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SPATIAL INTERPOLATION OF WEATHER DATA FOR OCCUPATIONAL HEALTH AND SAFETY RESEARCH IN CONSTRUCTION

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Abstract: Weather data help inform the sustainable management of construction workforce. Weather data can be used to predict the level of heat stress faced by workers and inform job rotation. Oftentimes, researchers struggle to obtain authorization from project owners or contractors when it comes to installing on-site weather station for collecting desirable data. Thus, researchers look to alternative data sources. This paper studies two alternative data sources: the weather stations validated by the world meteorological organization (WMO) and those provided by Weather Underground (WU), an online platform from The Weather Company, LLC. Specifically, we selected a project site in Seattle and estimated weather data for the site location on a geographical information system using inverse distance weighted interpolation. Weather data were collected from 35 weather stations within a 100 mile (160 km) radius from the project site through WU. We seek to understand: 1) through the spatial interpolation and for the locations which house the WMO stations, are the weather data derived from localized personal weather stations comparable to those measured by the WMO stations? 2) if they are comparable, for the location which houses the selected project site, are the weather data derived from localized personal weather stations areas comparable to those measured by the WMO stations?, and 3) if they are not comparable, how big is the difference when it is translated into the scale of heat stress? Eventually, our study hopes to develop a robust method to monitor construction workers' level of heat stress at specific project locations through localized weather data.

Keywords: Occupational Health and Safety, Heat Stress, Meteorological Data, Geographical Information System, Spatial Interpolation

1. INTRODUCTION

Weather data are useful in the sustainable management of the construction workforce. For example, temperature, humidity, wind, solar radiation, and atmospheric pressure are all measures that can be used to predict the level of heat stress faced by workers and inform job rotation or break arrangements. Outdoor works are challenging with the increased risk of heat-related illnesses such as heat rash, heat fainting, heat exhaustion, and heat stroke, especially considering the potential of the global climate change (Spector et al., 2014). Bonauto et al. (2005) found that high outdoor ambient temperatures were related with the heat-related illness claims incidence rate among roofing, highway, bridge and street construction workers. To monitor direct and indirect heat indexes, researchers install on-site heat stress monitors or weather stations to collect data. Oftentimes, researchers struggle to obtain authorization from project owners or contractors when it comes to installing on-site heat stress monitors or weather stations for collecting desired weather data. Alternative data sources, such as weather stations located within the same area as the targeted project sites, then become the next pragmatic target. These weather stations, however, could still be quite distanced from the sites and do not reflect the microclimate at the project sites.

Whilst there is no specific guidelines on the use of these alternative sources for occupational health and safety (OHS) research, the U.S. Department of Energy (DOE) provides guidelines on the use of alternative sources of weather data for building energy simulations. For instance, EnergyPlus^{TM}, an energy simulation software funded and developed by the DOE, allows use of the typical meteorological year (TMY) or the World Meteorological Organization (WMO) weather sources within 20–30 miles (32-48 km) from the new or remodeled construction project site (EnergyPlus, 2016). Also, the WMO/TMY weather station source could be used if the elevation of project site does not deviate more than few hundred feet (~30 meters) from the elevation of the weather station (EnergyPlus, 2016). The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) also shared the useful information about which weather station data should be used in the energy simulation programs for the commercial building project to predict energy consumption and costs (Crawley et al., 1998). Based on the inspiration of these building energy simulation researches, the current study investigates whether the WMO/TMY weather data would be applicable to predicting construction workers' heat stress levels.

This study uses two alternative data sources, including weather stations validated by the WMO and those provided by the online platform from The Weather Company, LLC., Weather Underground (WU) at https://www.wunderground.com/. WU provides real-time weather data from the National Weather Service and data collected by platform members' personal weather stations. For proof of concept, this study selected a project site in Seattle's South Lake Union region and estimated the weather data for the site location on a geographical information system (GIS) using inverse distance weighted interpolation and the weather data collected from WU. This study seeks to understand:

- *Research Question 1:* Through the technique of spatial interpolation and for the locations that house the WMO/TMY weather stations, are the weather data derived from nearby personal weather stations statistically comparable to those measured by the WMO/TMY weather stations? (see Figure 1)
- *Research Question 2:* If they are comparable, are the weather data derived from personal weather stations near the project site statistically comparable to those measured by the WMO/TMY weather stations located 10–20 miles (16–32 km) away from the project site? (see Figure 2)
- *Research Question 3:* If they are not statistically comparable, how big is the difference when it is translated into the scale of heat stress? Why is it meaningful to detect the difference regarding to the scale of heat stress?

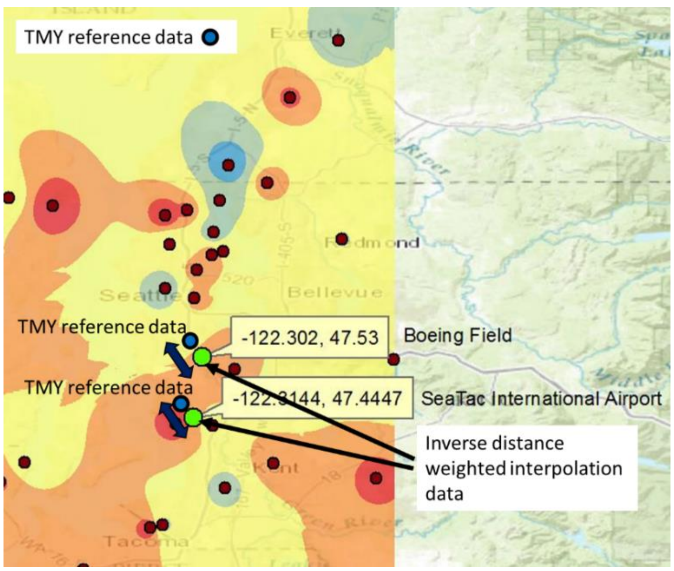

Figure 1: Visualization of the concept of research question 1

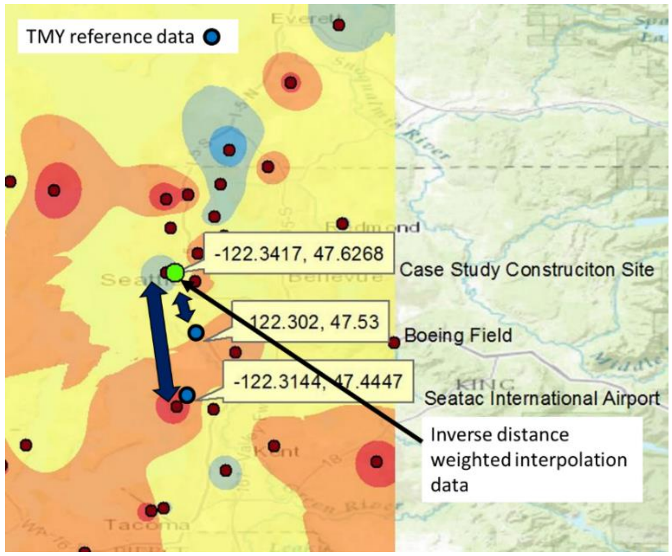

Figure 2: Visualization of the concept of research question 2

2. METHODS

A total of 35 weather stations on the WU platform are within a 100-mile (~160 km) radius of the project site. When extracting data from these weather stations, the following two requirements were considered: 1) the data should cover the duration from June 15 to June 19, 2015, as the authors had also collected actual physiological responses for a small group of roofers (Lee et al., under review) during the same period; 2) weather stations feeding the data should be equipped with solar radiation sensors in order to provide solar irradiation information for Wet Bulb Globe Temperature (WBGT) conversion, which indicates the heat index. The data were collected during the five consecutive days from 7 a.m. to 5 p.m. at 1-hour interval. A total of 55 data samples (=11 samples per day x 5 days) were collected. Inverse distance weighted (IDW) interpolation was applied to estimate five parameters, including the ambient temperature, solar irradiance, wind speed, relative humidity, and atmospheric pressure weather data at the construction site, at Boeing Field, and at SeaTac airport, respectively.

The IDW interpolation is estimated as the Equation 1,

$$[1]\ u(x,y) = \frac{\sum_{i=1}^{n} w_i(x,y)u_i}{\sum_{i=1}^{n} w_i\,(x,y)}$$

,where $u(x,y)$ is an interpolated value at the estimation location, (x, y) is the estimation location, u_i, i=1,…,n, are the locations of the sampling points within the search neighborhood, and n is the number of sampling points. The weights, $w_i(x,y)$, are calculated by the Equation 2,

$$[2]\ w_i(x,y) = \frac{1}{d_i^p}$$

,where d is a given distance, w is a simple IDW weighting function, and p controls how much distance-based smoothing occurs, for which the most commonly used value is 2 (Babak and Deutsch, 2009).

The IDW analysis was conducted with the use of ArcGIS version 10.2.2. The estimated five parameters (i.e., ambient temperature, solar irradiance, wind speed, relative humidity, and atmospheric pressure) were converted into WBGT using Liljegren et al.'s (2008) method. The WBGT is one of the widely-used heat indexes for work and rest regimen planning by the U.S. Occupational Safety and Health Administration (OSHA), the American Conference of Governmental Industrial Hygienists, and the U.S. Military. For hypothesis tests, the following null hypotheses are developed to help answer research questions 1 and 2:

- (1-1) there is no difference between the estimated mean WBGT by the IDW interpolation at Boeing Field and the mean WBGT estimated from reference weather station at Boeing Field,
- (1-2) there is no difference between the estimated mean WBGT by the IDW interpolation at the SeaTac airport and the mean WBGT estimated from reference weather station at the SeaTac airport,
- (2-1) there is no difference between the estimated mean WBGT by the IDW interpolation at the construction project site and the mean WBGT estimated from the reference weather station at Boeing Field, and
- (2-2) there is no difference between the estimated mean WBGT by the IDW interpolation at the construction project site and the mean WBGT estimated from the reference weather station at the SeaTac airport.

Because data are paired through time stamps, a series of paired t-test were conducted at the level of alpha 0.05 for these hypotheses testing. For the statistical analysis, STATA version 13 (College Station, TX, USA: StataCorp LP) was used.

3. RESULTS

In the descriptive statistics for the estimated WBGT at the construction site, Boeing Field, and SeaTac in Table 1, the lowest mean was observed at the construction site located in the South Lake Union area. The means of estimated WBGT and referenced WBGT at Boeing Field were closer (see Figure 3, left), and the means of estimated WBGT and referenced WBGT at SeaTac airport were more distanced (see Figure 3, right).

Table 1: The descriptive statistic for WBGT by IDW interpolation and from the reference weather stations

Variable (WBGT)	Number of samples	Mean (°C)	Standard Deviation (°C)	95% confidence interval (°C)		Mean Difference (°C)
IDW interpolation						
Construction Site	55	17.1	3.02	16.28	17.92	2.7[a]; 1.2[b]
Boeing Field	55	19.7	3.65	18.69	20.66	0.1
SeaTac Airport	55	19.1	3.59	18.11	20.05	0.8
Reference stations						
Boeing Field	55	19.8	3.21	18.91	20.64	
SeaTac Airport	55	18.3	2.97	17.47	19.08	

[a]Note. Compared with WMO station at Boeing Field
[b]Note. Compared with WMO station at SeaTac Airport

The estimated WBGT at Boeing Field, SeaTac airport, and the construction sites show normal distributions. The WBGT from the reference WMO/TMY stations at Boeing Field and SeaTac airport are also normally distributed, but some suspicious outliers with high values of WBGT were observed (Figure 3 and Figure 4).

Because a clear reason for the presence of outliers is unknown in the data analysis process, and because the data point is considered a gold standard measurement, the potential outliers were not removed. The normal distributions of WBGT data from each IDW measurement and gold standard reference met the requirement of the Two-sample t-test.

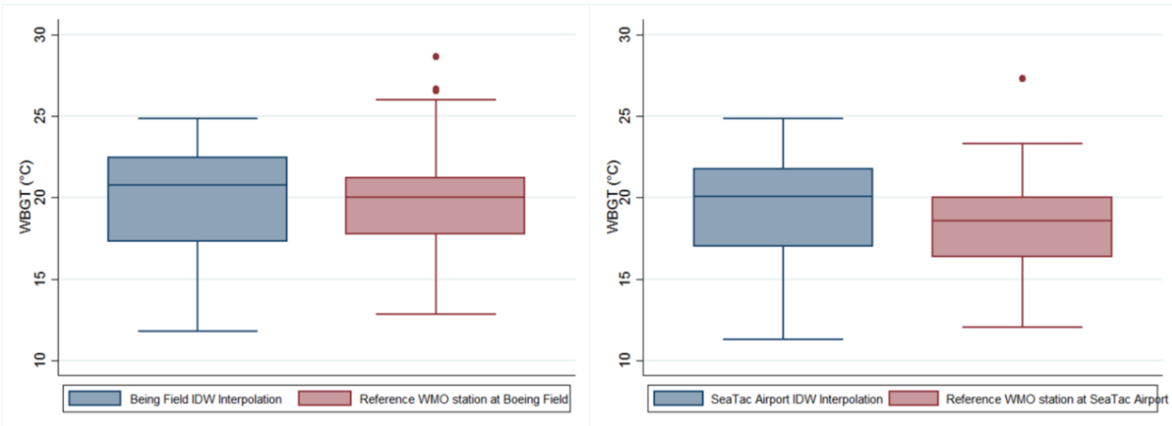

Figure 3: Box and whisker plots for (1-1) and (1-2)

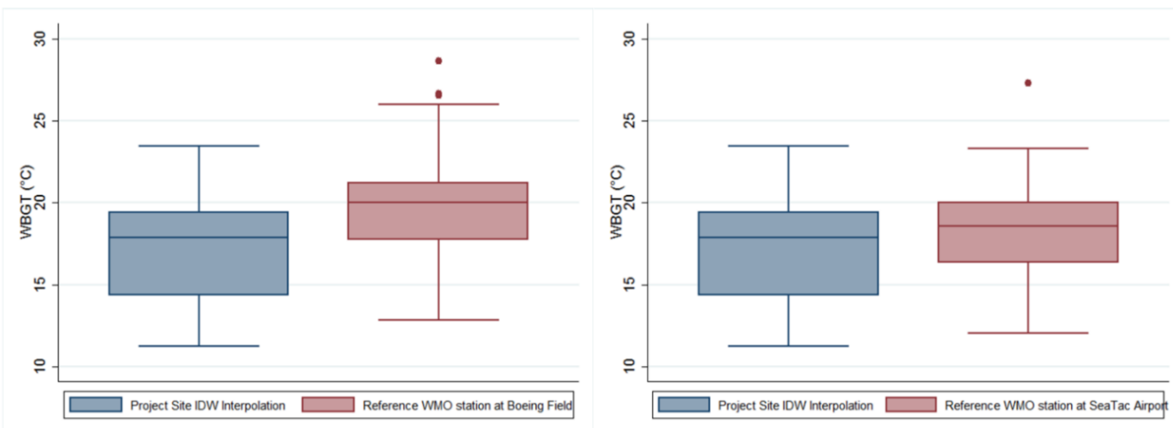

Figure 4: Box and whisker plots for (2-1) and (2-2)

In the hypotheses testing for (1-1) and (1-2), there was no significant difference between the mean WBGT from the reference WMO/TMY data at Boeing Field and the estimated WBGT data by interpolation for Boeing Field ($n = 55$, $t(54) = -0.2794$, $p = 0.7810$). However, there was a significant difference between the mean WBGT estimated from the reference WMO/TMY data at the SeaTac airport and the estimated WBGT based on the interpolation at the SeaTac Airport ($n = 55$, $t(54) = 3.4681$, $p < 0.05$). Regarding the hypotheses testing for (2-1) and (2-2), there were significant differences between the estimated mean WBGT at the case study site and the mean WBGT from the reference weather stations, both at Boeing Field ($n = 55$, $t(54) = -8.2254$, $p < 0.05$) station and the SeaTac airport ($n = 55$, $t(54) = -5.6482$, $p < 0.05$) station. The mean difference of WBGT between the case study site and Boeing Field was approximately 2.7°C. The mean difference in the WBGT between the case study site and the SeaTac airport was approximately 1.2°C.

4. DISCUSSION

The mean difference (2.7° C) in the WBGT between the case study site and Boeing Field was higher than the mean difference (1.2°C) in the WBGT between the case study site and the SeaTac airport. This is potentially because there was a larger difference in the solar irradiance and wind speed at the construction site and Boeing Field (Figure 5).

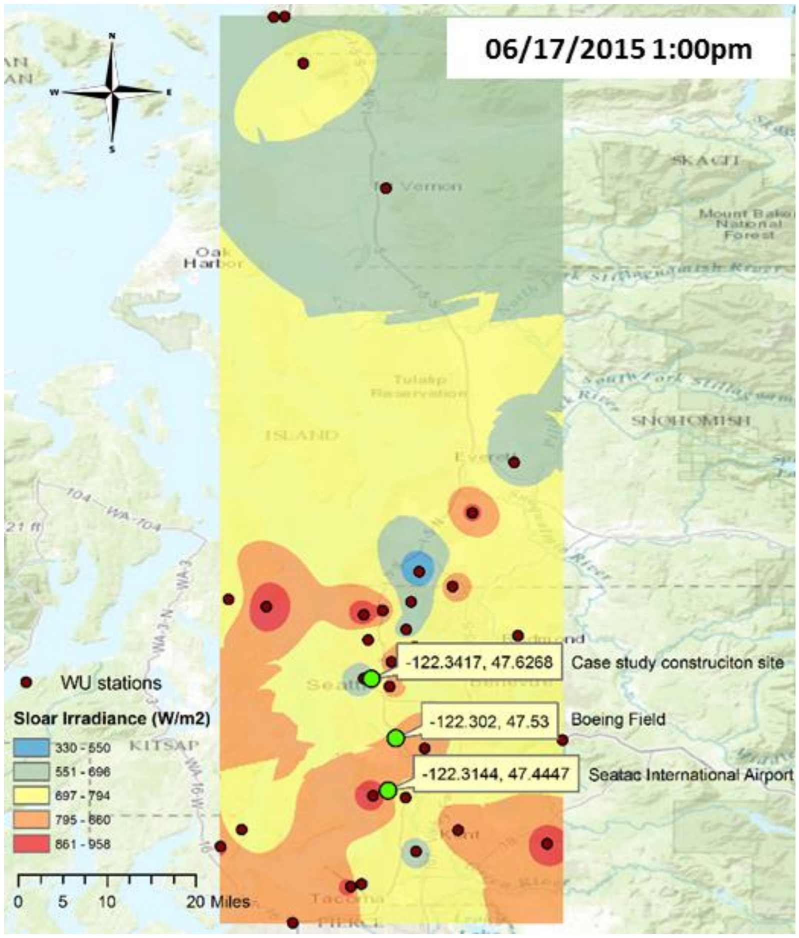

Figure 5: Sample interpolation result for solar irradiance

Higher solar irradiances were observed at Boeing Field and the SeaTac airport. At Boeing Field, the lower wind speed was estimated compared to the construction site and the SeaTac airport (Figure 6). Eventually, lower wind speed and higher solar irradiance led to higher WBGT at Boeing Field.

The analysis results showed that the mean WBGT difference between the estimated WBGT at the project site and Boeing Field WBGT reference data was around 2.7°C. This difference was bigger than the WBGT difference between the estimated WBGT at the project site and the SeaTac airport, around 1.2°C. To investigate whether the 2.7°C (or 1.2°C) WBGT error might underestimate the association between adverse health-related issues (e.g., perceived exertion) and the WBGT, an empirical heat stress model from Chan et al. (2012) was applied for proof of concept (Equation 3). This model looks into construction workers' demographic information, smoking and drinking habits, work duration, and physiological responses and produces a rating of perceived exertion (RPE) based on the Borg CR10 Scale (Borg, 1990) with 1 being "very very easy" and 10 being "maximal exertion". The model can be described by the following formula, where: WBGT was the Wet Bulb Globe Temperature (in °C), T was the work duration (in hours), API was the air pollution index, A was age, PBF was the percentage of body fat (%),DH was drinking habit, SH was smoking habit, EC was energy consumption, RER was respiratory exchange rate, and RHR was the resting heart rate (Chan et al., 2012). DH and SH were measured by three levels of categories: 0 = none, 1= occasionally, 2= usually.

$$[3]\ RPE = -5.43 + 0.11\,WBGT + 1.40\,T + 0.10\,API + 0.06A - 0.07PBF + 2.28DH + 0.50SH + 0.14EC + 0.16RER - 0.01RHR$$

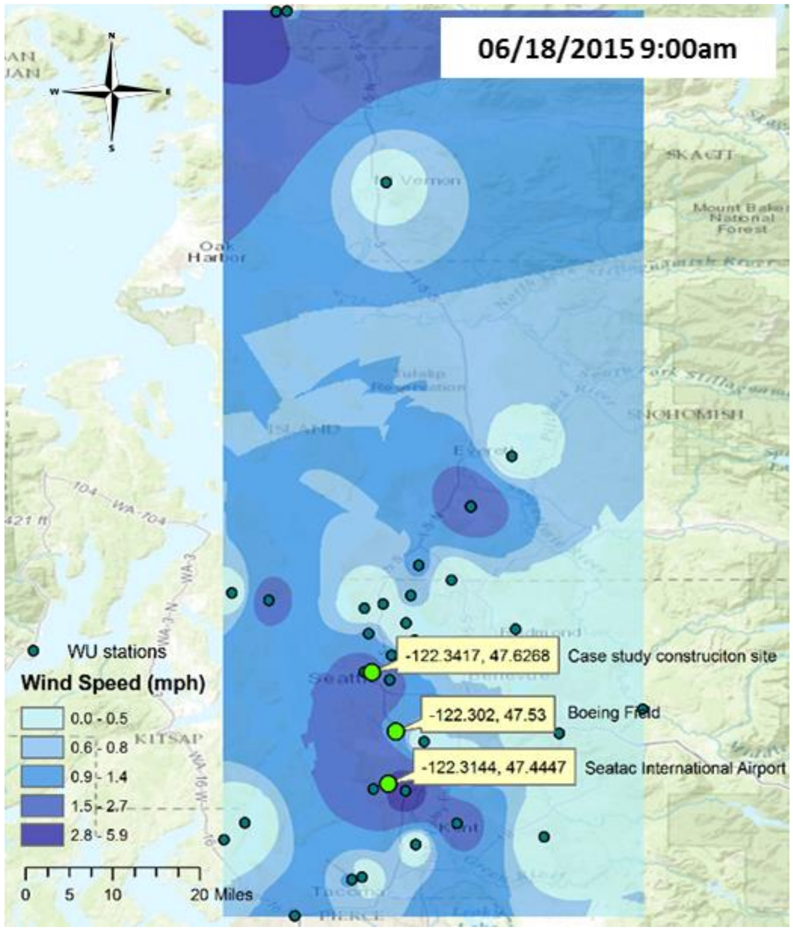

Figure 6: Sample interpolation result for wind

Based on the empirical model investigating the association between the construction workers' perceived exertion and WBGT, the effect of a one-unit increase of WBGT on exertion level was minimal compared to other factors such as the duration of work and alcohol drinking habits. The 2.7°C WBGT difference was also not large enough to move the perceived exertion one level higher.

According to the OSHA work/rest regimen, as shown in Table 2, the level of workload (i.e., light, moderate, or heavy) is another consideration regarding WBGT in deciding the percentage of work and rest for each hour. With a light workload, the lowest WBGT threshold limit value is 30.6 °C (Table 2), which means construction workers performing heavy installation and demolition tasks cannot continuously work if WBGT is over the threshold limit value. Based on the case study, data collected in Seattle presents a very rare chance of recording above 30.6 °C WBGT (Table 1). Thus, the mean 2.7 °C WBGT difference between the estimated WBGT at the construction site and the TMY Boeing Field would not change the work/rest regimen, though the worker would be performing light load tasks. However, the lowest WBGT threshold limit is 25.9 °C, which requires a work and rest adjustment over the permitted continuous work when workers are involved in heavy workload tasks. Thus, the 2.7 °C WBGT difference estimated for the WBGT lower than the reference location could result in a wrong decision about the work/rest regimen. Because construction jobs are categorized as heavy workload operations such as concrete trades (Lee and Migliaccio, 2016), the local-specific weather data should be implemented for occupational health etiology research and decisions about the work/rest regimen, rather than using the reference data points. This conclusion is made based on the authors' priori data analysis that the IDW method is valid to interpolate the local-specific WBGT. Other interpolation methods, such as Kriging modeling (Holdaway, 1996), should be tested for more accurate estimation of the local-specific weather conditions.

Table 2: OSHA work/rest regimen and permissible heat exposure threshold limit value (originally introduced by Lide, 1995)

Work/Rest Regimen	Work Load		
	Light	Moderate	Heavy
Continuous Work	30.0°C	26.7°C	25.0°C
75% Work, 25% Rest, Each Hour	30.6°C	28.0°C	25.9°C
50% Work, 50% Rest, Each Hour	31.4°C	29.4°C	27.9°C
25% Work, 75% Rest, Each Hour	32.2°C	31.1°C	30.0°C

This study found the possibility of using open source weather data from the WU online platform when OHS researchers are not allowed to measure the heat stress level on site. The proposed heat stress computation methods from the weather data have the potential to help industrial hygienists, safety professionals or field supervisors to access the specific localized heat stress index information for planning and task rotation purposes.

The estimated WBGT index from the proposed method is useful for construction workers' safety and health management. Field supervisors should provide on-site drinking water or hydrating drinks in sufficient quantities for workers to maintain adequate hydration status (US Department of Labor, 1999). The measurement and prediction of the heat stress index help indicate when it is necessary to adjust the work schedule, such as moving tasks which require a heavy workload to the cooler part of a day (Plog et al., 1996). If excessive heat stress that causes heat-related illness is predicted or measured, workers should be given space and time to get sufficient rest under the shade or in cool areas (US Department of Labor, 2014). The development of sensors has enabled the measurement of the physiological factors of each individual worker. Heat stress and strain management methods need to consider individual characteristics.

5. LIMITATIONS AND FUTURE WORK

The objective of the current study was to find a new approach to estimate the WBGT heat index for OHS research, as well as validate the proposed method. Therefore, the scope of this study did not include the subjective/objective level of workers' heat stress monitoring or a prediction model development using the estimated WBGT data as the one independent variable that effects on workers' heat stress level.

The reference WMO/TMY data were collected through a third-party website providing the 2015 data without a monetary budget. However, some of reporting error by the third-party website of the original WMO data source could be the reason for the suspicious outliers observed in Figure 3 and 4. By purchasing and using the official TMY data of the EnergyPlus™ affiliated website—White Box Technologies, Inc. (http://weather.whiteboxtechnologies.com)—the analysis of the current study will be conducted again. In terms of the IDW interpolation, data from weather stations more than 60 miles (~96 km) from the case study site could be excluded from the data analysis. A future study using a different IDW interpolation smooth option will be conducted. More weather station data will be collected, and that data will be investigated regarding how the additional data changes the current study results.

6. CONCLUSIONS

The IDW interpolation for weather data using GIS was a potentially valid method for estimating a construction project site's specific weather conditions and the prediction of heat stress levels from WBGT conversion. At Boeing Field, the estimated WBGT by IDW interpolation and reference weather station were statistically compatible. However, we found that the estimated WBGT by IDW interpolation and reference weather station at the SeaTac airport were not statistically compatible based on paired t-test. There were significant differences between the estimated mean WBGT at the case study site and the mean WBGT from the reference weather stations, both at Boeing Field and the SeaTac airport stations. Further investigation should be conducted to clearly find the reason for any deviations. If the reasons for difference are due to the construction site microscopic weather conditions being different from the open space in airport areas, the facts will support the reliability and standardized methods for weather data interpolation for specific construction sites, and those methods should be developed for OHS research. Eventually, through further studies, we hope to develop a robust method to more accurately monitor construction workers' levels of heat stress at specific project locations using the weather data available through localized sources.

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