Industrial Health 2013, **51**, 56–67

Original Article

Mapping Occupational Heat Exposure and Effects in South-East Asia: Ongoing Time Trends 1980−2011 and Future Estimates to 2050

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Received October 16, 2012 and accepted November 7, 2012

Abstract: A feature of climate impacts on occupational health and safety are physiological limits to carrying out physical work at high heat exposure. Heat stress reduces a workers work capacity, leading to lower hourly labour productivity and economic output. We used existing weather station data and climate modeling grid cell data to describe heat conditions (calculated as Wet Bulb Globe Temperature, WBGT) in South-East Asia. During the hottest month in this region (March) afternoon WBGT levels are already high enough to cause major loss of hourly work capacity and by 2050 the situation will be extreme for many outdoor jobs.

Key words: Climate change, Heat exposure, Occupational health, Work capacity, Labour productivity

Introduction

The links between human physiology, climate conditions and effects on health and work capacity have been discussed in detail in physiology and ergonomics texts[1, 2]. High heat exposure creates a risk of heat exhaustion, heat stroke, heat related performance loss, and is subjectively perceived as unpleasant or dangerous[3–5]. People working or involved in heavy physical activity are particularly affected[6–8], because physical activity produces additional intra-body heat that must be dissipated. A natural reaction to heat, by a working person, is to reduce physical activity, which reduces the body's internal heat production[9]. This may be called "autonomous adaptation" to climate conditions[10, 11]. An outcome of this preventive reaction is reduced hourly work capacity, labour productivity, and economic output during exposure to heat[12–14].

An enterprise can compensate for this heat effect by carrying out heat sensitive work during the cooler night hours of the hot season or by scheduling such work into the cooler season, but, as climate change continues, the duration of "cool periods" will diminish. Another factor influencing heat stress is the humidity level that often goes up during night hours reducing the cooling impact. All heat stress indexes, used in human health assessments, combine temperature and humidity into the index[1]. In addition, much work has to be carried out during daylight, which reduces the available "cool hours". For instance, many agricultural workers need to work outdoors in the sun and if their pay is based on their product output, they may work beyond safe heat exposure limits and die of heat stroke, as has happened even in the USA[15].

The mechanisms behind the health and productivity effects of heat have been described in some detail in recent

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reports[9, 11, 16–18] and will not be repeated here. A collection of papers on different aspects of heat exposure at work was published in December 2010 in the journal "Global Health Action" showing relevant examples from different job situations and different countries. In addition, there are indirect health risks caused by increasing heat exposure, such as the increased risk of mosquito biting at dawn and dusk, when agricultural workers have to spend more time outdoors working, if it has become too hot to work during the middle of the day[19].

Climate change will increase average global temperature[20] and bring more super-hot days to highly populated tropical and sub-tropical areas. The increasing temperature of ocean surface water will create more evaporation of water and higher absolute humidity of the atmosphere. These trends will create longer periods of excessive heat exposure for people working outdoors or in non-cooled indoor factories and offices. Research on climate change impacts on occupational health needs to estimate and analyze the heat exposure levels during different parts of the year and day in each location: city, village, province, country, or region. This report shows possibilities to describe ambient climate-related thermal exposures in workplaces in different geographic areas using weather station data and grid cell data.

Methods

We used daily climate data from weather stations (mainly at airports) and monthly grid cell data since January 1, 1980. To describe monthly distributions and trends of heat exposure we used new software that calculates the heat stress index WBGT[21]. Assuming that workplace heat exposure levels are generated from ambient climate conditions, we estimated such levels and trends for non-cooled indoor workplaces (or in full shade outdoors) and outdoor workplaces in the sun.

Weather station data

Daily climate data from NOAA/GSOD (US National Oceanographic and Atmospheric Administration/ Global Summary of the Day) is available from their website free of charge (website: http://www7.ncdc.noaa.gov/CDO/dataproduct). We downloaded every day from 1980 to 2011. The dataset includes: daily maximum, mean and minimum temperature (Tmax, Tmean and Tmin); mean dew point (Td); rainfall; average wind speed; maximum wind speed. Hourly data of the same variables is also available for many of the weather stations (same website).

While the NOAA data base is very up to date and comprehensive, it contains minimal data corrections. Depending on local conditions (e.g. stations being moved, renamed, equipment being replaced, interruptions in recording due to power cuts, upheavals like wars and strikes, etc.) climate data over the 32 yr period considered for this study is incomplete even in some larger cities. Our software only analyses data which has at least 90% of daily data available for a month. So, for each country, a number of weather stations listed in the complete GSOD database on the web may have been excluded to improve the quality of the data we use here.

The GSOD data set contains humidity data, which is fundamental to occupational heat stress calculations. The more limited, but more closely quality controlled, GHCN data set (Global Historical Climatology Network from NOAA) has no humidity data. One study that used an automatic quality assurance system[22] identified less than 1% errors in 1.5 billion climate data recordings from weather stations. We expect the percentage errors in the GSOD data set to be small as well, but, when possible, any outputs should be compared with data from different data sets. This is one reason why we have included the CRU grid cell data in our software and this analysis. The CRU data also provides information on locations where the weather station data is incomplete.

Our study focuses on the ASEAN region (Association of South East Asian Nations) (see the white area in Fig. 1), which is the same area that is called South East Asia in various global climate studies[16]. In Fig. 1 the locations of weather stations we use from the NOAA database are also marked.

In ASEAN our selection from the GSOD database contained 447 weather stations (Table 1), many of which have very limited data series. In this first report on results we only include data from 10 main weather stations with relatively complete data sets for a number of years (Table 1).

Grid cell averaged climate data

We also used global data in 0.5° × 0.5° grid cells (50 km square at the equator), with monthly estimates from the model CRU-3 (University of East Anglia, UK, Climate Research Unit = CRU)[23]. This dataset is available from their website (http://badc.nerc.ac.uk/browse/badc/cru/data/cru_ts_3.10), and it includes every month 1980−2009. This gives: Tmax, Tmean, water vapor pressure/dew point, wind speed, (other variables may be added, e.g. monthly rainfall)[24, 25].

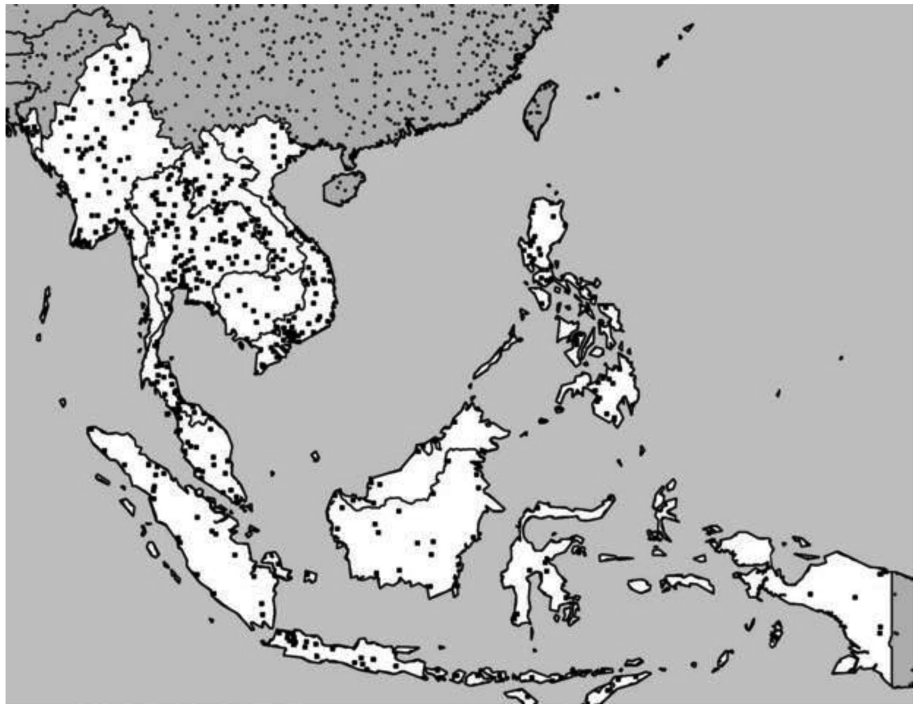

Fig. 1. ASEAN geographic area with locations of NOAA weather stations marked.

Table 1. Number of weather stations included in our database

Country (alphabetical order)	Number of selected weather stations in the GSOD database for this country	Main indicator weather station, years included, % of all days covered
Brunei Darussalam	3	Brunei airport, 1981–2011, 97%
Cambodia	8	Phnom Penh, 1993–2011, 84%
Indonesia	138	Jakarta-Soekarno, 1985–2011, 85%
Lao PDR	20	Vientiane, 1980–2011, 99%
Malaysia	30	Kuala Lumpur Subang, 1980–2011, 98%
Myanmar/Burma	38	Yangon, 1990–2011, 92%
Philippines	69	Manila, 1981–2011, 86%
Singapore	4	Singapore Changi, 1981–2011, 98%
Thailand	137	Don Muang (Bangkok airport), 1980–2011, 99%
Vietnam	37	Hanoi, 1980–2011, 98%

Sites with at least one month of daily recordings during 90% of days; most of them visible in Fig. 1.

We obtained monthly assessments of actual climate data in grid cells for the period 1961 to 2002 for 0.5 × 0.5 degree grid cells (50 km square at the equator)[24, 25]. We also used Global Climate Modelling results (BCM2 model = Bergen Climate Model, version 2; website: openclimategis.org/aps/models/bccr-bcm2.0.html) that had been produced for a WHO project (ENSEMBLES data) by CRU in the United Kingdom[23] including climate variable levels for 0.5 × 0.5 degree grid cells. The data presented here are 30 year averages with 1975 and 2050 as midpoints.

Calculations of heat stress index, WBGT

The basic input data from GSOD on daily mean and maximum temperature (and hourly mean temperatures for indicator weather stations) as well as dew point (a descriptor of absolute humidity) were used to calculate the heat stress indicator WBGT (Wet Bulb Globe Temperature; see ref [1]) using published mathematical formulas[26, 27]. In order to standardise the calculations for indoor workplaces (or in full shade outdoors) it was assumed that wind speed (air movement over the skin) was 1 m/s and there was no heat radiation exposure. This makes the results fit the heat exposure situation for a person who moves around in daily

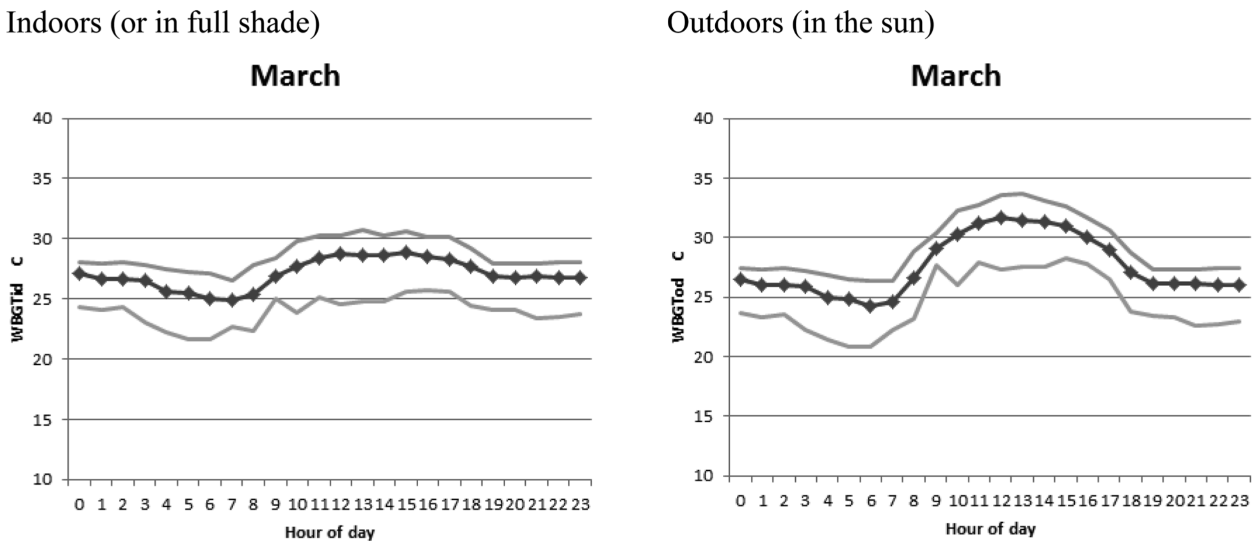

Fig. 2. Calculated average hourly WBGT levels in Bangkok (Don Muang airport) in March 1999; indoors (or in full shade outdoors) and outdoors in the sun.
line with large points in the middle is monthly averages of daily data each hour; line above and below shows the 5th and 95th percentiles of daily data, n=31.

tasks or work and is not exposed to the sun. By using the daily maximum temperature and average dew point, the results represented likely indoors heat exposures in the hottest part of the day in most tropical locations.

Difference between hourly WBGT levels in the shade (or indoors) and in the sun

In order to describe the likely occupational heat exposure levels it is important to make estimates both for indoor levels (or in full shade outdoors) and outdoor levels (in full sunshine). The NOAA weather station data seldom included sun heat radiation (SR) or cloudiness levels. We had the opportunity to link NOAA data on temperature and humidity with a NASA website data on solar radiation (http://power.larc.nasa.gov). Mathematical formulas for calculating WBGT with and without SR data is available[26–28], and we used these formulas with hourly data to calculate the indoor and outdoor WBGT levels for the four hottest afternoon hours (12.00−15.59 h) when the SR is at its highest level (labeled WBGTmax). Calculations were made for the four indicator stations with the most complete hourly data sets available for 1999, as an example of a year within the time range of this study (1980–2011). Fig. 2 shows, as an example, the hourly variation of WBGT in Bangkok. Indoors, the WBGT levels are very stable at appr 28°C during the period 12.00−15.59. Outdoor levels are highest at 12.00, and after that slope down slightly in the range 31.5 − 31°C.

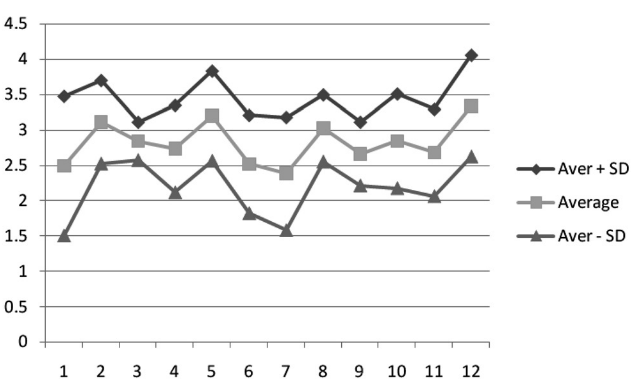

Fig. 3. Differences outdoor minus indoor values of WBGTmax (afternoon values) each month in 1999 as averages of four cities: Hanoi, Bangkok, Kuala Lumpur and Manila.
(averages and range +SD to –SD)

As a preliminary step to the calculation of heat stress indoors and outdoors we compared the outdoor and indoor WBGT levels in the afternoons for each month at the four indicator stations. As Fig. 3 shows, the monthly differences are mainly in the range 2 to 4°C. The annual average difference is 2.6°C. Future climate modelling does not include estimates of SR and cloudiness, so our WBGT estimates are limited to indoor level calculations. We conclude that for our mapping of afternoon heat exposures and the associated work capacity loss calculations, we can add 3°C to the indoor WBGT values as approximate estimates of outdoor values.

Table 2. Heat related work capacity or productivity losses (% loss from 26°C level) at different hourly WBGT levels for moderate (300W) and heavy (400W) labour

WBGT (°C)	< 26	26	27	28	29	30	31	32	33	34	35	36	37	38	>38
Labour, 300W, % loss	0	0	0	3	9	17	25	35	45	55	64	74	81	85	90
Labour, 400W, % loss	0	0	9	17	25	35	45	55	64	74	81	85	88	90	90

300W values based on Wyndham, 1969[12].

Heat related loss of hourly work capacity and labour productivity

While WBGT describes the heat stress, it does not directly quantify the effect of heat stress on working people. Miller *et al.*[29], have shown that provided the worker is not constrained by personal or company requirements, increasing heat stress will trigger a physiological response in the worker to prevent the body core temperature from exceeding safe levels. More rest and slower work means that less work will be done ("self-pacing"), which has a financial impact on the individual, the enterprise he/she works for, the local community, and the region/country[9].

Table 2 shows the labour productivity losses at different WBGT levels described by Wyndham[12] for South African mine workers carrying out "moderate" physical level of work (300W). This dataset is the most detailed available, but other more limited studies support the same concept of heat related productivity loss. The international standard (ISO, 1989)[30] includes a "safety margin" to protect the majority of workers, so those values cause a greater reduction of work loss than the real life studies. We assume that the difference between the acceptable hourly rest/work fractions for moderate (300W) and heavy (400W) labour activity in the ISO (1989)[30] standard can be used to estimate approximately the likely productivity losses in heavy labour jobs (Table 2). We assume that the maximum loss at the highest WBGT is 90%, which means that we assume that 6 minutes of work per hour can still be carried out.

Graphic presentations of results

The new software Hothaps-Soft[21] facilitates presentations of local monthly distributions and time trends of climate conditions. A number of different data presentation outputs are available, including threshold analysis, which shows the number of days above a selected level for any of the climate variables. This makes it possible to describe occurrence of "extreme events".

The monthly grid cell data from CRU is used to compare climate trends for a weather station and the surrounding grid cell. We also use the grid cell data to produce maps over different parts of the world. In this report we have mapped WBGTmax data for March, the hottest month in parts of South-East Asia, and the associated calculated losses of work capacity (maps of other months will be available on the web-site: www.ClimateCHIP.org). Any of the grid based variables can be mapped using a colour pattern to show different levels. In this report we have mapped WBGTmax data for selected months in South-East Asia, and the associated calculated losses of work capacity.

Results and Discussion

Heat conditions; monthly distributions

Figure 4 shows that Don Muang airport in Bangkok is hot all year round, with WBGTmax indoors reaching an average of 26°C in 2007–2011 for all months except December. In all months except November the latest 5 yr averages are higher than in the 1980s. WBGTmax levels indoors in March, April and May reach 30°C, a very high exposure level for any kind of work. The 25th and 75th percentiles are close to the means, and the 5th and 95th percentiles show the broader range for individual days.

The results for the other nine indicator stations are similar except that in Hanoi and Vientiane the differences between the coolest months and the hottest months are greater. The hottest months have similar high levels of WBGTmax at all of the 10 indicator stations.

Heat condition trends

There are many ways to present the time trends of the climate data and heat stress indexes. Only a few examples will be shown here. Figure 5 indicates the upward trend of Tmax, Td and WBGTmax (indoor) recorded at one of the stations (Singapore, Changi airport), and the corresponding values (Tmax and Td) for the CRU grid cell where this station is located. The best fitting line shows that the annual averages of Tmax increase from appr. 31°C in 1980 to 32°C in 2009. The annual average dew point (Td) also increases and the resulting rate of increase of WBGTmax is 0.34°C per decade with a standard error of 0.058°C. So this calculated increase is highly statistically significant

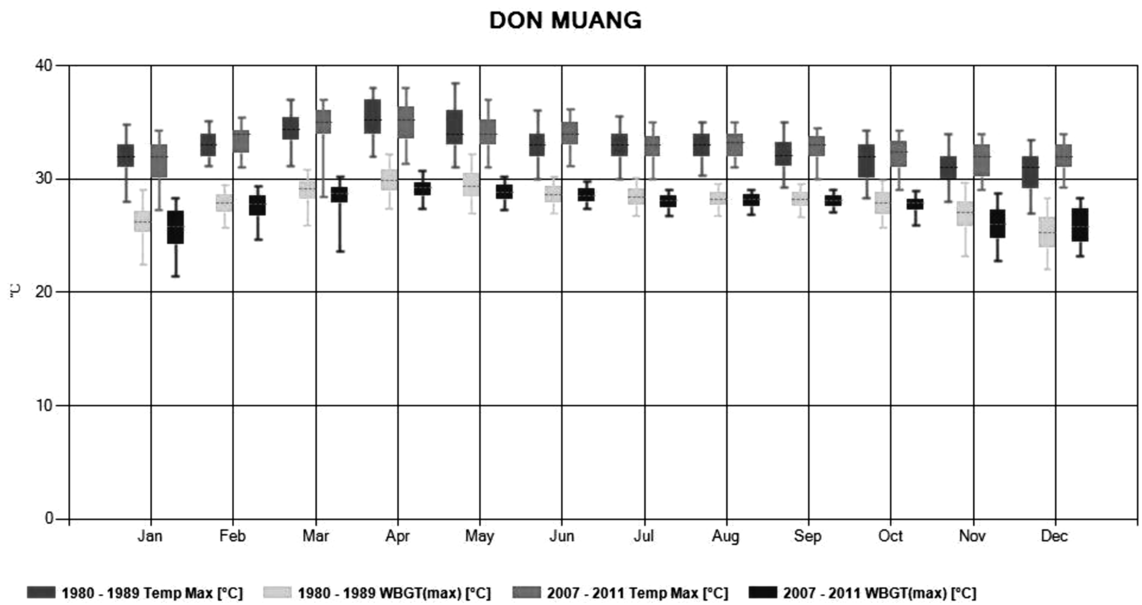

Fig. 4. Monthly average of daily Tmax and WBGTmax (indoors) at Bangkok airport (Don Muang), 1980-1989 and 2007-2011 (°C).

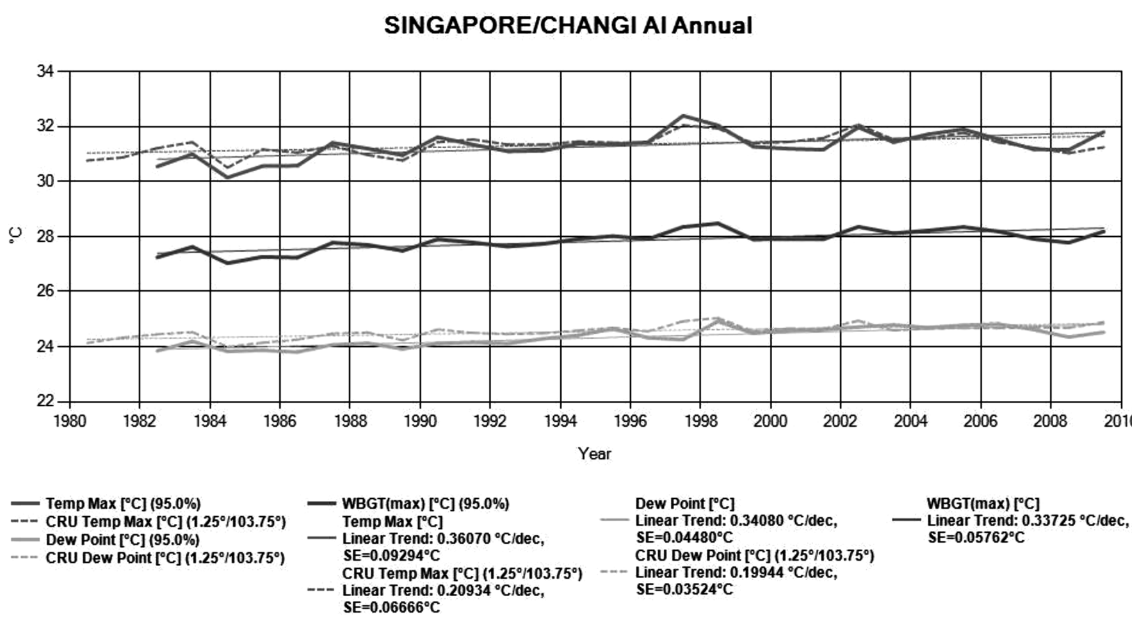

Fig. 5. Annual averages during 1980 to 2009 of daily maximum temperatures Tmax, dew point Td and WBGTmax in Singapore. Linear fitted lines for time trends are also included, showing rate coefficient and its standard error.

Linear fitted lines for time trends are also included, showing rate coefficient and its standard error.

(95% confidence interval = 0.22−0.46°C increase per decade). The WBGT is calculated only from the weather station data, not the CRU data.

Figure 6 shows another way of assessing time trends. Here the number of days each year when WBGTmax is greater than 29°C has been calculated for Singapore airport by Hothaps-Soft.

The number of "super-hot" days ranges from 0 to 116 d, and the large annual variation is likely to be due to major regional climate variations (maybe the ENSO variation). If we fit a line to the data from Singapore, we get an increase of 21 d per decade (from 10 to 70 d within the three decades) with a standard error of 5.4 d (Fig. 6).

In order to assess the overall trends from 1980 to 2009

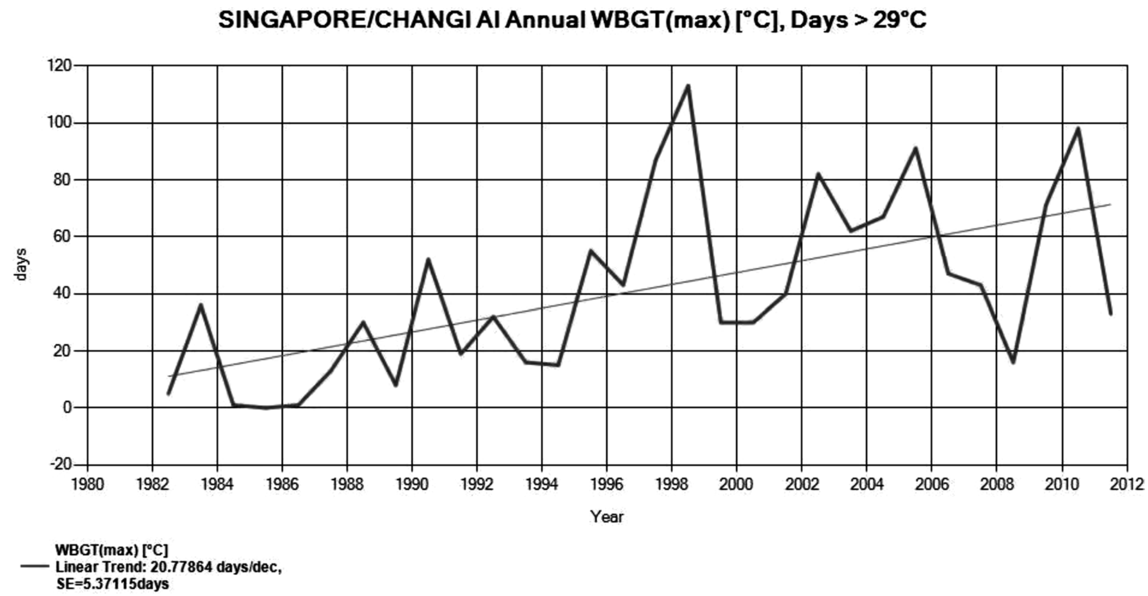

Fig. 6. Annual number of days when WBGTmax (indoors) is higher than 29°C, Singapore.

Table 3. Time trend (increase per decade) estimates for Tmax, Td and WBGTmax, as well as for the number of days when WBGTmax is > 29°C

Country	Main indicator weather station, years included, % of all days covered	Time trends; change °C per decade; 1980–2009					
		Tmax (GSOD)	Tmax (CRU grid cell)	Td (GSOD)	Td (CRU grid cell)	WBGTmax (GSOD)	Trend, days per year when WBGTmax > 29 °C
Brunei Darussalam	Brunei airport, 1981–2011, 97%	0.39*	0.08	–0.07	0.07*	0.16*	9.3
Cambodia	Phnom Penh, 1993–2011, 84%	–	0.29*	–	0.07	(–0.13)	–
Indonesia	Jakarta-Soekarno, 1985–2011, 85%	–	–0.03	–	0.06*	(0.46*)	–
Lao PDR	Vientiane, 1980–2011, 99%	0.09	0.20*	0.06	0.12*	0.07	2.3
Malaysia	Kuala Lumpur Subang, 1980–2011, 98%	0.32*	0.23*	0.02	0.33*	0.17*	36*
Myanmar-Burma	Yangon, 1990–2011, 92%	–	–0.04	–	0.15*	(0.23*)	–
Philippines	Manila, 1981–2011, 86%	0.01	–0.27	0.41*	0.24*	0.19*	15*
Singapore	Singapore Changi, 1981–2011, 98%	0.36*	0.21*	0.34*	0.20*	0.34*	21*
Thailand	Don Muang (Bangkok airport), 1980–2011, 99%	0.30*	0.29*	0.16	0.21*	0.22	17
Vietnam	Hanoi, 1980–2011, 98%	0.64*	0.1	–0.18	–0.001	0.24*	12*

The * identifies values that are statistically significantly > 0. $p<0.05$.

(end year for CRU data) we can compare the trend coefficients (increase per decade) and use two standard errors as the cut-off for statistical significance. Table 3 shows that the trends are often significantly > 0. Some trends are negative, but in none of the stations is the trend negative both for weather station and grid cell data. To interpret the changes of occupational heat stress, the trends for the number of "super-hot" days may be the most important.

Maps of heat conditions and trends

We carried out a detailed analysis using CRU estimates for 1975 (= average of 1961−1990) based on real weather station recordings but expressed in the form of grid cells. As examples we show here maps for the hottest month (March) in parts of this region. Figure 7 shows that in 1975 (baseline year for much climate trend analysis, mean of 1961–1990) indoor WBGT in the afternoons of March were relatively low, but in central Thailand and Cambodia levels above 29°C occurred in some grid cells (but it is cool in March in Vietnam and much of Lao PDR) (maps for other months at: www.ClimateCHIP.org).

The values in the sun (estimated at 3°C higher than indoor values) went as high as 33 degrees in parts of Thailand and Cambodia (Fig. 7).

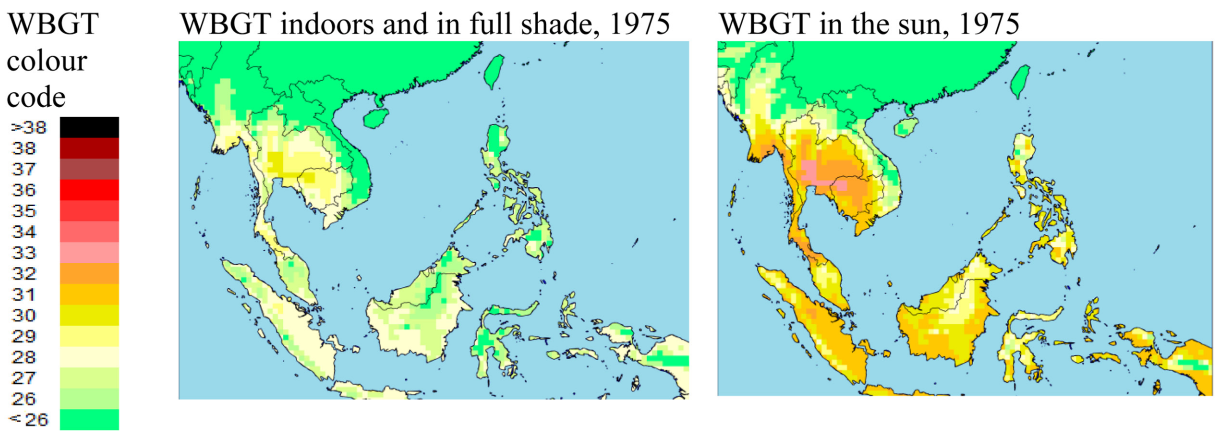

Fig. 7. Maps of WBGTmax (afternoon values) in South-East Asia in March 1975, comparing levels in the shade, or indoors with no cooling, and levels in the sun.

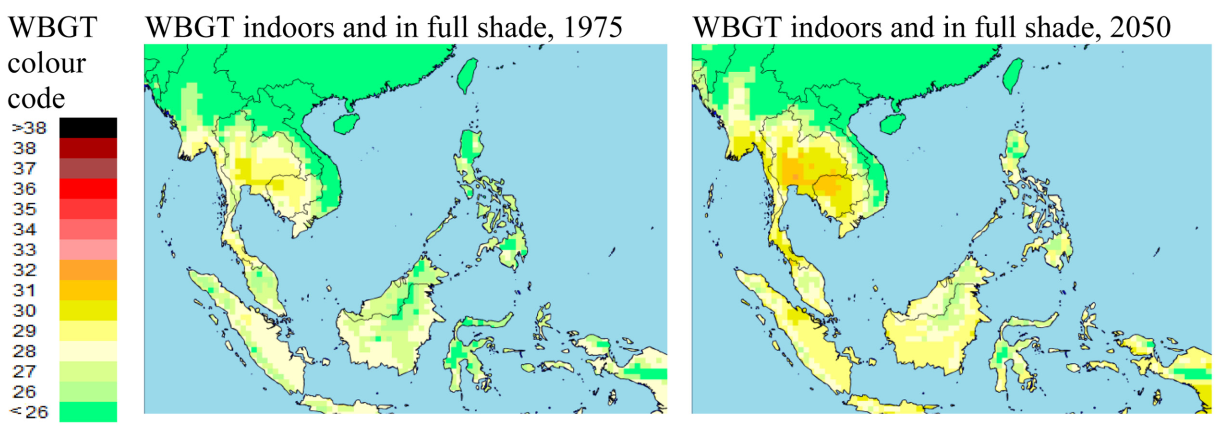

Fig. 8. Maps of WBGTmax (afternoon values) indoors or in full shade in South-East Asia in March, 1975 and 2050.

Then we calculated grid cell estimates for WBGTmax in March 2050 (= average 2035−2065) from the BCM-2 model by CRU. Figurs 8 and 9 show maps indicating the trends. A close analysis shows a few degrees increase of the monthly average WBGTmax in many of the hot parts of South-East Asia during this 75 yr period. We have intermediate data for 2000 and 2030, and these show a continuous trend for most grid cells.

The estimates for workplaces in the sun have some very high levels already in 1975 (Figs. 7 and 9) and when we compare with the estimates for 2050 WBGTmax levels as high as 34–35°C can be seen (Fig. 9). These heat stress levels will certainly be important for local workplaces.

Maps of work capacity and labour productivity loss

We can now apply the grid cell based WBGTmax calculations to assess with the exposure-response relationships in Table 2 the associated reductions in the percentage of afternoon work time that can be fully utilized. Already in 1975 there were some limitations on work capacity in the shade (or indoors) for heavy work (Fig. 10). The limitations are much more pronounced with the higher estimated WBGT levels in the sun (Fig. 10). In the hottest locations 30–40% of afternoon work time is lost in the shade and 60–70% in the sun.

For moderate work (Fig. 11) the restrictions were not so severe in 1975, but in the sun in the hottest locations there is still need for up to 50% of rest during work time in order to keep up production. These outdoor conditions in the sun are likely to affect workers in agriculture and construction in particular.

Finally we show the examples of grid cell distributions of work loss in 2050 based on the WBGT estimates for that year (Fig. 12). Heavy work in the shade is now affected in the hottest areas (in Thailand and Cambodia) so that 50–60% of afternoon work time is lost due to heat.

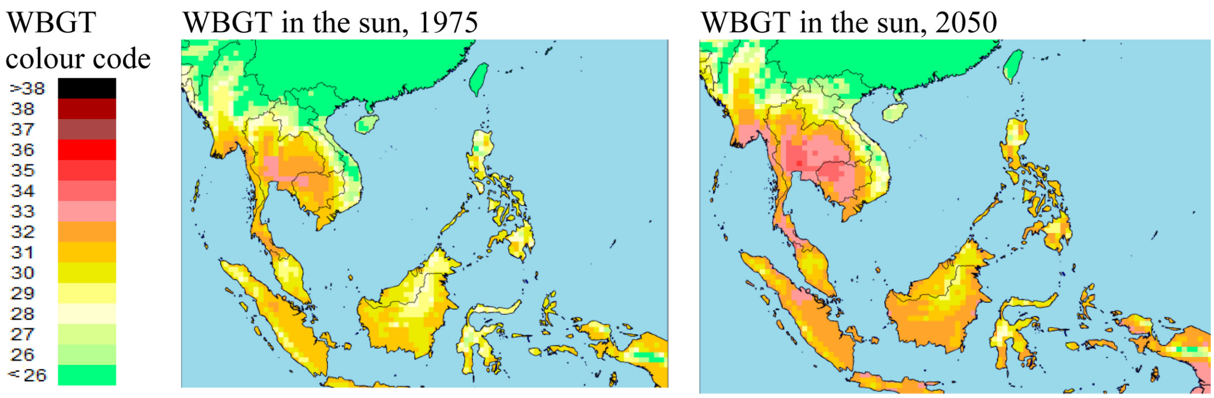

Fig. 9. Maps of WBGTmax (afternoon values) outdoors in the sun in South-East Asia in March 1975 and 2050.

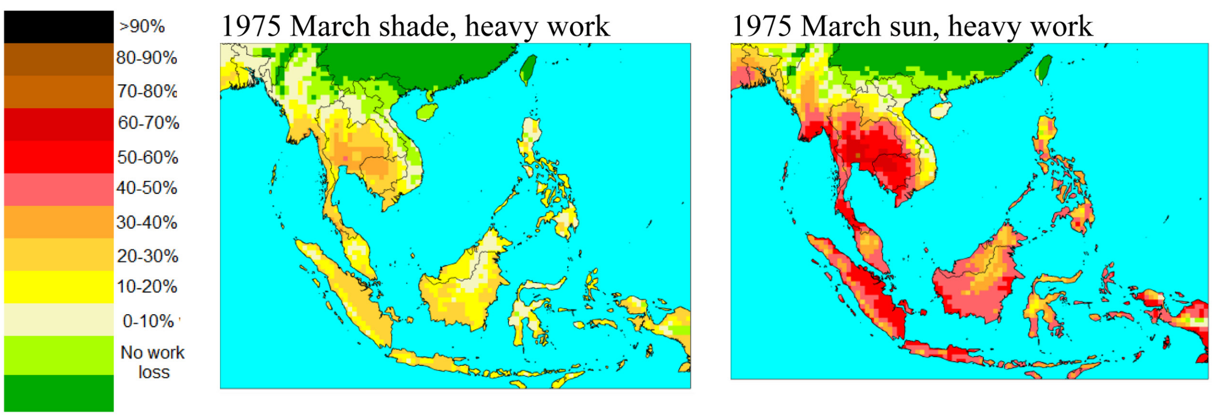

Fig. 10. Maps of "work loss" in percent of available afternoon working hours in March in South-East Asia in 1975; comparison of heavy work (400W) in the shade and in the sun.

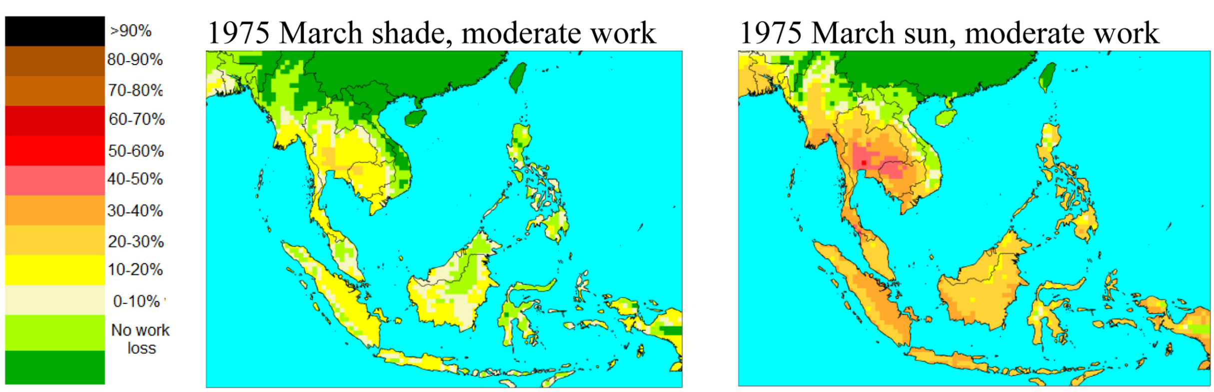

Fig. 11. Maps of "work loss" in percent of available afternoon working hours in March in South-East Asia in 1975; comparison moderate work (300W) in the shade and in the sun.

Heavy work in the sun has losses up to 80% and above, and even moderate work is affected so that more than 50% of afternoon work time is lost.

These examples show the major impact that climate change is likely to have on labour productivity in South-East Asia. If people work beyond the physiological limits they would risk health effects due to heat as an occupational health hazard. We could express the change in work capacity by producing maps subtracting the 1975 grid cell values from the 2050 values, and this will be done in more detailed follow-up analysis of these estimates. We are also able to make maps for each month and to calculate the ac-

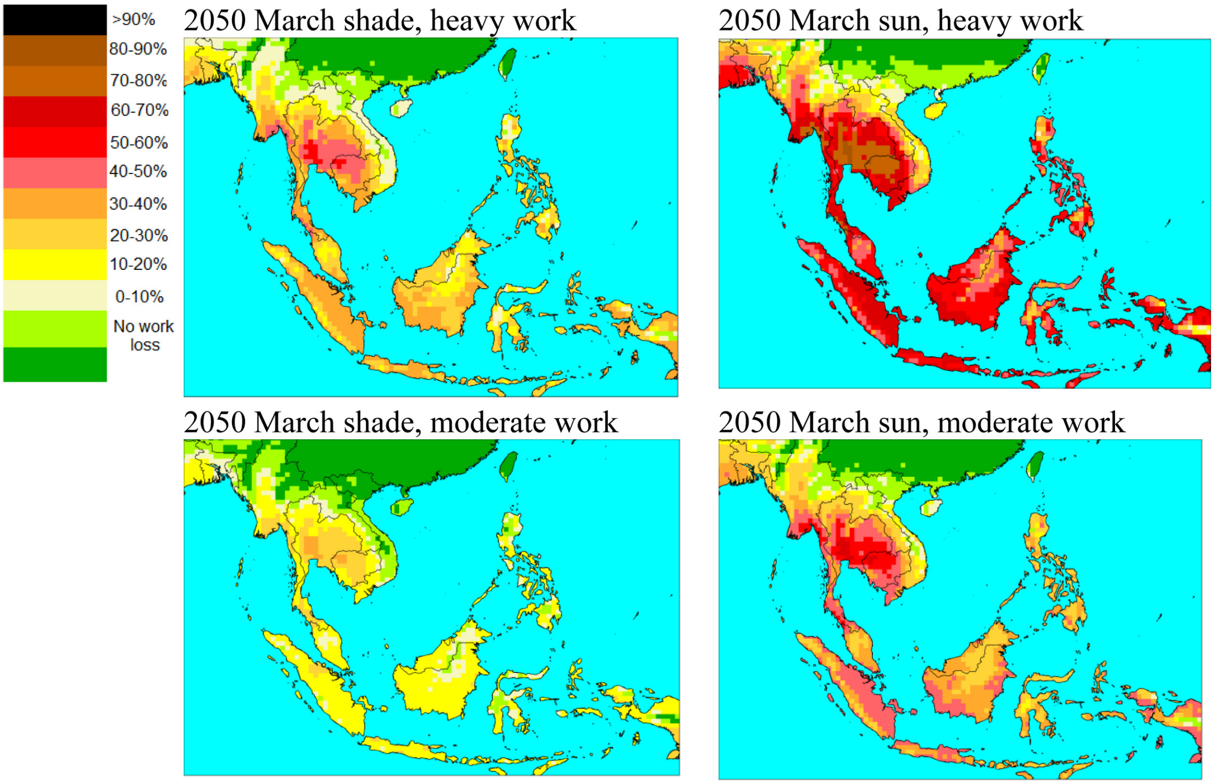

Fig. 12. Maps of "work loss" in percent of available afternoon working hours in March in South-East Asia in 2050; comparison heavy (400W) and moderate work (300W) in the shade and in the sun.

cumulated annual loss of work capacity due to increasing heat (see: www.ClimateCHIP.org).

This type of map analysis can provide important inputs into calculations of the economic impacts of climate change in different countries and regions. We have just shown results for one month here, but with estimates for each of the 12 months in each grid cell we can calculate the annual losses of work capacity for a year in different work situations.

The first global attempt to such economic analysis was published in the Climate Vulnerability Monitor 2012[31)] and the basis was an early version of our estimates of work hours lost[32)]. The results are approximate, but very substantial for the larger countries in the region. The estimates in the Monitor are for 2010 (based on climate change since 2000) and 2030 (based on modeling of continued change). In 2010 the cost in US$ (PPP) of labor productivity losses were 30 billion US$ in Indonesia, 15 billion in Thailand, 10 billion in each of Malaysia and the Philippines, and 8 billion in Vietnam. In 2030 these losses are expected to increase to 250 billion US$ in Indonesia, 150 billion in Thailand, 95 billion in Malaysia and 85 billion in each of the Philippines and Vietnam[31)].

Further research, including health and productivity impact assessments and economic analysis, on this aspect of climate change and health can certainly be motivated by these estimates of the likely work capacity losses. Local and national analysis is needed to take into account not only the local climate conditions, but also workforce composition and cultural and social practices in each community. A major focus is needed on the ways by which current and future workplaces can be made less exposed to the increasing heat. This could involve new architectural designs and efficient use of urban design. Computer modeling of local heat variations can be a useful tool. In addition, the workplace heat exposures create a need for good basic occupational health services that support personal level cooling and rehydration. Work schedules and applications of technology should also be assessed as methods to reduce the heat related occupational health and safety risks.

Conclusions

Occupational heat exposures are important health hazards that are associated with the local climate.

Heat exposures are already high in large parts of South-East Asia, and they will increase as climate change brings more hot days.

The physiological limits to how much heat humans can cope with, in order to avoid serious heat stroke, are well known. The risk of heat strain and heat stroke can be quantified and estimated from measurements or modeling of climate variables. The heat stress index WBGT is the most commonly used variable for such estimates in relation to work.

By mapping WBGT levels in a geographic region, we can get an interpretable picture of potential occupational heat stress risks in the region. We also presented maps of "heat related work capacity loss", which can guide the need for preventive interventions.

Such maps of heat related loss can also be used as a basis for estimates of potential economic losses due to climate change.

Acknowledgements

This study was supported by institutional research funds from the Center for Global Health Research, Umea University, Sweden, and National Center for Epidemiology and Population Health, Australian National University, Australia. ENSEMBLES data used in this work was funded by the European Union FP6 integrated project ENSEMBLES (contract number 505539) whose support is gratefully acknowledged. The authors declare no conflicts of interest.

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