
alertCond = getAlertCondition(maxWbgt, regionCategory)

displayWbgtInfo(todayDate, maxWbgt, hrToHr, alertCond)
```

This code performs IP geolocation in the **`getLatLon()`** function to retrieve the latitude and longitude of an area where WBGT Tracker is used and passes them to the function **`getWbgt()`**. This function returns the current WBGT and WBGT forecasts (today's, tomorrow's and weekly forecasts) with NDFD.

The Python code extracts the highest WBGT from today's forecast and identifies the duration (from what time to what time) of the highest WBGT with the **`maxWbgtHrToHrDuration()`** function. Then, it determines the heat alert condition for the highest WBGT ("extreme," "high risk," "moderate risk," "less than ideal," or "good") according to a given regional category. The

regional category is set in the **`regionCategory`** variable. Category 1 is used by default, but it can be changed to Categories 2 or 3.

In the end, the Python code calls the **`displayWbgtInfo()`** function to show all the collected data on the e-paper display (Fig. 5). It takes about 15 seconds to refresh the display. As mentioned earlier, the display can keep showing the data even after Raspberry Pi is turned off. You can bring WBGT Tracker to a practice or a match without a power source.

To clear the information displayed, run the following Python code, which is available as **`clear.py`** in the **`code`** folder at [20].

```
from inky import InkyPHAT
from PIL import Image, ImageFont, ImageDraw

display = InkyPHAT()
image = Image.new("P", (display.WIDTH, display.HEIGHT), display.BLACK)
display.set_image(image)
display.show()
```

X. 5 Future Work

WBGT Tracker can be improved further in several ways. Currently, it uses WBGT forecasts from NOAA's NDFD and performs early safety warnings for athletes ahead of their practices or matches. The next step is to perform real-time safety warnings during a practice or match in addition to early warnings. On-site WBGT measurement is required to issue accurate real-time warnings. A challenge here is to develop a compact WBGT meter with, for example, an air temperature sensor, a humidity sensor and a thermistor in a black globe, and integrate it with WBGT Tracker. Most traditional WBGT thermometers on the market are bulky and not that portable like WBGT Tracker.

When on-site measurement is implemented, WBGT Tracker would be able to notify athletes and coaches on the field/court of any sudden rises in WBGT with, for example, alarm sounds and text messages. It can also remind them how often and how long they should take breaks.

Another improvement is to adjust NOAA's forecasts based on where WBGT Tracker is used. Although WBGT forecasts are carefully calculated in NDFD [22], they can be very different from the actual WBGT on particular ground surfaces. For example, in tennis, hard courts are the most common surface type, which is made of concrete and/or asphalt. Both materials absorb heat more and raise air temperature more than natural surfaces [5]. According to recent research findings [23], WBGT measurements on tennis hard courts are higher than a standard WBGT estimate. The difference/error increases proportionally as the estimated WBGT increases. It is nearly 1°C (1.8°F) when the estimated WBGT is higher than 87.8°F (31°C). Therefore, it might

make sense for WBGT Tracker to adjust NOAA's forecast when used for tennis practices or matches on hard courts.

X. 6 Conclusion

WBGT Tracker implements a widely-accepted heat safety policy for outdoor athletes [12] and allows them to be aware of the environmental conditions for their activities. This chapter describes how to set up hardware and software components to build WBGT Tracker. Its Python code is available at [21].

References

[1] S. King, Olympics 2024: How extreme weather could impact Paris games, BBC, June 2024.

[2] British Association for Sustainable Sport, Rings of Fire: Heat Risks at the 2024 Paris Olympics, 2024.

[3] D. J. Casa and R. L. Stearns, Preventing Sudden Death in Sport and Physical Activity. Second edition, Jones & Bartlett Learning, 2017.

[4] National Federation of State High School Associations, Heat Illness Prevention, online course, https://nfhslearn.com/.

[5] N. Raukar and J. Weaver, Heat Illness Prevention – Keep the Marching Band Playing, National Federation of State High School Associations, 2022.

[6] E. R. Nadel, C. B. Wenger, M. F. Roberts, J. A. Stolwijk, and E. Cafarelli, Physiological defenses against hyperthermia of exercise, Annals of the New York Academy of Sciences, Volume 1, Issue 1, 1977.

[7] National Institute for Occupational Safety and Health, Heat Stress – Heat Related Illness, 2022.

[8] C. P. Yaglou and D. Minard, Control of Heat Casualties at Military Training Centers, American Medical Association Archives of Industrial Health, 16(4), 302–316, 1957.

[9] United States Tennis Association, 2018 US Open Tennis Championships Extreme Weather Policy, 2018.

[10] United States Soccer Federation, U.S. Soccer Heat Guidelines, http://www.recognizetorecover.org/environmental.

[11] D. J. Casa, J. K. DeMartini, M. F. Bergeron, D. Csillan, E. R. Eichner, R. M. Lopez, M. S. Ferrara, K. C. Miller, F. O'Connor, M. N. Sawka, and S. W. Yeargin, National Athletic Trainers' Association Position Statement: Exertional Heat Illnesses, Journal of Athletic Training, 50(9), 2015.

[12] A. Grundstein, C. Williams, M. Phan, E. Cooper, Regional heat safety thresholds for athletics in the contiguous United States, Applied Geography. Volume 56, 2015.

[13] National Federation of State High School Associations, Heat Acclimatization and Heat Illness Prevention Position Statement, April 2022.

[14] J. Cates and J. D. Rheeling, Wet Bulb Globe Temperature (WBGT) – Why Should Your School Be Using It?, National Federation of State High School Associations, 2023.

[15] https://www.miaa.net/educational-athletics/sports-medicine

[16] Massachusetts Interscholastic Athletic Association, MIAA Heat Modification Policy, August, 2021.

[17] https://shop.pimoroni.com/products/inky-phat

[18] https://vlab.noaa.gov/web/mdl/ndfd

[19] https://github.com/pimoroni/inky

[20] https://geocoder.readthedocs.io/

[21] https://github.com/HSSBoston/wbgt

[22] NOAA Meteorological Development Laboratory, MDL Leads the Way in Providing Wet Bulb Globe Temperature Forecasts to the Public, 2021.

[23] H. Yamaguchi, T. Mori, H. Hanano, K. Oishi, K. Ikeue, Y. Yamamoto and K Ishii, Using wet-bulb globe temperature meters to examine the effect of heat on various tennis court surfaces, Scientific Reports, 14, 15548, 2024.