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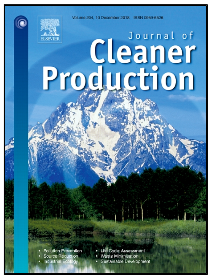

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Loss of work productivity in a warming world: differences between developed and developing countries

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Abstract Comparable estimates of the heat-related work productivity loss (WPL) in different countries over the world are difficult partly due to the lack of exact measures and comparable data for different counties. In this study, we analyzed 4363 responses to a global online survey on the WPL during heat waves in 2016. The participants were from both developed and developing countries, facilitating estimates of the heat-related WPL across the world for the year. The heat-related WPL for each country involved was then deduced for increases of 1.5, 2, 3 and 4°C in the global mean surface temperature under the representative concentration pathway scenarios in climate models. The average heat-related WPL in 2016 was 6.6 days for developing countries and 3.5 days for developed countries. The estimated heat-related WPL was negatively correlated with the gross domestic product per capita. When global surface temperatures increased by 1.5, 2, 3 and 4°C, the corresponding WPL was 9 (19), 12 (31), 22 (61) and 33 (94) days for developed (developing) countries, quantifying how developing countries are more vulnerable to climate change from a particular point of view. Moreover, the heat-related WPL was unevenly distributed among developing countries. In a 2°C-warmer world, the heat-related WPL would be more than two months in Southeast Asia, the most influenced region. The results are considerable for developing strategy of adaptation especially for developing countries.

Keywords: Heat waves, work productivity loss, representative concentration pathways, global warming targets, adaptation, mitigation

1. Introduction

The global average surface temperature increased significantly by 0.85 (0.65–1.06) °C from 1880 to 2012 (IPCC, 2014). Global warming has resulted in an increased frequency in the occurrence of heat waves, affecting the living and working environments of millions of people and creating threats to their health (Kovates, et al., 2008; Costello et al., 2009). Recent examples include the record-breaking heatwave in Europe in 2003, which caused >70,000 deaths (Robine et al., 2008), and the 2013 heatwave in eastern China, which affected more than half a billion people in nine provinces (Sun et al., 2014).

Heat stress affects the health of workers and reduces the work productivity (absenteeism, reduced work capacity and loss of productivity) by changing the ambient working environment (Ramsey, 1995; Pfaffenbach and Siuda 2010). It has been reported that when physical activity is high in a hot working environment, the core body temperature of workers may increase above 38°C, affecting physiological mechanisms and decreasing both their mental and physical capacity (Ramsey, 1995; Bridger, 2003). Heat stress may therefore have economic effects as the health of the labour force is a primary input to economic production (Witterseh et al., 2004). In addition, the effect of the heat stress on the work productivity is also unevenly distributed due to the different adaptability of heat exposure (Huang et al., 2017). Recognizing the regional differences is important for developing the climate mitigation measures and raise protection awareness, especially for the vulnerable countries and regions.

However, the knowledge of the effects of heat stress on work productivity for different countries remains limited. A commonly accepted indicator for measuring the capacity to work is the wet bulb globe temperature (WBGT) index (Kjellstrom et al., 2009; ISO, 1989), which is based on meteorological records. Dunne (2013) assessed that the heat stress reduced the labour capacity to 90% in peak months of extreme climatological heat stress over the past few decades for tropical and mid-latitudes. Other heat exposure indices, such as the predicted four-hour sweat rate and the heat stress index, are correlated with the WBGT (Kerslake et al., 1972). However, although there is agreement that work productivity decreases with increasing WBGT (Smith et al., 2014), this simple index can hardly reflect the regional difference of heat adaptability and the impacts of other non-meteorological factors such as worker's clothing, acclimatization and microenvironment (Budd et al., 2008). Surveys based on social-science studies were applied to quantify the impact of heat stress on the work capacity. By a tailored version of the work productivity and activity impairment (WPAI, Reilly et al., 1993) questionnaire, Zander (2015) investigated the self-reported reductions in productivity due to absenteeism and presenteeism in Australia during 2013/2014. His results show that the economic cost due to the heat amounts to 0.33 to 0.47% of Australia's GDP. The WPAI instrument was firstly designed to study the economic burden of diseases in health economics, by collecting the employees' percentages of health-induced working time loss, impairment while working, activity impairment and the overall work impairment score. However, previous surveys using designed questionnaires were mainly made in developed countries (Lefevre et al., 2015, Sheridan, 2007). The number of samples was usually very small (hundreds or even tens) and not suitable for identifying the regional differences across the world.

To obtain a global view of the effects of heat stress on productivity, we simplified the WPAI questionnaire by directly asking employees about absenteeism and presenteeism during hot days in the summer of 2016. This paper analyzed valid data from 4363 respondents of a global online survey on heat-related work productivity loss (WPL). Participants are not only from Europe, North America, Australia, and East Asia, where the heat wave effects have been relatively-well studied, but also from regions such as South Africa, Southeast Asia, Central Asia, South America, where the effects of climate change have not received sufficient attention as a result of data and information unavailability. The WPL (units: days) was defined and calculated as a function of absenteeism, presenteeism and employee's work efficiency loss. Then, we assessed the difference in WPL between groups of developed and developing countries/regions, under global warming scenarios of 1.5, 2, 3 and 4°C, emphasizing the regional differences of the effect of heat stress on work productivity especially between the developing and developed countries under different global warming targets. The data and methods are described in Section 2; the results are illustrated and discussed in Section 3; further discussions are given in Section4. The main conclusions are summarized in Section 5.

2. Methods and data sources

2.1. Questionnair Data

The data used in this paper were from a global online survey on heat wave-related WPL, which was conducted during 3 August-22 November 2016 by an APP weather company. Participants were asked questions about their absenteeism and presenteeism during the summer of 2016 (seen in Table A1 in Appendix). These questions are simple and easy to understand by people with different cultures without causing misunderstanding. Results are comparable among regions. The WPL (unit: days) was defined and calculated as:

$$WPL = Days_{absenteeism} + Days_{presenteeism} \times Loss_{efficiency} \quad (1)$$

The $Days_{absenteeism}$ is the number of the days that the employee takes off from work as a result of symptoms caused by heat. The $Days_{presenteeism}$ is the number of the days that employee is required to work despite feeling discomfort from symptoms caused by heat. The $Loss_{efficiency}$ is the loss of efficiency when the employee is required to work despite experiencing heat-related symptoms. The design of the questionnaire and the calculation of WPL were synthesized from Lerner (1999), Reilly (1993) and Derick (2013).

In addition, the questionnaire also included a number of questions about the type of work, the workplace environment, the symptoms the employee experienced in summer 2016 and what they preferred to do when there was a heat wave. This survey helped to measure the heat-induced loss of productivity on a global scale to explain the effect of global warming on the social economy of humans. More than 7000 questionnaires were returned, but 4363 participants completed all three of the questions (seen in Table A1 in Appendix). Our analysis is based on these 4363 valid questionnaires.

2.2. Fifth Coupled Model Intercomparison Project (CMIP5) output

Simulated daily surface temperatures were drawn from 33 global coupled ocean–atmosphere general circulation models (CGCMs) participating in the CMIP5 (Table A2 in Appendix). The all-forcing projections (2016–2100) under Representative Concentration Pathways (RCPs), RCP8.5, RCP4.5 and RCP2.6 were used. The radiative forcing under RCP8.5 (a high-emission scenario) increases throughout the 21st century and reaches about 8.5 W m^{-2} by 2100. The intermediate scenario RCP4.5 (medium-emission scenario) reaches about 4.5 W m^{-2} by 2100. The low-emission scenario RCP2.6 is described (Moss et al., 2010; Taylor et al., 2012) as a peak-and-decay low scenario in which radiative forcing reaches a maximum in the middle of the 21st century before decreasing to 2.6 W m^{-2}. The RCPs thus represent a broad range of climate outcomes.

2.3. Administrative boundaries data

A dataset of administrative boundaries (GADM, 2015) was used to mask the surface air temperature data of the 33 CGCMs based on the outlines of each country in a shapefile. The results could therefore be presented at a national scale.

2.4. Gross domestic product per capita (GDPPC)

The 2016 GDPPC (US dollars) for each country was obtained from the International Monetary Fund web site (www.imf.org/external/).

2.5. WPL under RCP scenarios

Equation (1) was used to calculate the average WPL (in days) for each country in 2016 (*N* days). To calculate the WPL under the different RCPs scenarios, we assumed a constant physiological heat stress tolerance over time (Dunne et al., 2013). The temperature threshold for loss of work productivity was defined by sorting the 2016 temperatures in descending order and then choosing the *N*th temperature as the temperature threshold representing the physiological tolerance to heat stress. The WPL in each year from 2012 to 2100 for each country was then defined as the number of days above this temperature threshold.

3. Results

3.1. The spatial distribution of WPL

Figure 1 shows that 62 countries and regions with more than 10 respondents were included in the survey, with a total 4043 respondents (Table A3 in Appendix). A total of 783 cases of excess human mortality associated with heat from 164 cities in 36 countries were previously reported in a review (Mora et al., 2017) of papers published between 1980 and 2014. Excess mortality has predominantly been reported for mid-latitude cities, with fewer reports from North Africa, Southeast Asia, South America and Central Asia. Our survey covered some of these areas, providing comparable data to conduct a quasi-global analysis on the heat-related WPL.

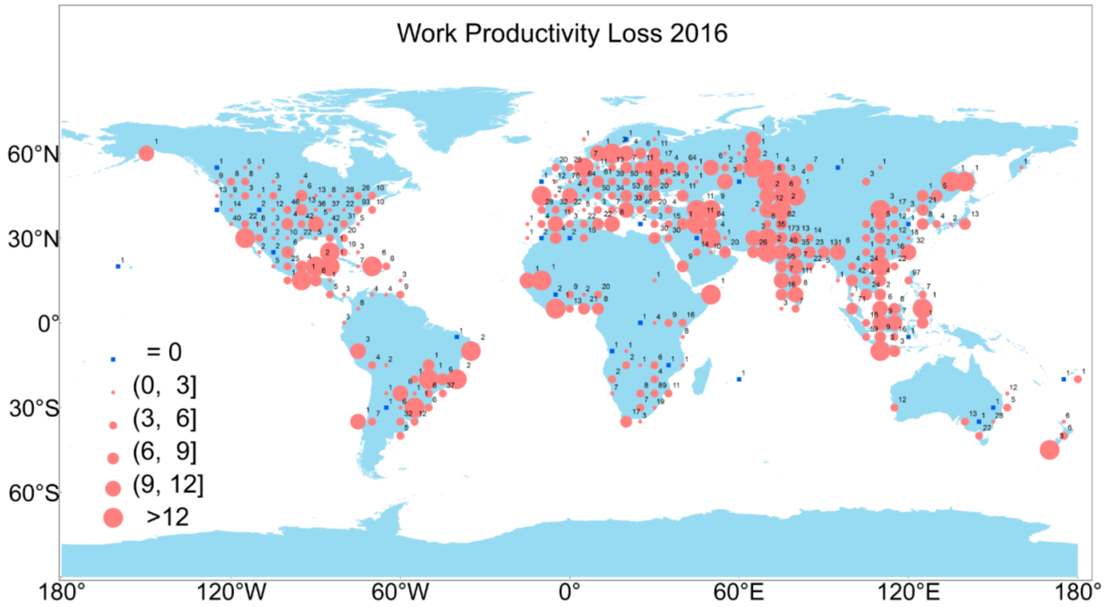

Figure 1. Global loss of work productivity for 2016 (in days). Larger circles indicate greater losses. The numbers in the legend are samples for each grid with a resolution of 5° ×5°. The total number of valid samples is 4043.

3.2. The linear relationship between work productivity and GDPPC

Workers in low- and middle-income countries/regions are more vulnerable to excessive heat stress (Kjellstrom et al., 2009), but little research has been conducted to quantify the relationship between the effects of heat waves and the level of development of a country. We calculated a linear relationship between the WPL related to heat waves and the GDPPC in US dollars based on different combinations of countries/regions grouped by sample size. The results showed a significant negative correlation, particularly for a large sample of respondents. The WPL ranged from 2 to 9 days for different countries/regions. The greatest negative correlation coefficient of −0.63 ($P<0.01$) was found when the respondent sample size was >60 over 19 countries/regions (Fig. 2) (Table A4 in Appendix). These results suggest that the WPL is inversely proportional to the GDPPC and that developing countries/regions are particularly vulnerable to the adverse effects of global warming. A reason is that air conditioning is not widely available in low- and middle-income countries, whereas it is used extensively in workplaces in high-income countries (Sheridan, 2007; Kjellstrom et al., 2009). Increasing temperature can create very unhealthy environments for people who are not able to protect themselves with air conditioning or other cooling means. Several studies have shown that high-income groups and workers with a higher level of education are more likely to take personal heat protective measures (Khare et al., 2015; Kunz-Plapp et al., 2016).

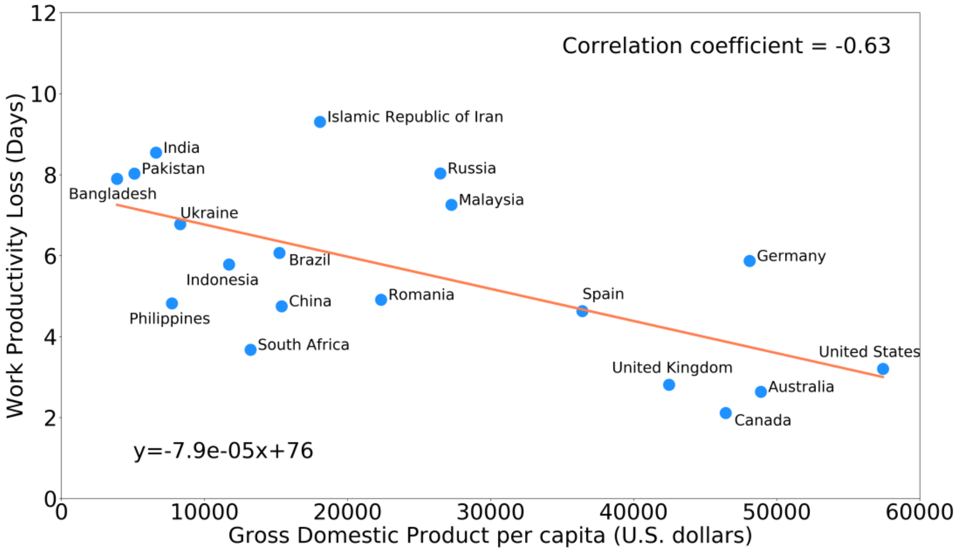

Figure 2. Linear relationship between the loss of work productivity (days) and GDPPC (US dollars) based on results from 19 countries/regions.

3.3. The WPL under the RCPs scenarios

People are likely to be affected more often by heat waves in the future as a result of global warming (Beniston et al., 2007; Revi et al., 2014; Patz et al., 2005). The Paris climate conference set a goal of keeping global warming to <2°C above pre-industrial levels and to pursue efforts to limit global warming to 1.5°C, recognizing that this would significantly reduce the risks and impacts of climate change (United Nations Paris Agreement, 2015). There have been many studies on developing methods to mitigate climate change, such as biochar cost reduction (Maroušek, 2014; Maroušek et al., 2017). However, given that temperatures had reached 0.85 (0.65–1.06)°C above pre-industrial levels by 2012 (IPCC, 2014) , some analysts have argued that there is little chance of meeting the 1.5 or even 2°C target (Sanford et al., 2014; Donnelly et al., 2017). We therefore assessed the WPL under global warming scenarios of 1.5, 2, 3 and 4°C to take into account the uncertainty in future climate change.

We analysed global climate simulations using representative concentration pathway (RCP) scenarios for the period 2012–2100. We focused on three scenarios (RCP2.6, RCP4.5 and RCP8.5), each of which corresponds to a specific radiative forcing pathway. We used the output of 33 global CGCMs (Table A2 in Appendix) from the CMIP5. Figure 3 shows the global surface air temperature time series during the 21st century and a set of 1.5, 2, 3 and 4°C global warming targets. Global warming will probably exceed 1.5°C around 2030 and 2°C around the 2040s (Table A5 in Appendix). The year in which the temperature increase exceeds 2°C under the high-emission scenario is 13 years earlier than that under the low-emission scenario. It will exceed 3°C around 2076 under RCP4.5 and 2058 under RCP8.5. A 4°C warmer world will be likely around 2076 under the RCP8.5 scenario. Widespread global risks (e.g. the extinction of many species, risks to food security and compromised human activity) will occur if global warming exceeds 4°C

(IPCC, 2014).

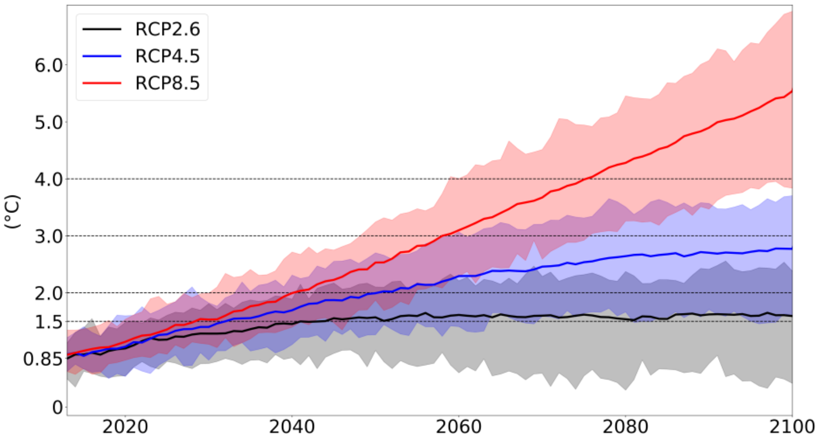

Figure 3. Global temperature time series based on RCP scenarios for the period 2013–2100 with respect to the temperature in 2012. The horizontal dotted lines indicate the thresholds for an increase of 1.5, 2, 3 and 4 °C.

To calculate the WPL under the RCP scenarios, we assumed a constant tolerance to physiological heat stress over time. The WPL was calculated under scenarios of 1.5, 2, 3 and 4°C global warming. We assessed the difference in WPL between groups of developed and developing countries/regions, rather than among individual countries/regions. Among these 19 countries (Fig. 2, Table A4 in Appendix), the developing countries/regions group includes Bangladesh, Pakistan, India, Philippines, Ukraine, Indonesia, South Africa, Brazil, China, the Islamic Republic of Iran, Romania, Russia and Malaysia. The developed countries/regions group includes Spain, the UK, Canada, Germany, Australia and the USA.

Figure 4 shows that the average WPL was 6.6 days for developing countries/regions and 3.5 days for developed countries/regions in 2016. In the 1.5°C warmer world, the loss was about 9 days for developed countries, but about 20 days for developing countries, almost three-fold larger than in 2016. The impacts of heat stress at this level appear to be endurable. The WPL increased by 3 days from the 1.5 to 2°C scenario for the developed countries/regions, but increased by 11 days for the developing countries/regions. This suggests that the increase in risk and the impacts of global warming are greater for developing countries/regions than for developed countries/regions. There are more sustained periods of extreme heat in this scenario, presenting an increased risk over single days of high temperatures (Anderson et al., 2009). Risk and the effects of heat will increase with increases in the intensity or duration of heat waves. In the 3°C warmer world, the WPL was 22 days for developed countries/region and 61 days for developing countries. When global temperatures were increased by 4°C, the WPL was 33 days for developed countries/regions, but 94 days for developing countries/regions. It means that developing countries/regions, which are particularly vulnerable to climate change, experience more adverse effects of global warming than developed countries/regions.

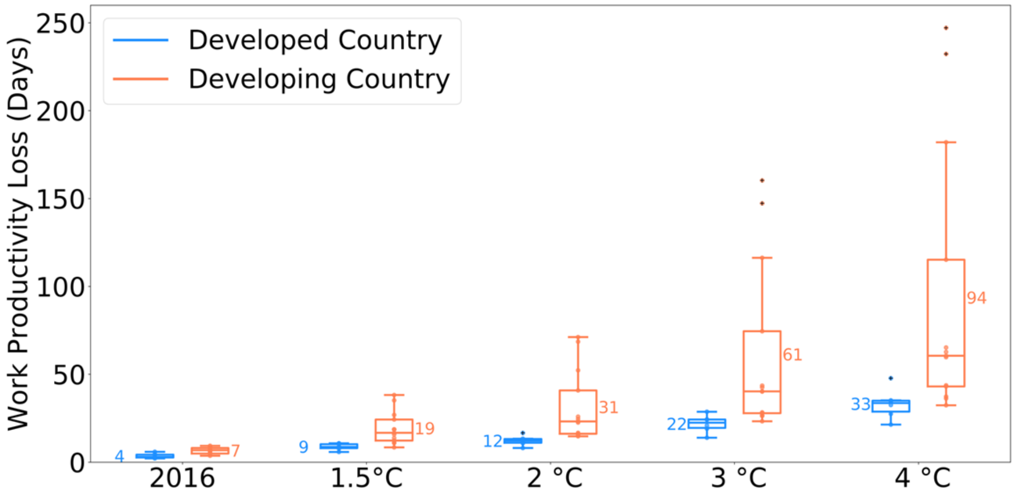

Figure 4. Boxplot of loss of work productivity for developed countries/regions and developing countries/regions with 1.5, 2, 3 and 4°C warming targets under RCP2.6, RCP4.5 and RCP8.5 scenarios (units: days).

The WPL was not evenly distributed among developing countries and there were large regional differences. For example, in the Philippines, Indonesia and Malaysia (Southeast Asia), the average WPL were about 28, 36 and 40 days, respectively, in a 1.5°C warming world; about 51, 68 and 72 days in a 2°C warming world; about 114, 157 and 145 days in a 3°C warming world; and about 182, 247 and 232 days in a 4°C warming world. This shows that in a 1.5°C warming world, developing countries suffer the same WPL as developed countries in a 4°C warming world.

4. Discussion

In this study, based on the global online survey dataset, we quantify the impact of heat stress on WPL in the summer of 2016. Our results suggest that the average WPL due to heat should be 6.6 days for developing countries/regions and 3.5 days for developed countries/regions in 2016. The quantitative estimate of the heat-related WPL could serve as a base for establishing the heat-related economic loss model. Workers in tropical countries are likely to be at the highest risk of heat stress. This result is consistent with the conclusion of Dunne (2013), whose results were calculated via the heat exposure index (WBGT). However, the analysis of Dunne (2013) didn't indicate some vulnerable regions such as Central Asia and northern Europe, as the sensitivity of these regions is mainly related to the lower adaptability to heat. The present research based on the global survey data did identify some vulnerable regions that could have been overlooked in previous studies.

In addition, we analysed the global climate simulations of the representative concentration pathways (RCPs) scenarios for the period 2012-2100. The work productivity could reduce to less than 72% (91%) for summer by 2050 in developing (developed) countries. These results are comparable to that of 80% in Dunne (2013). Remarkably, in the 2°C-warmer world, the heat-related WPL in Southeast Asia, the most influenced region, could be more than two months.

These analyses were based on the hypothesis that the human physiology of heat stress tolerance will not change in the future. The prediction of the future losses of work productivity was based on global climate simulations of RCP scenarios for the period 2012–2100. There are therefore some uncertainties in these quantitative results, but the main conclusions should remain reasonable. Under the current global mean warming targets, heat stress will affect most regions in the world, with some countries/regions being more vulnerable than others. Contrasting developing countries with developed countries is one of the ways of exploring regional differences. It is important to recognize regional differences in setting global mean warming targets and developing the adaptation strategy.

5. Conclusion

Overall, we emphasize that the regional differences should be well considered as the WPL is in general inversely proportional to the level of national development. The heat-related losses of work productivity for global warming targets of 1.5, 2, 3 and 4°C under RCPs scenarios show a global pattern, which helps to quantify how much developing countries will be more affected by global warming than developed countries will. This should be considered when addressing the urgent and immediate needs of mitigation and adaptation for those developing countries/regions that are particularly vulnerable to the adverse effects of global warming. Our results suggest that countries in the most influenced region (Southeast Asia) would suffer in a 1.5°C-warmer world the same WPL as the developed countries would in a 4°C-warmer world. The results provide some quantitative measures considerable for developing adaptation strategy especially for developing countries.

Acknowledgements

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Appendix

Table A1
Parts of online survey questions.

	Questions	options		
1	How many days did you take off from work because of the hot days/heat wave induced symptoms?	A: 0 days D: 7–9 days G:>15 days	B: 1–3 days E: 10–12 days	C: 4–6 days F: 13–15 days
2	How many days did you have to work, rather than taking off, even when you felt discomfort because of the hot days/heat wave induced	A: 0 days D: 7–9 days G:>15 days	B: 1–3 days E: 10–12 days	C: 4–6 days F: 13–15 days

	symptoms?	
2.1	If so, how serious has this impact been on your work efficiency when you have to work (e.g. distracted by discomfort, making mistakes, slowing down, taking unfinished work home)?	A: No impact (0%) B: Little impact (25%) C: Some impact (50%) D:Strong impact (75%) E: Serious impact, cannot work (100%)

Table A2

CMIP5 models used in this study. "*" indicates that the output of this model is available for a corresponding RCP scenario.

Models	RCP26	RCP45	RCP85	Models	RCP26	RCP45	RCP85
ACCESS1-0	/	*	*	GFDL-ESM2M	*	*	*
ACCESS1-3	/	*	*	HadGEM2-AO	*	*	*
bcc-csm1-1	*	*	*	HadGEM2-CC	/	*	*
bcc-csm1-1-m	*	*	*	HadGEM2-ES	*	*	*
BNU-ESM	*	*	*	inmcm4	/	*	*
CanESM2	*	*	*	IPSL-CM5A-LR	*	*	*
CCSM4	*	*	*	IPSL-CM5A-MR	*	*	*
CESM1-BGC	/	*	*	IPSL-CM5B-LR	/	*	*
CESM1-CAM5	*	*	*	MIROC-ESM	*	*	*
CMCC-CESM	/	/	*	MIROC-ESM-CHEM	*	*	*
CMCC-CM	/	*	*	MIROC5	*	*	*
CMCC-CMS	/	*	*	MPI-ESM-LR	*	*	*
CNRM-CM5	*	*	*	MPI-ESM-MR	*	*	*
CSIRO-Mk3-6-0	*	*	*	MRI-CGCM3	*	*	*
EC-EARTH	/	*	*	MRI-ESM1	/	/	*
GFDL-CM3	*	*	*	NorESM1-M	*	*	*
GFDL-ESM2G	*	*	*	TOTAL	22	31	33

Table A3

Sample sizes of questionnaire by country.

	Country/Region	sample size	work productivity loss 2016 (days)	GDPPC (U.S. dollars)
1	United States	666	3.2	57436
2	India	563	8.5	6616
3	Pakistan	191	8.0	5106
4	Russia	139	8.0	26490
5	South Africa	136	3.7	13225
6	Ukraine	106	6.8	8305

7	Philippines	105	4.8	7728
8	United Kingdom	105	2.8	42481
9	China	103	4.7	15399
10	Islamic Republic of Iran	102	9.3	18077
11	Germany	100	5.9	48111
12	Indonesia	95	5.8	11720
13	Australia	94	2.6	48899
14	Malaysia	82	7.3	27267
15	Bangladesh	71	7.9	3891
16	Canada	69	2.1	46437
17	Spain	66	4.6	36416
18	Romania	66	4.9	22348
19	Brazil	65	6.1	15242
20	Italy	55	6.0	36833
21	Argentina	54	3.8	20047
22	Mexico	54	5.6	18938
23	Thailand	48	7.8	16888
24	Vietnam	46	4.6	6429
25	Nigeria	44	5.3	5942
26	Algeria	43	5.0	15026
27	Greece	42	4.5	26669
28	Poland	35	6.4	27764
29	Netherlands	35	5.6	51049
30	Turkey	33	7.4	24912
31	France	33	3.4	42314
32	Taiwan Province of China	31	10.1	48095
33	Korea	30	7.7	37740
34	Egypt	30	7.5	12554
35	Portugal	29	3.8	28933
36	Serbia	26	3.4	14493
37	Kazakhstan	25	12.6	25145
38	Saudi Arabia	25	5.6	55158
39	Israel	24	3.2	35179
40	Kenya	24	4.5	3361
41	Hungary	23	10.8	27482
42	Ghana	21	4.0	4412
43	Croatia	20	3.2	22795
44	United Arab Emirates	20	6.2	67871
45	Hong Kong SAR of China	20	4.8	58322
46	Tunisia	20	5.6	11634
47	Albania	19	9.4	11840
48	Bulgaria	19	2.9	20327

49	Slovak Republic	18	8.2	31339
50	Morocco	18	6.4	8330
51	Belarus	17	14.2	18000
52	Czech Republic	15	5.4	33232
53	New Zealand	15	6.4	37294
54	Japan	15	5.6	41275
55	Nepal	14	5.5	2479
56	Singapore	14	3.4	87855
57	Mozambique	12	3.9	1215
58	FYR Macedonia	12	8.1	14597
59	Switzerland	11	0.8	59561
60	Uzbekistan	10	5.8	6563
61	Belgium	10	0.2	45047
62	Uruguay	10	1.9	21527
/	TOTAL	4043	/	/

Table A4

Assessment the loss of work productivity under global warming scenarios of 1.5, 2, 3 and 4°C for each country (19 countries; the respondent sample size was >60). The all-forcing projections (2016–2100) under RCP8.5, RCP4.5 and RCP2.6 were used.

GDPPC (U.S. dollars)	Countries	1.5°C			2°C			3°C		4°C
		RCP 26	RCP 45	RCP 85	RCP 26	RCP 45	RCP 85	RCP 45	RCP 85	RCP 85
3891	Bangladesh	22	17	18	25	26	23	35	46	65
5106	Pakistan	16	15	16	22	21	24	40	41	60
6616	India	21	17	19	25	24	28	42	44	63
7728	Philippines	35	26	23	47	55	52	106	121	182
8305	Ukraine	15	12	15	18	13	19	23	28	36
11720	Indonesia	44	31	34	64	66	73	146	167	247
13225	South Africa	9	8	8	16	15	14	27	27	44
15242	Brazil	31	21	24	49	40	39	77	73	115
15399	China	12	11	11	16	16	15	27	29	43
18077	Iran	16	17	17	21	24	23	41	40	61
22348	Romania	12	11	10	17	14	17	25	29	37
26490	Russia	12	12	13	16	17	16	21	24	32
27267	Malaysia	48	39	32	74	74	68	136	153	232
36416	Spain	8	10	13	8	18	19	25	31	48
42481	United Kingdom	8	7	8	11	12	10	18	19	28
46437	Canada	6	6	5	9	8	8	15	13	21

48111	Germany	12	10	11	12	14	13	22	25	33
48899	Australia	9	7	10	12	11	13	22	26	35
57436	United States	9	9	9	12	13	13	20	22	35

Table A5.
Average years for global warming exceeding 1.5, 2, 3 and 4°C under the RCP2.6, RCP4.5, RCP8.5 scenarios with the 10–90% uncertainty range (in parentheses) among the models used.

Temperature increase (°C)	RCP2.6	RCP4.5	RCP8.5
1.5	2034 (2023–2049), 20 models	2030 (2023–2042), 31 models	2027 (2021–2033), 33 models
2	2053 (2043–2066), 11 models	2049 (2037–2066), 30 models	2040 (2034–2044), 33 models
3	–	2076 (2062–2091), 16 models	2058 (2050–2068), 33 models
4	–	–	2076 (2065–2084), 32 models

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Highlights

1. We synthesized valid data from 4363 respondents of a global on line survey. This is the most extensive global survey of the effect of heat stress on the work productivity currently available to our knowledge. Based on the global survey, we identified regions of vulnerability to heat waves that might have been overlooked in the past. For instance, previous studies based on commonly used heat exposure indices could hardly indicate vulnerable regions such as Central Asia and northern Europe.

2. Our research provided the first comparative assessment of the impact of heat stress on work productivity losses in different countries around the world and hence pointed out particular vulnerable regions from a new point of view. The estimated loss of work productivity was well correlated with the gross domestic product per capita (cc=-0.63), potentially providing a reasonable measure (parameter) for developing models of heat-related economic loss.

3. We quantitatively assessed the difference in future work productivity losses between groups of developed and developing countries/regions under global warming scenarios of 1.5, 2, 3 and 4°C. Our results suggested that countries in Southeast Asia in a 1.5°C-warming world would suffer the same work productivity loss as the developed countries would in a 4°C-warming world. This quantitatively addressed the severe situation that developing countries would face under global warming.