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Estimating the magnitude and risk associated with heat exposure among Ghanaian mining workers

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Abstract

Many occupational settings located outdoors in direct sun, such as open cut mining, pose a health, safety, and productivity risk to workers because of their increased exposure to heat. This issue is exacerbated by climate change effects, the physical nature of the work, the requirement to work extended shifts, and the need to wear protective clothing which restricts evaporative cooling. Though Ghana has a rapidly expanding mining sector with a large workforce, there appears to be no study that has assessed the magnitude and risk of heat exposure on mining workers and its potential impact on this workforce. Questionnaires and temperature data loggers were used to assess the risk and extent of heat exposure in the working and living environments of Ghanaian miners. The variation in heat exposure risk factors across workers' gender, education level, workload, work hours, physical work exertion, and proximity to heat sources were significant ($p<0.05$). Mining workers are vulnerable to the hazards of heat exposure which can endanger their health and safety, productive capacity, social well-being, adaptive capacity and resilience. An evaluation of indoor and outdoor Wet Bulb Globe Temperature (WBGT) in the working and living environment showed that mining workers can be exposed to relatively high thermal load, thus raising their heat stress risk. Adequate adaptation policies and heat exposure management for workers are imperative to reduce heat stress risk, improve productive capacity and the social health of mining workers.

Keywords: Adaptation strategies, Ghana, Heat exposure, Mining workers

1. Introduction

In general, excessive heat exposure risks have been identified in many occupational settings, including agriculture, oil and gas, construction, manufacturing, firefighting, military and mining (Dutta et al., 2015; Xiang et al., 2014). The risk of heat exposure denotes the likelihood of heat-related hazards (e.g. illness and injury) to workers as the consequence of heat exposure in an occupational setting (see Aven & Renn, 2009; Nunfam & Afrifa-Yamoah, 2021). The health, safety, productivity and social well-being of various workers in these occupational environments are increasingly under serious threat due to extreme heat exposure. The impact of heat-related illnesses, injuries, and reduced productivity among workers due to workplace heat exposure is being aggravated by the current trend of rising heat stress in Ghana, which some scholars have arguably attributed to global warming and climate change (Kjellstrom et al., 2016a; Kjellstrom et al., 2016b) related to anthropogenic-induced increases in greenhouse gas (GHG) emissions (United Nation Framework Convention on Climate Change (UNFCCC), 2010). Under conditions of GHG-based global warming, intensifying temperature and perhaps increasing relative humidity (RH) outdoor workers are more frequently exposed to excessive heat events, of longer duration during the hot season in tropical areas. The need to combat excessive heat exposure as a global risk phenomenon to environmental well-being and human subsistence, including workers, has been expressed in the 2030 Sustainable Development Goals (SDGs) (Leal Filho et al., 2018; United Nations (UN), 2015).

The global climate is increasingly experiencing hotter and humid conditions, especially in the tropical and sub-tropical regions of the world. Notably, since the 1850s, average global temperature has increased by 0.6 ± 0.2 °C and is anticipated to further escalate by between 1.4 °C and 5.8 °C in 2100 (IPCC, 2014b; WMO, 2021). Furthermore, on the continent of Africa, the average temperature has increased by approximately 0.7 °C since 1850s and is estimated to increase more rapidly during the remainder of the 21st Century (IPCC, 2014a). Similarly, Ghana is characterised by high temperatures with the average annual temperature variation ranging between 24 °C to 30 °C and yet temperatures can be as low as 18 °C and high as 40 °C in the southernmost and northernmost parts of Ghana, respectively (Asante & Amuakwa-

Mensah, 2015). Following the 1960s, Ghana has experienced an average increase in temperature of 1.0 °C, which is expected to increase further to 2.0 °C by 2050 (Government of Ghana, 2013, 2015). Changes in temperature and humidity are critical variables in assessing the extent of human heat exposure risk and its implications for human comfort, safety, health, productivity, and social well-being (Kjellstrom et al., 2016b; Steadman, 1984). High humidity and temperature conditions hamper the body's natural thermoregulation response and subsequent increases in core body temperature. Under extreme heat exposure conditions when the human body exceeds its tolerable heat range (35 - 37 ºC) it loses its temperature regulatory capacity of sweating, which is a life-threatening condition (Crimmins et al., 2017). The health risk to individuals is exacerbated through the added effects of dehydration and if the high thermal load continues during the night. This is particularly relevant in a developing world context where people do not have access to adequate air conditioning at night and so they remain under heat stressful conditions, even while at rest (Arundel et al., 1986; Kjellstrom et al., 2018).

The mining industry has significantly contributed to socioeconomic growth and development in Ghana. The sector has increasingly served as a key source of generating internal revenue, foreign exchange and employment in Ghana (Bank of Ghana, 2018; Ghana Revenue Authority, 2018). The large-scale mining (LSM) sector, which is dominated by multinational organisations, recorded increased employment from 10,503 workers in 2016 to 11,628 in 2017 (Ghana Chamber of Mines (GCM), 2018). The small-scale mining (SSM) sector is commonly operated informally by local people with inadequate technology. The SSM sector directly employs an estimated one million people and has provided indirect support for nearly 4.5 million people (McQuilken & Hilson, 2016).

Considering the importance of the mining industry to socioeconomic development, the risk of occupational heat exposure to workers as heat stress levels at workplace intensifies due to global climate change should not be marginalised. LSM activities are conducted under well-managed occupational health and safety management systems which require workers to wear restrictive protective clothing for extended work shifts in hot and humid work environments either under the sun, close to heat radiating operational equipment or underground. SSM is informal with scant regard for the occupational health and safety of miners, it is also commonly characterised by heavier physical work as processes are not mechanised, workers also often have limited access to water and medical care. However, these miners generally work less hours and wear cooler clothing. During the summer months all Ghanaian miners work under hot and humid conditions and generally their living environments are also hot, thus they are not afforded an opportunity to cool down adequately at night. Mining workers in tropical developing countries like Ghana are more vulnerable to heat exposure and SSM in particular are faced with adaptation barriers (Nunfam et al., 2020). The consequences of this include, but are not limited to, heat-related illnesses, injuries, mental impairment, reduced productive capacity and social ill-health. Occupational heat stress also diminishes mental concentration and increases the risk of accidents and injuries (Bridger, 2003; Ramsey, 1995; Richards & Hales, 1987).

In the context of Ghana, few local studies have focused on investigating the trend and impact of heat exposure risk on outdoor workers in a given locality (although an exception is the study of farmers in Bawku East of Northern Ghana by Frimpong et al., 2017). Notably, local knowledge of the risk and magnitude of heat exposure in the working and living environment due to increasing temperature and relative humidity on mining workers in Ghana is not available. Moreover, the extent of heat exposure risk and impact may vary according to the type of workers and their background characteristics (Nunfam et al., 2019b; Nunfam et al., 2019c). The consequence of this can be inadequate execution of suitable and effective heat exposure policies in occupational settings (Parsons, 2009). Occupational heat exposure risk is expected to increase as global temperatures and other climate change effects intensify (Kjellstrom et al., 2009). Therefore, the essence of this study to incorporate local perspectives of heat exposure magnitude and risk is worthwhile (Alexander et al., 2011; Klein et al., 2014; Orlove et al., 2010; Riedlinger & Berkes, 2001). There are several scientific, ethical and practical justifications for our considerable use of local knowledge in this study. Scientifically, local knowledge of heat exposure risk contributes to our understanding of the patterns and variability in such risks across the globe and help fill gaps in critical observational data needed for climate change analysis (Roth, 2004; Turnbull, 2002; Wilbanks, 2002). From an ethical viewpoint, personal experiences of heat exposure risk at the local level are a significant source of data for discourse on and evaluation of climate change impacts (Brace & Geoghegan, 2011; Burningham & Obrien, 1994). Understanding people's perceptions of climate change based on heat exposure magnitude and risk from a practical perspective is relevant in providing suitable and locally based social protection, adaptation and mitigation strategies (Becken et al., 2013; Yaro, 2013). Consequently, the study sought to assess the magnitude and risk of heat exposure in the working and living environments on mining workers in the Western Region of Ghana. The study also aimed to test the hypotheses that there is no significant difference in heat exposure risk factors among the demographic and work characteristics of mining workers.

2. Methods and materials

2.1 Philosophy and study design

In the context of the post-positivist research paradigm, the descriptive cross-sectional survey approach was deemed suitable in this study to assess the research problem. Hence, complementary data from several sources, including survey and self-reported responses from workers, and measurement of heat exposure via temperature and humidity data loggers, were used to describe the magnitude of heat exposure and its attendant risk on mining workers in Ghana at a point in time (Creswell & Clark, 2017; Mertens, 2015).

2.2 *Study setting, population, sampling procedure and sample size*

The study was conducted in the former Western Region (now redemarcated as Western North and Western Region) of Ghana, a region well-known for both SSM and LSM operations. An estimated population of over one million mining workers comprising those directly engaged in SSM (McQuilken & Hilson 2016) along with 13 LSM companies that employed 11,628 workers in 2017 (Ghana Chamber of Mines (GCM) 2018). Purposive sampling was used to select eight out of an estimated 177 SSM operators and five out of the 13 LSM companies if they were willing and interested to participate in the study. Given the selected mining companies, a sample size of 384 mining workers comprising various categories of age, gender, educational level, and job position were randomly selected to participate in the study after expressing their interest and consent (Krejcie & Morgan, 1970). The study yielded a response rate of 83.3% because of retrieving 320 out of 384 questionnaires from SSM (161) and LSM (159) mining workers. Survey participants were selected if they were literate (i.e. able to read, write and speak the English language), worked for a licensed mining company, were an adult of above the minimum Ghanaian legal working age of 18 years and competent to give informed consent. Also, at two out of the five mine sites, four mining workers (experienced occupational and environmental hygiene officers) were conveniently selected and these workers aided the project by placing and over-seeing thermal data loggers in representative working and living environments.

2.3 Sources and methods of data collection

Both primary and secondary heat exposure data were used in the assessment of heat stress risk of mining workers in this study. Primary data comprised mining workers' background characteristics, heat exposure risk factors and estimated Wet Bulb Globe Temperature (WBGT) values based on hourly temperature and RH data (October 2017 - September 2018) collected in the Western Region of Ghana. Secondary data included average annual temperature and RH data (1967 - 2017) from two meteorological stations, namely, Sefwi Bekwai and Tarkwa in the Western Region of Ghana (Nunfam, 2019; Nunfam et al., 2019b) and relevant literature related to occupational heat exposure and heat mitigation.

A questionnaire was used to elicit background characteristics and heat exposure risk factors from the 320 respondents. The validated instruments of the High Occupational Temperature Health and Productivity Suppression (HOTHAPS) programme and analogous research studies on heat exposure assessment served as a guide in the design of the questionnaire (Kjellstrom et al., 2009a; Kjellstrom et al., 2009b; Nunfam et al., 2021; Xiang et al., 2015). The self-reported question items centred on respondents' demographics (e.g. age, sex and education), work characteristics (e.g. workload, hours of work, work environment, physical work exertion, and work around heat sources), workplace heat exposure risk, environmental risk factors, work-related risk factors and concerns about workplace heat exposure risk. The adapted questionnaires were pretested in Ghana to ensure its feasibility and clarity, reduce survey bias and avoid ambiguous and leading questions. This study also received ethics approval from the Human Research Ethics Committee of Edith Cowan University (Project # 17487) on 16th August 2017 and the fieldwork was conducted from October 2017 to September 2018, with responses kept confidential and anonymous.

The extent of heat stress risk is inextricably linked to the intensity of workers' exposure to environmental-related heat exposure factors (e.g. temperature and humidity), occupational-related heat susceptibility factors (e.g. workload and working hours) and individual-related vulnerability factors (e.g. age and sex). Considering the hazards of heat exposure to working people, different indices (e.g. Wet Bulb Globe Temperature (WBGT) index, the Universal Thermal Climate Index (UTCI), Heat Stress Index (HSI), heat stress scales, and simple temperature/humidity averages) have been developed for its measurement and validation (Bernard & Pourmoghani, 1999; Brode et al., 2012; Kjellstrom et al., 2009a; Lemke &

Kjellstrom, 2012; Liljegren et al., 2008; Nunfam et al., 2021). These indices are used in measuring the magnitude of outdoor and indoor heat exposure on various cohorts of high risks workers in both temperate and tropical regions of the world (Adam-Poupart et al., 2013; Dutta et al., 2015; Frimpong et al., 2017; Lundgren et al., 2014; Venugopal et al., 2015).

Lascar EL-USB-2-LCD data loggers were used to capture daily records of hourly ambient temperature and RH, and these were used to estimate hourly WBGT indices over a 12-month duration. The WBGT is a widely used index to measure heat stress risk of workers. The Lascar instrument is a battery-powered device equipped with sensors and microprocessors to accurately monitor and record temperature, RH and dew point. It has a long-life lithium battery which permits logging for 12 months with the capacity to record and store many thousands of measurements in the range 0-100% for RH and -35 to +80 °C (-31 to +176ºF) for temperatures (ClimateChip, 2016). Four Lascar EL-USB-2-LCD data loggers were set up to measure temperature and humidity levels in the working and living environments of four mining workers for the period (October 2017 to September 2018). The Lascar sensors were relatively easy to set up and did not need any maintenance over the period of usage in the selected remote mine sites or an external power supply. The Lascar data loggers were used to measure ambient temperature and RH every hour for 12 months (October 2017 to September 2018). Under the trust, monitoring and supervisory care of four selected workers, each Lascar was attached strategically to a convenient but representative setting either indoors (within homes or resting places for workers with cooling systems) and/or in full shade outdoors (e.g. strapped underneath a suitable tree branch or shaded construction) within the working environment (mine site) or at their homes, all without exposure to direct sunshine (Byass et al., 2010). So, in all, four Lascar loggers were deployed, one in each of the following settings: (1) indoor work environment (e.g. office space); (2) outdoor work environment (e.g. mine site); (3) indoor living environment; and (4) outdoor living environment. Time and cost constraints prevented the addition of extra loggers in each of these settings, so the results are used as an indicator of broad WBGT levels and potential for heat exposure in each setting, but are broadly in line with other studies assessing heat exposure of workers (Dapi et al., 2010; Frimpong et al. 2017; Venugopal et al. 2015).

The WBGT index uses four climate-related heat exposure variables (temperature, humidity, air velocity, and radiant heat) based on measures of air temperature (Ta), natural wet bulb Temperature (Tnwb) and globe temperature (Tg). Unlike the other indices, the WBGT is relatively simple, flexible and usable to measure heat exposure conditions. It is also an approved index by the International Organisation for Standardisation (ISO) as being suitable for measuring workplace heat stress (ISO, 1989; Parsons, 2013). Heat exposure studies among various workers in Thailand, India, Ghana, Zimbabwe, Nicaragua and Nepal have used Lascar measurements to effectively approximate WBGT values (Frimpong et al., 2017; Krishnamurthy et al., 2017; Ngwenya et al., 2018: Pradhan et al., 2013). As exemplified in an empirical study of heat exposure on farmers in Ghana, the Lascar was validated and found to have a strong correlation ($r = 0.988$) with the QuesTemp 34 heat stress monitor for the WBGT index (Frimpong et al., 2017). QuesTemp 34 is a standard instrument for accurately measuring WBGT including radiant heat but is very expensive and cumbersome as compared to the Lascar dataloggers which were preferred in this study. However, the magnitude of heat exposure is influenced by variables such as differences in individual work environment (e.g., indoor, in the shade, or outdoor), exposure duration, extent and type of activity, type of clothing and acclimatisation. It also depends on other factors (e.g. age, sex, obesity, and pre-existing health status) of the worker.

2.4 Data processing and analysis

Computer software including Microsoft Excel 2016 and IBM Statistical Product and Service Solutions (SPSS) version 25 were used in data processing and analysis. Descriptive statistics (e.g. mean, standard deviation, frequency and percent) and inferential statistics (e.g. Chi-Square) were used to assess the magnitude and risk of heat exposure on mining workers. The hypothesis related to the difference in heat exposure risk factors among workers with different background characteristics was assessed through the Chi-Square test of independence at a significance level of ($p < 0.05$). Cramer's V was used to measure effect size where significant differences were detected, with the following descriptive categories used (very small: 0.01, small: 0.20, medium: 0.50, large: 0.80, very large: 1.20, & huge: 2.0) (Cohen, 1988; Sawilowsky, 2009).

Validated methods have been developed for calculating indoor and outdoor WBGT from hourly recordings of temperature and humidity sourced from local weather stations (Bernard & Pourmoghani, 1999; ClimateChip, 2016; Liljegren et al., 2008). Hourly recordings of these same data were obtained in the micro-climatic environment of workers by means of Lascar thermal sensors and dataloggers and these data were used to estimate hourly WBGT indices for the 12 month sampling period. The estimated hourly WBGT values were then used to calculate average 24 hour, average daytime (typical shift for workers from 8:00 am - 4:00 pm), daytime maximum (highest WBGT between 12:00 pm - 4:00 pm), and average night-time (8:00 pm - 6:00 am) WBGT for each month and across the 12-month monitoring period in both the working and living environments of the mining workers. As the four Lascar sensors were placed indoors or in full shaded areas outdoors and they could not account for measures of globe temperature, the method for calculating WBGT indoors was the best and most appropriate for all sensors (Bernard & Pourmoghani, 1999). The method states that: $WBGTid = 0.67Tnwb + 0.33Ta$, where indoor wind speeds (*ws*) is estimated at 1.0 *m/s*, natural wet bulb temperature (*Tnwb*) is calculated from dewpoint (*Td*) ($Td = T - [(100 - RH) / 5]$) by iteration, and *Ta* is the ambient temperature (Bernard & Pourmoghani, 1999; Lemke & Kjellstrom, 2012). The WBGT indices were used in conjunction with international standards (e.g. ISO

7243) for the analysis of risk or safe work to determine appropriate and recommended maximum work-to-rest ratio (Table 1) for various kinds of work intensities and type of clothing (ISO, 1989; National Institute of Occupational Health [NIOSH], 1986; NIOSH, 2016).

Insert Table 1 about here

3. Results

3.1 The difference in heat exposure risk factors across the background characteristics of mining workers

Overall, a very high proportion (91.9%) of respondents felt mine workers faced heat exposure risks (Table 2). However, the proportion of respondents reporting that mine workers were at risk of heat exposure was not found to be significantly different between males and females, nor between different age groups or education levels (Table 2).

Environmental-related factors that influenced the risk of workplace heat exposure on mining workers were mostly attributed (by respondents) to the heat radiation from the sun and other sources around the workplace (37.5%), the extent of hot air around the workplace (32.5%), and lack of air movement around the workplace (17.3%). Responses were not significantly different between younger and older respondents, nor between education levels of respondents (Table 2). However, the gender difference in these identified environmental risk factors was statistically significant ($p < 0.05$) with a lower proportion of females identifying air movement as being an important risk factor compared to males (Table 2).

Work-related heat exposure risk factors identified by respondents included the type of physical workload (22.6% responding), duration of working hours (20.3%), duration of rest/break hours (12.9%), access to drinking water (11.5%), and access to shade (11.1%). These responses were not significantly different between age groups, nor education-level groups (Table 2). However, the discrepancy in work-related heat exposure risk factors differed significantly across gender ($p < 0.001$), with a greater proportion of males suggesting access to water and shade as major risk factors, and far more females (proportionally) identying the importance of type of work as a heat risk factor (Table 2).

Overall respondents were mostly very much concerned (69.1%) and moderately concerned (16.6%) about workplace heat exposure risk, with relatively few reporting a little concern (9.7%) and no concern (4.7%). These proportions were not found to differ signficantly by age or gender except by education (P < 0.05)(Table 2).

The differences in heat exposure risk factors across work characteristics of mining workers are shown in Table 3. In terms of reported workplace heat exposure risk, there were significant differences in responses depending on workers' workload ($p < 0.001$), hours of work ($p < 0.05$), and time spent working around heat sources ($p < 0.001$), although effect sizes were relatively small (Table 3). In particular, heat exposure was identified as a greater risk to workers who engaged in heavier work, worked more hours, and were more exposed to heat source(s). However, the variation in workplace heat exposure risk to mining workers across the category of work environment and physical work exertion were not statistically significant (Table 3).

The environmental-related factors which were reported by respondents to influence workplace heat exposure risk differed significantly amongst worker's workload categories (i.e. light, moderate, heavy, or very heavy work), work hours (under 10 hours vs 10 hours and over), physical work exertion (not at all demanding vs very demanding) and and worker's proximity to heat sources (Table 3). However, the differences in identfied environmental-related factors between indoor and outdoor workers was not statistically significant (Table 3).

Respondents views on work-related factors which influence the risk of workplace heat exposure differed across the categories of workload, work hours, physical work exertion (all $p < 0.001$), and worker's proximity to heat sources ($p < 0.05$). However, the difference in reported work-related factors between indoor and outdoor workers was not statistically significant (Table 3).

Finally, respondents were significantly more concerned about workplace heat exposure risk where they engaged in heavier work ($p < 0.05$). However, concern levels were not signficantly different in terms of worker's working hours, work environments (indoor vs outdoor), physical work exertion, and proximity to heat source(s) (Table 3).

3.2 Patterns and magnitude of heat exposure in the working and living environments of mining workers

In the context of the ambient air conditions experienced by the four mining workers, the magnitudes of average WBGTs measured across the year outdoors (in the shade) were broadly similar to that measured indoors, (although generally they were 0.2 - 0.5 ºC greater in the outdoor environment compared to indoors (Tables 4 & 5). Similarly, WBGT averages were typically around 0.4 ºC higher in the working environments compared to the living environment (Tables 4 & 5). These results can be explained by the fact that, of the four settings measured, the highest average WBGTs were consistently recorded in the outdoor working environment, although, again, average monthly and yearly values were generally similar across all four settings. As only one Lascar datalogger was employed to measure weather conditions in each of the four settings, differences between settings cannot be statistically tested (and was beyond the scope of the current study); rather results are used to gauge broad levels of typical heat exposure based on the four mining workers. However, the fact that there was reasonable consistency and only subtle differences in average conditions between the settings, suggests heat exposure will be broadly similar irrespective of where workers are located. Inadequate use of cooling systems (e.g. air conditioning and fans) due to frequent and extensive power outages may have resulted in the unexpected higher WBGT within indoor living environment compared to oudoor living environment. Seasonal patterns in average WBGT and exploration of exposure levels are now covered for each of the settings individually.

Insert Table 4 about here

Insert Table 5 about here

Monthly average WBGT (24 hr) in the indoor working environment showed a distinct seasonal pattern with values above the annual mean (27.1 ºC) from March 2018 to May 2018 with a peak (28.1 ºC) in April 2018 during the onset of the major wet season, and lowest WBGT from August 2018 (26.2 ºC) to September 2018 (26 ºC) in the period characterised by a short dry season (Fig. 1). Furthermore, the average daytime WBGT (measured indoors at work during the typical working hours of 8:00 am to 4:00 pm) for each month was at a high (29.3 ºC) in April 2018 and a low (27.0 ºC) in September 2018, while the average night-time WBGT during rest periods (8:00 pm-6:00 am) showed a high (27.9 ºC) and a low (25.6 ºC) in September 2018 (Fig. 1). Thus, seasonal differences in average WBGT were much higher during the daytime compared to night-time. The average daytime maximum WBGT in the indoor workspace (i.e. that measured during at hottest period of the day) per month was found to be highest in April 2018 with 30.5 ºC and lowest in September 2018 with 28.6 ºC (Fig. 1). The seasonal variations in temperature could be explained by the higher frequency of hot and humid weather conditions typical of the March to April period in Ghana.

Insert Fig 1 about here

The level of heat exposure measured as average monthly WBGTs (24 hr, daytime, daytime maximum, and night-time) measured outdoor in full shade of the typical working environment for mining workers is shown in Fig. 2. The seasonal trend in average WBGT (24 hr) outdoors in full shade of the working environment was above the mean (27.5 ºC) from February 2018 to July 2018, with the highest (28.6 ºC) in March 2018, but was lower from August 2018 to September 2018, with the lowest (26.2 ºC) in September. Similarly, the magnitude of average daytime WBGT outdoor per month in the working environment showed higher levels from February 2018 to July 2018, with the highest (29.9 ºC) in March 2018 and lowest (26.9 ºC) in September, while the extent of average night-time WBGT recorded outdoor for each month in the working environment was greater from February 2018 to May 2018 (with the highest average of 28.3 ºC in March 2018) compered to the lowest (25.5 ºC) recorded in September 2018. The period of highest average WBGT occurred during the rainy season while the periods of lowest averages occurred during the period of a short spell of the dry season. In terms of the average daytime maximum WBGT for each month, the highest (32.0 ºC) was recorded in March 2018, and the lowest (27.8 ºC) occurred in September 2018 (Fig. 2).

Insert Fig 2 about here

Figure 3 shows seasonal fluctuations in average monthly WBGTs (24 hr, daytime, daytime maximum, and night-time) in the living indoor environment of the four mining workers. Average WBGT (24hr) indoors in the living environment was above the mean (26.7 ºC) from February 2018 to May 2018 with a peak (27.6 ºC) in March 2018 during the major rainy season, and the lowest (25.3 ºC) in August 2018 during the short spell of the dry season. Similarly, the average daytime WBGT indoors in the living environment was much higher from February 2018 to May 2018, with the highest average daytime WBGT (29.9 ºC) in March 2018 and the lowest day WBGT (26.1 ºC) in August 2018. Conversely, the average night-time WBGT per month was fairly consistent across the year except for 1-2 months (Fig. 3). The average daytime maximum WBGT in the living indoor environment was greatest in March 2018 (monthly mean of 32.0 ºC, which was the equal highest of all settings), whilst the lowest (27.0 ºC) occurred in August 2018 (Fig. 3).

Insert Fig 3 about here

Seasonal variation in average monthly WBGTs recorded outdoors in full shade in the living environment of mining workers is shown in Figure 4. The seasonal trend in the average WBGT (24 hr) outdoors (in shade) in the living environment was above the average (27.0 ºC) from February 2018 to May 2018 (with a maximum of 28.3 ºC in March) during the commencement of the major wet season, and the minimum (25.7 ºC) in August 2018 during the short spell of the dry season. Average daytime WBGT in the outdoor living environment was highest (28.3 ºC) in March 2018 and lowest (25.7 ºC) in August 2018. In comparison, the highest average night WBGT outdoor (shaded) in the living environment was 28.3 ºC in March, and the lowest 25.8 ºC in August 2018. In terms of average daytime maximum WBGT in the outdoor living environment, the highest (28.6 ºC) was recorded in March 2018, and the lowest (26.0 ºC) was recorded in August 2018. Unlike the other settings, there was much greater seasonal variation as well as far greater consistency in WBGT across daytime and night-time. Similarly, the daytime maximum WBGT was not that much greater than the daytime WBGT (Fig. 4).

Insert Fig 4 about here

4. Discussion

Even though heat exposure studies of workers are reported widely, the assessment of risk and magnitude of heat exposure on mining workers in Ghana is locally innovative. The study relied on results of a survey of heat exposure risk factors and 12 months of estimated WBGT indices. This was complemented by relevant literature to assess the extent of risk and magnitude of local heat exposure on mining workers to enlighten heat exposure management and policies in the mining sector in Ghana and other comparable workplace settings (e.g. agriculture, construction, manufacturing, oil and gas) across tropical regions of the world.

4.1 Heat exposure risks of mining workers

Several conceptual and empirical studies have demonstrated that the impacts of heat exposure on workers in various industries, including mining, are due to personal, environmental and occupational risk factors, and commonly manifest as heat-related comorbidities (e.g. heat exhaustion, heat cramps, heat rash, dehydration, heat oedema, heat syncope and heatstroke), injuries and mortality (Hunt et al., 2013; Lucas et al., 2014; Nunfam, 2021; Ryan 2017; Varghese et al., 2020; Xiang et al., 2014; Zare et al., 2019). As corroborated in comparable studies (Frimpong et al., 2017; Nunfam et al., 2019b), the results of our study on mining workers' heat exposure risk awareness, apprehensions and influencing factors consisted of environmental-related risk factors (e.g. workplace ambient temperature, air moisture, air movement and heat radiation), work-related risk concerns (e.g. type of physical workload, duration of work hours, type of protective clothing, access to cooling system, water and shade) and extent of concerns about workplace heat exposure risk. Like other vulnerable occupational settings, heat exposure risk (e.g. heat-related illness and injury) experiences in workplaces commonly affects workers' health, safety, productive capacity, social connectedness, cognitive judgement and, by extension, the overall productivity of the mining industry (Kenny et al., 2020; Kjellstrom et al., 2016b; Nunfam & Afrifa-Yamoah, 2021; Nunfam et al., 2018; Nunfam et al., 2019a).

Relative to present and predicted rises in temperature related to global climate change, the substantial difference in identified heat exposure risk factors (both environmental risk and work-related risk factors) across workers' gender have useful ramifications for the development of policies on workplace heat exposure. Also, the significant difference in the extent of concerns about workplace heat exposure as a risk factor across workers' education levels is an important predictor and contributory factor in the formulation and execution of heat stress management educanunftion through heat exposure-related health and safety information, communication, education and training (Lee et al., 2015). Thus, informed workplace heat exposure policies based on workers' gender and education among other factors (e.g. job tasks, clothing) have the possibility to ensure the effective deployment and holistic use of the social and productive human capital potentials of workers for reduced heat exposure-related illnesses, injuries and fatalities, and increased productivity in the mining sector and other vulnerable occupational settings.

Furthermore, our finding on the significant disparity in heat exposure risk factors across work characteristics (e.g. workload, hours of work, physical work exertion and proximity to heat sources) has the potential to influence mining workers' health, safety, productive capacity, human and social capital improvement, and the extent of workplace heat exposure adaptation and resilience planning (Nunfam & Afrifa-Yamoah, 2021; Nunfam et al., 2019a; Nunfam et al., 2019b). Sustainable productivity of mining does not only depend on access and use of advanced innovative technology but also relies on safe occupational settings and the extent to which the identified work characteristics are managed. Such safe working environments ought to be devoid of heat exposure risk hazards like excessive ambient temperature and humidity, heat radiation, poor air circulation, and inadequate adaptive capacity of workers. Therefore, it is imperative to ensure safer occupational environments by incorporating the identified work characteristics into workplace and national health and safety policies and practices, as well as heat exposure adaptation policies to regulate workload, hours of work, physical work exertion and proximity to heat sources among workers.

4.2 The magnitude of heat exposure on mining workers

Our results on the extent and seasonal trends in the monthly average WBGT (minimum: 25.3 ºC - maximum: 28.6 ºC) from October 2017 to September 2018 are in line with the recorded patterns of Ghana's meteorological data, especially average annual temperatures which generally varies from 24 °C to 30 °C across Ghana (Government of Ghana, 2013, 2015). It also falls within the scale, variability and trend of mean annual minimum temperature (22.5 ºC) and maximum temperature (32.4 ºC) measured from a meteorological station proximate to the study area (Nunfam et al., 2019b). Unlike the brief measurement period (12 months) of average WBGT (24 hr, daytime, daytime maximum, and night-time) across the year of this study, the rise in mean annual temperature and RH (1967 - 2017) in the Western Region of Ghana (Nunfam et al., 2019b) and the upward trend of yearly temperatures and RH from a nearby meteorological data (1961 - 2012) in Bawku East in Northern Ghana were statistically significant (Frimpong et al., 2014). Furthermore, studies of heat exposure on farmers demonstrated a strong association (r = 0.988) in WBGT indices between Lascar data loggers and QuesTemp 34 heat monitoring equipment (Frimpong et al., 2017). The correlated results of WBGT indices from both equipment and the similarity in degree of average temperature and WBGT values for both periods show the reliability, precision and effectiveness of the Lascar EL-USB-2-LCD data loggers in assessing the magnitude of heat exposure.

Based on the Lascar sensors, the estimated WBGT outdoors (27.5 ºC) and monthly average WBGT indoors (27.1 ºC) within the working environment of the mining workers is below core body temperature (37 ºC) (Kjellstrom et al., 2016a). Temperatures of this magnitude have the cooling potential of allowing heat generated in the body to evaporate effectively via sweating (Kjellstrom et al., 2018). However, the level of this average WBGT is reasonably high with potentially harmful heat exposure risk and impact on mining workers' work capacity and performance within such working environments. The tendency for work capacity in the mining sector, which is characterised by moderate to heavy labour intensity, to be reduced when hourly WBGT exceeds 26.0 ºC or become burdensome to perform at WBGT above 32.0 ºC is highly probable (Kjellstrom et al., 2016a).

Similarly, the risk of workers to heat exposure is exacerbated during the hottest part of the day during the hottest months (March to May) when the estimated average daily maximum WBGTs were found to exceed 29.5 ºC in both indoor and outdoor working environments. At these temperatures, mining workers with heavy work intensity are recommended to rest for at least half their working time to avoid heat stress and other heat-related health impacts (Table 1). Further, during these hottest months, the average WGBT across the whole working day exceeds 27.5 ºC for which at least 75% work and 25% rest is recommended for a heavy workload, as long as workers are acclimatised and are wearing light clothing. Moreover, further precautions are required in the hottest part of the day in March - April when WBGT can exceed 32.0 ºC such as mining workers taking longer breaks, drinking adequate water or perhaps not even working at all to cope with this level of heat (Table 1; ISO, 1989; NIOSH, 2016). The experience of high ambient temperatures with humidity can result in conditions beyond human physiological tolerable heat limits (35 - 37 ºC), as the human body no longer perspires to cool down (Crimmins et al., 2017). WBGTs (< 35 ºC) allows adequate evaporation because there needs to be at least a 2-3 ºC gradient between core and skin temperature for heat transfer. However, at core body temperature (above 37 ºC) and skin surface temperature (35 ºC and above) for continued periods coupled with long hours of heavy workload, hyperthermia (e.g. heat exhaustion) can arise (Sherwood & Huber, 2010). Workers with primary health conditions compared to healthy workers were more likely to have reduced heat tolerance because of impaired physiological thermoregulation, which could result in heat-related comorbidities and injuries (Semenza et al. 1999; Kenny et al., 2010). Thus, due to the potential heat exposure risk of relatively high temperature to mining workers, regulation 180 of the Minerals and Mining Regulation of 2012 (L.I.2182) enjoins a mine manager to ensure that the wet bulb temperature at the working environment in the mine does not exceed 32.5 ºC and workers should be provided with longer breaks and reduced working time when the wet bulb temperature exceeds 27 ºC at the minesite (Government of Ghana, 2012). Aside from workload, hours of work and proximity to heat sources, comparable findings of other studies show that work characterised by physical exertion as it pertains to the mining sector becomes unsafe when wet bulb temperatures rise above 32 ºC (Buzan et al., 2015; Liang et al., 2011).

The gravity of the inherently imminent heat stress hazard associated with the findings for mining workers is that WBGT indices were probably underestimated by excluding globe temperature because the WBGT indices were recorded in full shaded area (ClimateChip, 2016). Moreover, most mining work is not only heavy and physically exerting but are done under full sunshine or underground in protective clothing, for more extended hours, and with the aid of machinery and other equipment characterised by heat radiation. Under these circumstances, heat exposure policies without adequate ventilation and cooling systems, shade, acclimatisation programmes, frequent rehydration, appropriate rest/work schedules, measured workloads, and light coloured and cooling garments, mine workers may be highly vulnerable to heat-related illness, injuries and death. For instance, prolonged exposure and continued work at the magnitude of heat levels (27.0 - 32.0 ºC) without caution can results in heat-related illness (e.g. fatigue and heat cramps).

Furthermore, the extent of monthly average WBGT recorded outdoors in the shade (27.0 ºC) and indoors (26.7 ºC) within the living environment tends to affect workers' capacity for adequate rest, sleep and/or relieve from heat stress symptoms. Inadequate rest can affect workers engaged in heavy to very heavy workload to follow the recommendation to work 75% and rest for 25% per hour (See Table 1: ISO, 1989; NIOSH, 2016). This precautionary measure of imposing exposure limits reduces the relatively high risk associated with thermally stressful work and WBGT indices between 22.8 ºC-27.8 ºC which are considered as high risk (Binkley et al., 2002; Coris et al., 2004; Roberts, 1998). Aside the maximum average night-time WBGT indoors (26.7 ºC) of the living environment, our findings on the highest average WBGTs (24hr, daytime, daytime maximum, and night-time) within the indoor and outdoor living environments were above WBGT (27.5 ºC). However, resting environments with maximum WBGT exposure limits (27.5 ºC) for workers engaged in heavy workload are required to have 75% work intensity and 25% break duration as recommended in Table 1 (ISO, 1989; NIOSH, 2016). Similarly, mining companies are mandated by regulation to ensure that the wet bulb temperature at the working environment is not above 32.5 ºC and workers are allowed to observe longer rest hours and working time must be reduced when the wet bulb temperature exceeds 27 ºC in the mine (Government of Ghana, 2012). This cautionary measure prevents extended exposure and continuous work at heat levels (27.0 - 32.5 ºC), which results in fatigue and heat cramps. Notably, midday temperatures were possibly underestimated by 0.2 - 5 ºC because the intensity of heat radiation from the sun was excluded based on methods of WBGT calculations as the Lascar sensors were placed in full shaded areas (ClimateChip, 2016). Also, seasonal variability in the magnitude of average WBGT in the working and living environments showed that the highest monthly average WBGT occurred in the period March to April which is associated with the risk of hot and humid conditions in Ghana. This finding is similar to the seasonal variations of temperature in southern Ghana, where the highest average maximum temperature typically occurred in the period February to April (Ghana Meteorological Agency, 2016).

The adaptation policies and heat exposure management of mining firms ought to consider the scale of average WBGT (24hr, daytime, daytime maximum, and night-time) values, WBGT-heat stress risk levels and the approved criteria for maximum WBGT exposure threshold limits based on work/rest intensity (Table 1) (ISO, 1989; NIOSH, 2016). This has the utmost significance to reduce the risk of mine workers to heat exposure-related illnesses, injuries and fatalities. In most developed economies and large-scale multi-national mining firms, in contrast to most artisanal and small-scale mining companies, the heat exposure policies based on ISO 7243 and NIOSH approved WBGT heat exposure limits are often implemented (Table 1). Such policies are mostly informed by engineering, administrative, education and training, regulatory and social protection strategies as part of adaptation and resilience control measures to reduce the risk and impact of heat exposure on workers as temperature, and climate change intensifies (Kjellstrom et al., 2016b; Lucas et al., 2014).

5. Conclusions and policy recommendation

The intensifying temperatures being experienced with global climate warming in the 21st Century and beyond have the propensity to increase exposure to more intense heat across the world, including in many occupational and living environments. This study provides current and comprehensive local insight on the magnitude and risk of heat exposure on Ghanaian mining workers based on WBGT estimates derived from basic meteorological measurements obtained with the aid of Lascar data loggers for a period of 12 months. The variation in environmental and work-based heat exposure risk factors across workers' gender and the disparity in the extent of concern about workplace heat exposure risk across workers' education levels were significant. The substantial discrepancy in heat exposure risk factors across work characteristics (e.g. workload, hours of work, physical work exertion and proximity to heat sources) has the potential to compromise mining workers' health and safety, productive capacity, social well-being, adaptive capacity and resilience. The Lascar data loggers were reliable and useful in measuring the magnitude of heat exposure precisely and suitably as a cheaper alternative to other methods. The extent of indoor/outdoor average WBGT (24hr, daytime, daytime maximum, and night-time) estimates within the working and living environment of mining workers were relatively high with potential heat exposure risk and impact on mining workers without adequate heat exposure management and adaptation strategies. Hence, a concerted global and local effort at providing adequate and effective adaptation policies and heat exposure management for various cohorts of workers involved in heavy and physically exerting jobs for extended hours in hot and humid conditions is imperative. This will reduce the risk of heat stress, improve productive capacity and performance, and boost the social health, adaptive capacity and resilience of mining workers.

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Conflict of interest

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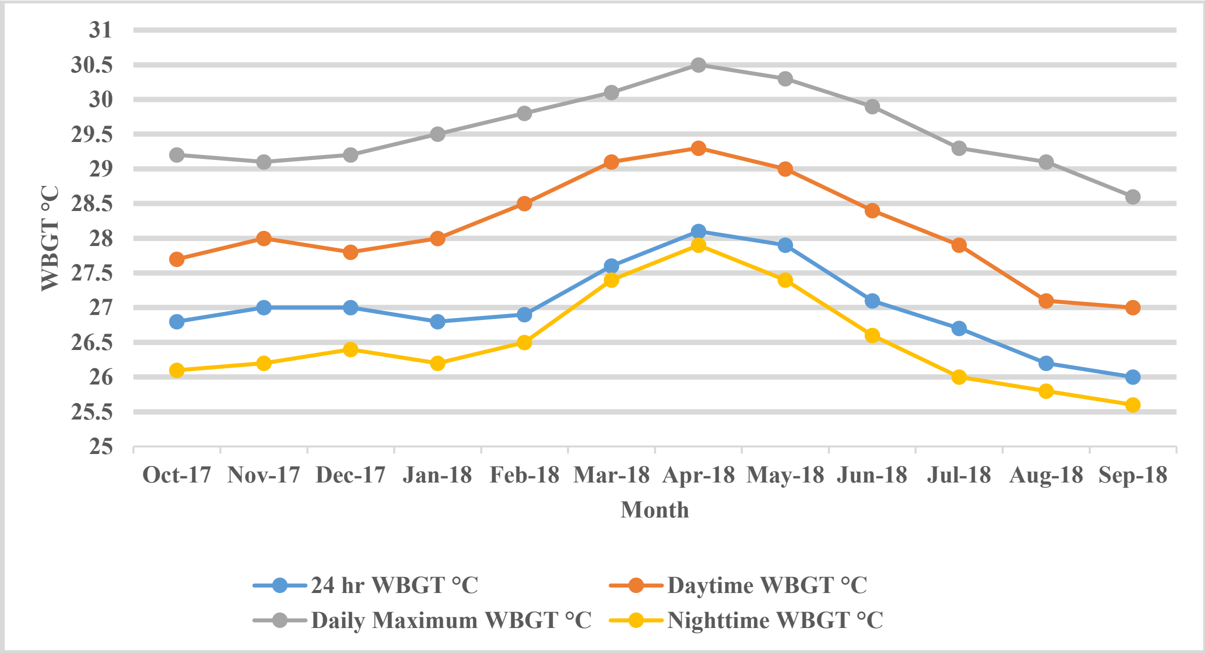

Fig. 1 Average monthly WBGT indoors in the work environment of mining workers

Source: Field survey, 2017-2018

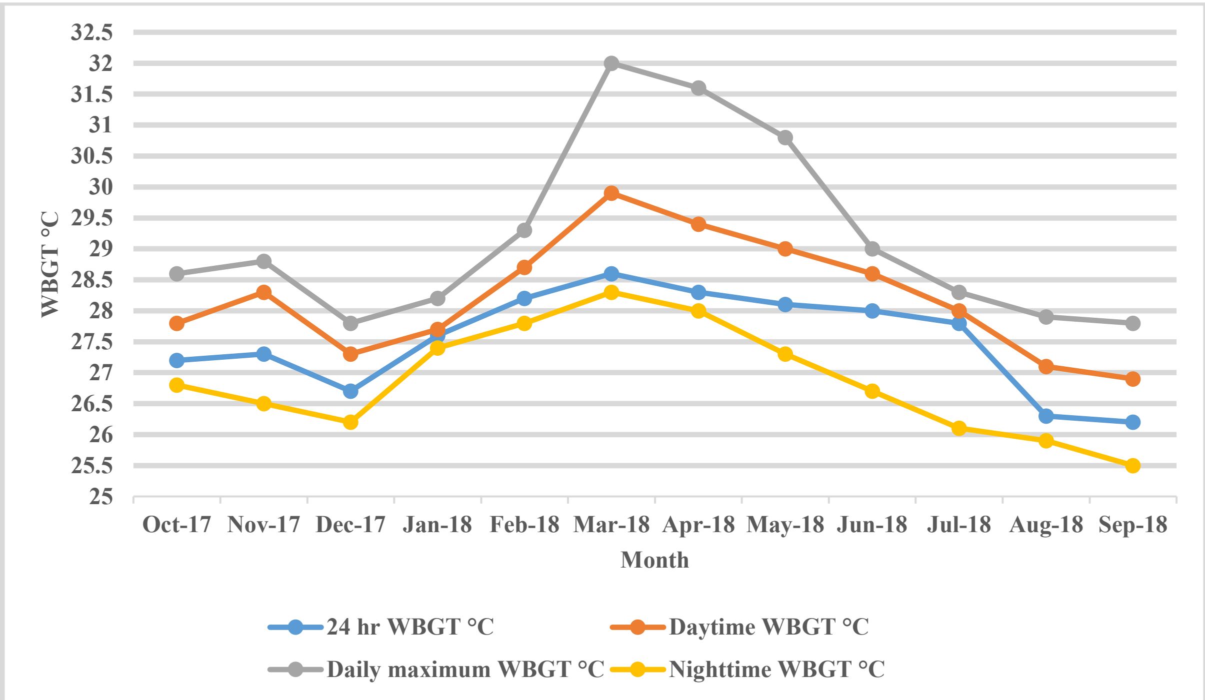

Fig. 2 Average monthly WBGT outdoors in full shade in the work environment of mining workers

Source: Field survey, 2017-2018

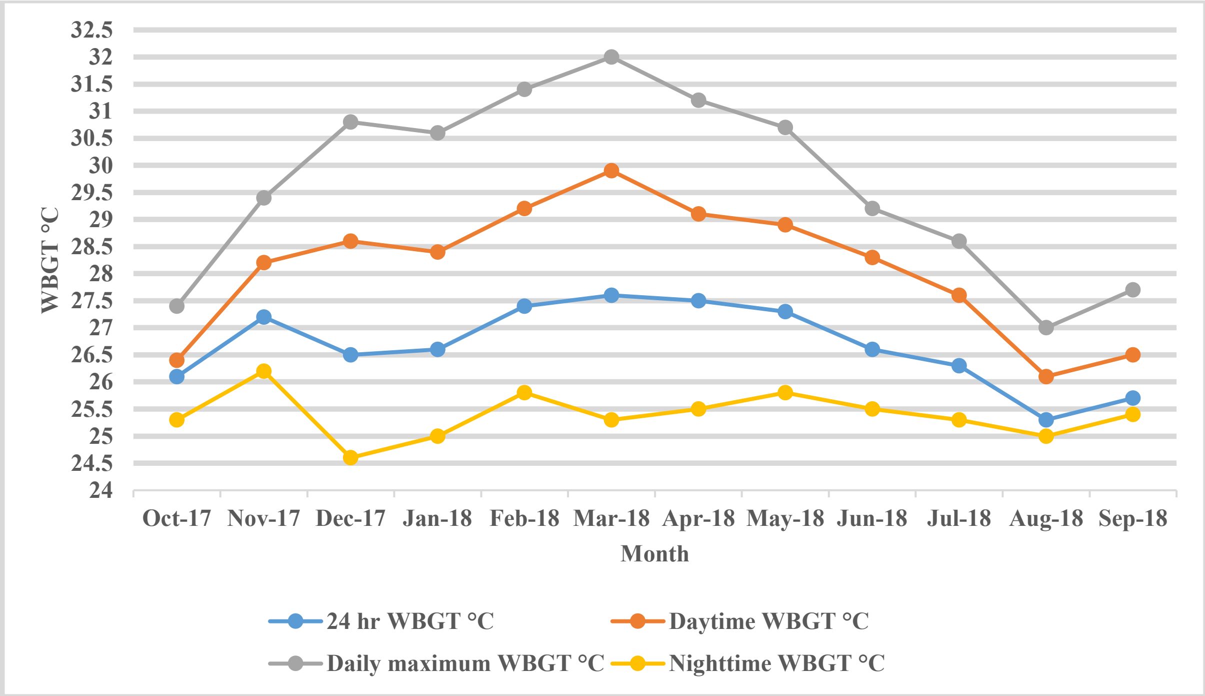

Fig. 3 Average monthly WBGT indoors in the living environment of mining workers

Source: Field survey, 2017-2018

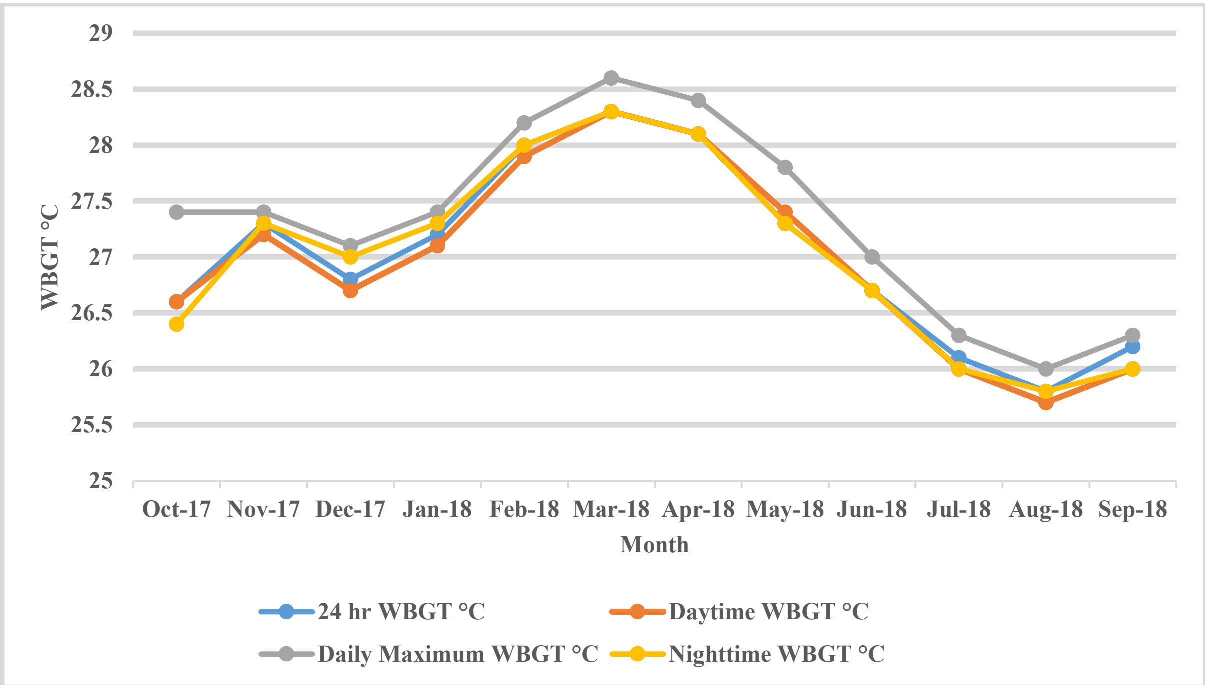

Fig.4 Average monthly WBGT outdoors in full shade in the living environment of mining workers

Source: Field survey, 2017-2018

Table 1. Approved criteria for maximum WBGT exposure limits (° C) based on various work intensities and work-rest proportions for a normal acclimatise worker in light clothing

Work/rest intensity	Workload			
	Light WBGT(° C)	Moderate WBGT(° C)	Heavy WBGT(° C)	Very heavy WBGT(° C)
Continuous work, 0% rest/hour[a]	31.0	28.0	27.0	25.5
75% work, 25% rest/hour[a]	31.5	29.0	27.5	26.5
50% work, 50% rest/hour[a]	32.0	30.5	29.5	28.0
25% work, 75% rest/hour[a]	32.5	32.0	31.5	31.0
No work at all, 100% rest/hour[b]	39.0	37.0	36.0	34.0

[a]Estimates extracted from ISO;
[b]Approved by NIOSH
Source: ISO, 1989; NIOSH, 1986

Table 2. Results of the difference in heat exposure risk factors across mining workers' demographic characteristics (Chi-Square test) (n=320); F=frequency

	Characteristics						
	Age		Sex		Education		Total
Heat exposure risk	Younger (21- 49yrs) F (%)	Older (50 - 61yrs) F (%)	Male F (%)	Female F (%)	Uneducated F (%)	Educated F (%)	F (%)
Workplace heat exposure risk							
Yes	271(91.9)	23(92.0)	235(79.7)	59(96.7)	8(88.9)	286(92.0)	294(91.9)
No	24(8.1)	2(8.0)	24(20.3)	2(3.3)	1(11.1)	25(8.0)	26(8.1)
	$\chi^2(1) = 0.000$, $p = 1.000$		$\chi^2(1) = 1.637$, $p = 0.201$		$\chi^2(1) = 0.000$, $p = 1.000$		
Environmental risk factors (n=542)*							
How hot the air is around the workplace	166(31.1)	10(25.0)	143(31.5)	33(37.5)	6(35.3)	170(32.4)	176(32.5)
The amount of air moisture in outdoor setting/workplace	37(7.4)	6(15.0)	35(7.7)	8(9.1)	1(5.9)	42(8.0)	43(7.9)
Air speed/movement around the workplace	87(17.3)	7(17.5)	83(18.3)	11(12.5)	5(29.4)	89(16.9)	94(17.3)
Heat radiation from the sun and other sources around the workplace	189(37.6)	14(35.0)	169(37.2)	34(38.6)	4(23.5)	199(37.9)	203(37.5)
No response	23(4.6)	3(7.5)	24(5.3)	2(2.3)	1(5.9)	25(4.8)	26(4.8)
	$\chi^2(4) = 1.237$, $p = 0.872$		$\chi^2(4) = 11.242$, $p < 0.05$, Cramer's $V = 0.187$		$\chi^2(4) = 1.641$, $p = 0.801$		
Work-related risk factors(n=738)*							
Type of physical workload	155(22.9)	12(18.8)	133(20.8)	34(34.7)	3(11.1)	164(23.1)	167(22.6)
Duration of working hours	138(20.5)	12(18.8)	133(20.8)	17(17.4)	5(18.5)	145(20.4)	150(20.3)
Type of protective clothing	59(8.8)	8(12.4)	56(8.8)	11(11.2)	0(0)	67(9.4)	67(9.1)
Access to cooling systems (e.g., air conditions & fans)	57(8.5)	7(10.9)	55(8.6)	9(9.3)	1(3.7)	63(8.9)	64(8.7)
Duration of break/rest hours	89(13.2)	6(9.4)	84(13.1)	11(11.2)	7(25.9)	88(12.4)	95(12.9)
Access to shade	76(11.3)	6(9.4)	75(11.7)	7(7.1)	5(18.5)	77(10.8)	82(11.1)
Access to drinking water	76(11.3)	9(14.1)	79(12.3)	6(6.1)	3(11.1)	82(11.5)	85(11.5)
Type of clothing	17(2.5)	2(3.1)	18(2.8)	1(1.0)	2(7.5)	17(2.4)	19(2.6)
No response	7(1.0)	2(3.1)	7(1.1)	2(2.0)	1(3.7)	8(1.1)	9(1.2)
	$\chi^2(8) = 12.505$, $p = 0.130$		$\chi^2(8) = 35.166$, $p < 0.001$, Cramer's $V = 0.294$		$\chi^2(8) = 8.504$, $p = 0.386$		
Concerns about workplace heat exposure risk							
Not at all concerned	12(4.1)	3(12.0)	13(5.0)	2(3.3)	2(13.3)	13(4.2)	15(4.7)
A little concerned	28(9.5)	3(12.0)	22(8.5)	9(14.8)	0(0)	31(10.0)	31(9.7)
Moderately concerned	46(15.6)	7(28.0)	48(18.5)	5(8.2)	0(0)	53(17.0)	53(16.6)
Very much concerned	209(70.8)	12(48.0)	176(68.0)	45(73.7)	7(3.2)	214(68.8)	221(69.1)
	$\chi^2(3) = 6.114$, $p = 0.106$		$\chi^2(3) = 5.743$, $p = 0.125$		$\chi^2(3) = 8.137$, $p < 0.05$, Cramer's $V = 0.164$		

*Multiple responses
Source: Field survey, 2017

Table 3. Results of the difference in heat exposure risk factors across mining workers' work characteristics (Chi-Square test) (n=320); F=frequency

Heat exposure risk	Characteristics: Workload				Hours of work		Work environment		Physical work exertion		Work around source of heat		Total
	Light	Moderate	Heavy	Very heavy	Under 10hrs	10hr and over	Indoor	outdoor	Not at all	Very well	Yes	No	
	F (%)	F (%)	F (%)	F (%)	F (%)	F (%)	F (%)	F (%)	F (%)	F (%)	F (%)	F (%)	F (%)
Workplace heat exposure risk													
Yes	21(100.0)	78(79.6)	115(95.8)	80(98.8)	97(85.8)	197(95.2)	197(93.4)	97(89.0)	52(86.7)	242(93.1)	265(95.0)	29(70.7)	294(91.9)
No	0(0)	20(20.4)	5(4.2)	1(1.2)	16(14.2)	10(4.8)	14(6.6)	12(11.0)	8(13.3)	18(6.9)	14(5.0)	12(29.3)	26(8.1)
	$\chi^2(3) = 29.335$, $p < 0.001$, Cramer's $V = 0.303$				$\chi^2(1) = 7.317$, $p < 0.05$, *Phi*= -0.163		$\chi^2(1) = 1.303$, $p = 0.197$		$\chi^2(1) = 1.893$, $p = 0.116$		$\chi^2(1) = 25.006$, $p < 0.001$, *Phi*= 0.297		
Environmental risk factors (n=542)*													
How hot the air is around the workplace	7(26.9)	33(23.7)	74(39.2)	62(33.0)	68(29.6)	108(34.5)	119(34.4)	57(29.1)	30(40.0)	146(31.3)	162(32.9)	14(28.0)	176(32.5)
The amount of air moisture in outdoor setting/workplace	1(3.9)	15(10.8)	12(6.4)	15(8.0)	18(7.9)	25(8.0)	31(9.0)	12(6.1)	5(6.7)	38(8.1)	39(7.9)	4(18.0)	43(7.9)
Air speed/movement around the workplace	2(7.7)	13(9.4)	28(14.8)	51(27.1)	48(21.0)	46(14.7)	53(15.3)	41(20.9)	4(5.3)	90(19.3)	91(18.5)	3(6.0)	94(17.3)
Heat radiation from the sun and other sources around the workplace	16(61.5)	58(41.7)	70(37.0)	59(31.4)	79(34.5)	124(39.6)	128(37.0)	75(38.3)	28(37.3)	175(37.5)	185(37.6)	18(36.0)	203(37.5)
No response	0(0.0)	20(14.4)	5(2.6)	1(0.5)	16(7.0)	10(3.1)	15(4.3)	11(5.6)	8(10.7)	18(3.8)	15(3.1)	11(22.0)	26(4.8)
	$\chi^2(12) = 84.491$, $p < 0.001$, Cramer's $V = 0.299$				$\chi^2(4) = 48.546$, $p < 0.001$, Cramer's $V = 0.389$		$\chi^2(4) = 4.340$, $p = 0.362$		$\chi^2(4) = 21.679$, $p < 0.001$, Cramer's $V = 0.260$		$\chi^2(4) = 29.672$, $p < 0.001$, Cramer's $V = 0.305$		
Work-related risk factors(n=738)*													
Type of physical workload	16(48.5)	51(24.8)	73(29.6)	27(10.7)	62(19.7)	105(24.8)	113(24.6)	54(19.4)	41(43.6)	126(19.6)	143(21.6)	24(31.2)	167(22.6)
Duration of working hours	3(9.1)	44(21.4)	46(18.6)	57(22.6)	71(22.5)	79(18.7)	95(20.7)	55(19.7)	12(12.8)	138(21.4)	133(20.1)	17(22.0)	150(20.3)
Type of protective clothing	4(12.1)	28(13.6)	22(8.9)	13(5.2)	18(5.7)	49(11.6)	48(10.5)	19(6.8)	16(17.0)	51(7.9)	57(8.6)	10(13.0)	67(9.1)
Access to cooling systems (e.g., air conditions & fans)	4(12.1)	25(12.1)	21(8.5)	14(5.6)	32(10.2)	32(7.6)	36(7.8)	28(10.0)	11(11.7)	53(8.2)	49(7.4)	15(19.5)	64(8.7)
Duration of break/rest hours	2(6.0)	15(7.3)	30(12.2)	48(19.0)	40(12.7)	55(13.0)	53(11.5)	42(15.1)	7(7.5)	88(13.7)	93(14.1)	2(2.6)	95(12.9)
Access to shade	1(3.1)	14(6.8)	22(8.9)	45(17.9)	37(11.8)	45(10.6)	46(8.2)	36(12.9)	5(5.3)	77(12.0)	78(11.8)	4(5.2)	82(11.1)
Access to drinking water	1(3.1)	19(9.2)	24(9.7)	41(16.3)	41(13.0)	44(10.4)	49(10.7)	36(12.9)	2(2.1)	83(12.9)	82(12.4)	3(3.9)	85(11.5)
Type of clothing	2(6.0)	7(3.4)	6(2.4)	4(1.6)	8(2.5)	11(2.6)	12(2.6)	7(2.5)	0(0)	19(13.0)	19(2.9)	0(0.0)	19(2.6)
No response	0(0)	3(1.4)	3(1.2)	3(1.1)	6(1.9)	3(0.7)	7(1.5)	2(0.7)	0(0)	9(1.3)	7(1.1)	2(2.4)	9(1.2)
	$\chi^2(24) = 67.401$, $p < 0.001$, Cramer's $V = 0.250$				$\chi^2(8) = 38.033$, $p < 0.001$, Cramer's $V = 0.338$		$\chi^2(8) = 9.702$, $p = 0.287$		$\chi^2(8) = 28.393$, $p < 0.001$, Cramer's $V = 0.272$		$\chi^2(8) = 15.499$, $p < 0.05$, Cramer's $V = 0.195$		
Concerns about workplace heat exposure risk													
Not at all concerned	1(4.8)	7(7.1)	5(4.2)	2(2.5)	8(7.1)	7(3.3)	12(5.7)	3(2.8)	4(6.7)	11(4.2)	14(5.0)	1(2.4)	15(4.7)
A little concerned	3(14.3)	15(15.3)	9(7.5)	4(4.9)	11(9.7)	20(9.7)	19(9.0)	12(11.0)	7(11.6)	24(9.3)	22(7.9)	9(22.0)	31(9.7)
Moderately concerned	2(9.5)	27(27.6)	16(13.3)	8(9.9)	15(13.3)	38(18.4)	34(16.1)	19(17.4)	10(16.7)	43(16.5)	46(16.5)	7(17.1)	53(16.6)
Very much concerned	15(71.4)	49(50.0)	90(75.0)	67(82.7)	79(69.9)	142(68.6)	146(69.2)	75(68.8)	39(65.0)	182(70.0)	197(70.6)	24(58.5)	221(69.1)
	$\chi^2(9) = 26.675$, $p < 0.05$, Cramer's $V = 0.168$				$\chi^2(3) = 3.291$, $p = 0.349$		$\chi^2(3) = 1.696$, $p = 0.638$		$\chi^2(3) = 1.093$, $p = 0.779$		$\chi^2(3) = 7.065$, $p = 0.070$		

*Multiple responses

Source: Field survey, 2017

Table 4. Descriptive statistics of estimated average WBGT (24hr) from October 2017 to September 2018 measured from Lascar EL-USB-2-LCD data loggers; M=mean (of each month); SD=standard deviation (of monthly data); Min=Minimum (lowest monthly average); Max=maximum (highest monthly average)

Site	Variable	Average monthly WBGT (° C)												Descriptive statistics			
		Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	*M*	*SD*	*Min*	*Max*
Lascar 1: Indoor work environment	WBGT indoors	26.8	27.0	27.0	26.8	26.9	27.6	28.1	27.7	27.1	26.7	26.2	26.0	27.1	0.619	26.0	28.1
Lascar 2: Outdoor work environment	WBGT outdoor in shade	27.2	27.3	26.7	27.6	28.2	28.6	28.3	28.1	28.0	27.8	26.3	26.2	27.5	0.794	26.2	28.6
Lascar 3: Indoor living environment	WBGT in home	26.3	27.2	26.5	26.6	27.4	27.6	27.5	27.3	26.6	26.3	25.3	25.7	26.7	0.732	25.3	27.6
Lascar 4: Outdoor living environment	WBGT outdoor in shade	26.6	27.3	26.8	27.2	28.0	28.3	28.1	27.3	26.7	26.1	25.7	26.2	27.0	0.828	25.7	28.3

Source: Field survey, 2017-2018

Table 5: Descriptive statistics of estimated average WBGT (daytime, daily maximum, and night-time) in the working and living environments of mining workers from October 2017 to September 2018 measured from Lascar EL-USB-2-LCD data loggers; M=mean (of each month); SD=standard deviation (of monthly data); Min=Minimum (lowest monthly average); Max=maximum (highest monthly average)

	Average WBGT (ºC)											
Variable	Daytime				Daily maximum				Night-time			
	M	*SD*	*Min*	*Max*	*M*	*SD*	*Min*	*Max*	*M*	*SD*	*Min*	*Max*
Indoor working environment	28.2	0.738	27.0	29.3	29.6	0.570	28.6	30.5	26.5	0.706	25.6	27.9
Outdoor working environment	28.2	0.931	26.9	29.9	29.2	1.481	27.8	32.0	26.9	0.888	25.5	28.3
Indoor living environment	28.1	1.213	26.1	29.9	29.7	1.694	27.0	32.0	25.4	0.423	24.6	26.2
Outdoor living environment	27.0	0.850	25.7	28.3	27.3	0.842	26.0	28.6	27.0	0.856	25.8	28.3

Source: Field survey, 2017-2018