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The Direct Impact of Climate Change on Regional Labor Productivity

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ABSTRACT. Global climate change will increase outdoor and indoor heat loads, and may impair health and productivity for millions of working people. This study applies physiological evidence about effects of heat, climate guidelines for safe work environments, climate modeling, and global distributions of working populations to estimate the impact of 2 climate scenarios on future labor productivity. In most regions, climate change will decrease labor productivity, under the simple assumption of no specific adaptation. By the 2080s, the greatest absolute losses of population-based labor work capacity (in the range 11% to 27%) are seen under the A2 scenario in Southeast Asia, Andean and Central America, and the Caribbean. Increased occupational heat exposure due to climate change may significantly impact on labor productivity and costs unless preventive measures are implemented. Workers may need to work longer hours, or more workers may be required, to achieve the same output and there will be economic costs of lost production and/or occupational health interventions against heat exposures.

KEYWORDS: climate change, heat, labor productivity

"Too hot" working environments are not just a question of comfort, but a concern for health protection and the ability to perform work tasks. This occupational health problem has been known for considerable time and protective methods have been developed. Still, many workers are exposed to unacceptably high temperatures and humidity in work situations that cannot be modified and heat strain and heat stroke are important issues not only for health but also for labor productivity.[1–4] In outdoor, and many indoor, jobs, particularly in low- and middle-income countries, air conditioning of the workplace is not, and will possibly never be, an option. Global climate change will increase average temperatures, as well as shift the distribution of daily peak temperature and relative humidity—so that heat episodes will become more frequent and more extreme.[5,6] In order to cope with heat, an instinctive adaptive action by a worker is to reduce work intensity or increase the frequency of short breaks. One direct effect of a higher number of very hot days is therefore likely to be the "slowing down" of work and other daily activities.[7] Whether it occurs through "self-pacing"[3] (which reduces output) or occupational health management interventions (which increases costs), the end result is lower labor productivity.

When the body carries out physical work, heat is produced internally which needs to be transferred to the external environment in order to avoid the body temperature increasing.[8] If body temperature exceeds 39°C, heatstroke may develop, and a temperature of 40.6°C is life-threatening. Before these serious health effects occur, at lower heat exposures, the effects are diminished "work capacity,"[8,9] diminished mental task ability,[2] and increased accident risk.[10] These effects

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all contribute to a reduced "work capacity" and lower labor productivity.

Reduced work capacity is a function of environmental humidity, radiant heat, air movement, and ambient temperature.[11] In humid and calm conditions, it can occur above 26°C for heavy physical work[12,13] but individual variations are large and a complex relationship between climate factors, sweat rate, and body temperature has been used to establish a "predicted heat strain model."[14] Heat strain can occur in arid climates,[15] indoor office environments,[16] and factories.[17] Unusual heat waves create particular problems, as during the 2003 heat wave in France.[18] The economic cost of the existing suboptimal climate in US workplaces has been estimated at many billions of dollars.[19]

Quantitative standards to protect workers from heat injury have been developed by the International Standards Organization (ISO)[13] and at the national level, eg, by the US National Institute for Occupational Safety and Health (NIOSH).[20] Most standards use "wet bulb globe temperature" (WBGT) to quantify different levels of heat stress and define the percentage of a typical working hour that a person can work and maintain core body temperature below 38°C, assuming that the remaining time is rest. The NIOSH standard also stipulates a WBGT level above which no worker should be expected to carry out ongoing tasks.[20] The standards are stricter for persons unacclimatized to heat than for those who are acclimatized. For unacclimatized persons faced with a very energy demanding work task, the need to reduce heat stress starts at WBGT above 22.5°C; for acclimatized persons, this reduction starts at a WBGT of 26°C.[13,20]

An assessment of the potential impact of climate change on "work capacity" and the associated economic costs has not yet been made. Occupational health risks have been given little attention in international or national climate change impact and vulnerability assessments.[21,22] This paper estimates the extent to which climate change may affect labor productivity due to increased ambient temperatures and/or humidity under future climate scenarios.

METHODS

We used global climate model data for different world regions in combination with the relationships between WBGT and work capacity to calculate the relative change in population work capacity at different future time periods and for different climate scenarios. The analysis went through 5 steps:

1. Classify populations by world region and climate type and select representative climate points.
2. Obtain daily climate model data for each point, representing the subregional climate zone in which at least 5% of the regional population live.
3. Calculate current and future distributions of daily daytime WBGT ("work WBGT") for each subregional climate zone and then generate a single *regional* work WBGT series using a population-weighted average.
4. Estimate current and future relative work capacity, in order to estimate potential labor productivity losses due to global climate change for each major labor sector (agricultural, industrial, service).
5. Combine sector-specific estimates to a single regional estimate using the changing distribution of working population across sectors.

We assumed that changes in labor productivity (an economic concept) are equal to changes in the work capacity (a physiological concept). We estimated "labor productivity" for 21 world regions, where countries are grouped according to health indicators and geography (Figure 1, Table 1). In order to take into account the diversity of climates within

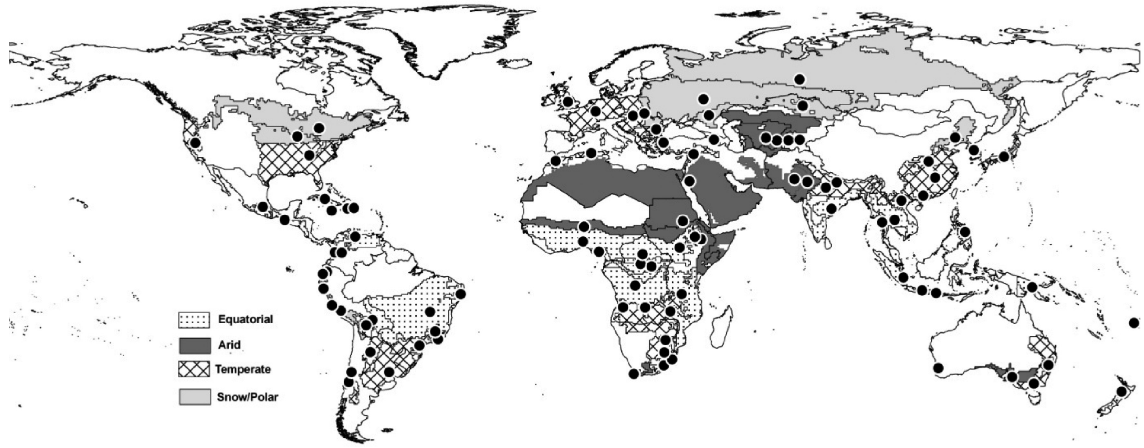

Fig. 1. Location of population-weighted centroids of climate zones which were matched to climate modeling points within the 21 world regions. Note that climate subtypes are not shown on the map.

Table 1.—Selected Climate Zones by Region

Region	Climate type: Basic climate class	Climate type: Climate class type	% of regional population living in zone (total in bold)	Number of climate grid points
Asia Pacific, High Income	Warm temperate	Warm temperate, fully humid, hot summer	63%	1
	Snow	Snow, winter dry, hot summer	11%	1
			74%	
Asia, Central	Arid	Cold desert	9%	1
		Cold steppe	16%	2
	Warm temperate	Warm temperate, summer dry, hot summer	13%	1
	Snow	Snow, fully humid, warm summer	13%	2
			52%	
Asia, East	Warm temperate	Warm temperate, winter dry, hot summer	35%	2
		Warm temperate, fully humid, hot summer	33%	1
	Snow	Snow, winter dry, hot summer	11%	1
			79%	
Asia, South	Equatorial	Equatorial, winter dry	34%	1
	Arid	Hot steppe	11%	1
		Hot desert	6%	1
	Warm temperate	Warm temperate, summer dry, hot summer	7%	1
		Warm temperate, winter dry, hot summer	27%	1
			86%	
Asia, Southeast	Equatorial	Equatorial, winter dry	26%	2
		Equatorial, monsoonal	13%	2
		Equatorial, fully humid	30%	2
	Warm temperate	Warm temperate, winter dry, hot summer	7%	1
			76%	
Australasia	Arid	Cold steppe	7%	1
	Warm temperate	Warm temperate, summer dry, hot summer	6%	1
		Warm temperate, fully humid, hot summer	35%	1
		Warm temperate, fully humid, warm summer	42%	2
			91%	
Caribbean	Equatorial	Equatorial, winter dry	67%	3
		Equatorial, fully humid	15%	1
			83%	
Europe, Central	Warm temperate	Warm temperate, fully humid, hot summer	9%	1
		Warm temperate, fully humid, warm summer	63%	1
	Snow	Snow, fully humid, warm summer	19%	1
			90%	
Europe, Eastern	Snow	Snow, fully humid, cool summer	6%	1
		Snow, fully humid, warm summer	71%	1
		Snow, fully humid, hot summer	6%	1
			83%	
Europe, Western	Warm temperate	Warm temperate, fully humid, warm summer	64%	2
			64%	
Latin America, Andean	Equatorial	Equatorial, winter dry	20%	2
	Arid	Hot desert	14%	2
	Warm temperate	Warm temperate, fully humid, warm summer	10%	1
		Warm temperate, winter dry, warm summer	7%	1
	Polar	Polar tundra	7%	1
			58%	
Latin America, Central	Equatorial	Equatorial, winter dry	29%	2
		Equatorial, fully humid	5%	1
	Warm temperate	Warm temperate, winter dry, warm summer	15%	1
		Warm temperate, fully humid, warm summer	5%	1
			55%	
Latin America, South	Arid	Cold steppe	10%	1
	Warm temperate	Warm temperate, winter dry, hot summer	7%	1
		Warm temperate, fully humid, hot summer	51%	1
		Warm temperate, summer dry, warm summer	7%	1
			76%	

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Table 1.—Selected Climate Zones by Region *(Continued)*

Region	Climate type: Basic climate class	Climate type: Climate class type	% of regional population living in zone (total in bold)	Number of climate grid points
Latin America, Tropical	Equatorial	Equatorial, summer dry	6%	1
		Equatorial, winter dry	35%	2
	Warm temperate	Warm temperate, fully humid, hot summer	33%	1
		Warm temperate, winter dry, hot summer	5%	1
			80%	
North Africa–Middle East	Arid	Hot desert	37%	1
	Warm temperate	Warm temperate, summer dry, hot summer	26%	4
			63%	
North America, High Income	Warm temperate	Warm temperate, summer dry, warm summer	8%	1
		Warm temperate, fully humid, hot summer	43%	1
	Snow	Snow, fully humid, warm summer	18%	1
		Snow, fully humid, hot summer	10%	1
			80%	
Oceania	Equatorial	Equatorial, fully humid	71%	1
			71%	
Sub-Saharan Africa, Central	Equatorial	Equatorial, winter dry	67%	2
		Equatorial, fully humid	7%	1
		Equatorial, monsoonal	8%	1
	Warm temperate	Warm temperate, winter dry, warm summer	5%	1
		Warm temperate, winter dry, hot summer	6%	1
			92%	
Sub-Saharan Africa, East	Equatorial	Equatorial, winter dry	31%	2
	Arid	Hot desert	9%	1
		Hot steppe	10%	1
	Warm temperate	Warm temperate, winter dry, warm summer	10%	1
		Warm temperate, winter dry, hot summer	6%	1
			66%	
Sub-Saharan Africa, South	Arid	Cold steppe	6%	1
	Warm temperate	Warm temperate, winter dry, hot summer	42%	2
		Warm temperate, winter dry, warm summer	19%	1
		Warm temperate, fully humid, hot summer	10%	1
		Warm temperate, fully humid, warm summer	10%	1
			87%	
Sub-Saharan Africa, West	Equatorial	Equatorial, monsoonal	8%	1
		Equatorial, winter dry	61%	1
	Arid	Hot steppe	22%	1
			91%	

Note. For each region, zones in which at least 5% of regional population live were selected. Shown are climate class and subtype, the percent of the regional population living in each zone type (total percent of regional population represented by the selected zones is in bold; total may exceed sum due to rounding), and the number of climate cells representing each zone type. Note that when more than one climate cell represents a zone type, it is because at least 2 spatially noncontiguous zones of the same type were selected within the region.

each region, we selected grid cells (from the 2.5 × 3.75 degrees climate model grid) representative of the main climate types in which people live within each region, based on the Köppen climate classification.[23] A Geographic Information System (GIS) was used to allocate the proportion of the regional population (year 2000) to each climate zone, using the Gridded Population of the World version 3 (GPW v3).[24] We then selected the climate zones in which at least 5% of the regional population resided (Table 1). A population-weighted center point was calculated for each of these climate zones and the climate grid cell in which this was located was then chosen. This gave a total of 93 grid cells (Figure 1, Table 1).

Daily data (24-hour averages) were extracted for these climate grid cells for the years 1960 to 2100 from the HadCM3 climate model,[25] for 2 climate scenarios: A2 and B2. These climate scenarios are derived from specified emissions scenarios that project future economic growth and technological development within a consistent storyline.[26] The A2 scenario assumes a high population growth and medium rapid economic development and therefore represents a moderately "high" emissions scenario. The B2 scenario assumes that greenhouse gas emissions are reduced through technological change and that there is more emphasis of governments addressing environmental problems through policy implementation. The increase in global mean temperature by the 2080s from preindustrial levels is projected to be 3.4°C (range 2.4°C to 6.4°C) and 2.4°C (range 1.4°C to 3.8°C) for A2 and B2, respectively.[27]

WBGT is usually calculated from measurements of the natural wet bulb temperature (T_{nwb}), the globe temperature (T_g), and the dry bulb air temperature (T_a). WBGT outdoors is $0.7\ T_{nwb} + 0.2\ T_g + 0.1\ T_a$, and WBGT indoors is $0.7\ T_{nwb} + 0.3\ T_g$. T_{nwb} and T_g outdoors are likely to be much higher than T_{nwb} and T_g indoors because of the influence of solar radiation. The specialized measurements for WBGT are not available from routine weather stations, and various formulas have been developed to estimate WBGT from routinely collected meteorological data. The Australian Bureau of Meteorology[28] and the American College of Sports Medicine[29] proposed a method for estimating WBGT from air temperature (T_a) and relative humidity (RH), assuming moderately high heat radiation levels in light wind conditions (approximately outdoor work in hot calm environments with some, but not extreme, sun exposure or indoor work with some local heat source). Other authors have proposed different formulas (eg, Bernard and Pourmoghani[30]). For this first analysis of the potential labor productivity impact, we chose to use the simpler method using the Australian Bureau of Meteorology equations:

$$\mathrm{WBGT} = 0.567 \times T_a + 3.94 + 0.393 \times E$$

$$E = RH/100 \times 6.105 \times \exp(17.27 \times T_a/(237.7 + T_a))$$

where T_a = 24-hour average shaded dry bulb air temperature in °C; E = 24-hour average absolute humidity (water vapour pressure) in hPa, hector Pascal; RH = 24-hour average relative humidity in %. The constant 3.94 represents impact of WBGT from radiated heat from the sun in outdoor work in calm wind conditions. The equations calculate the average heat exposure, but during specific days (eg, cloudy, windy days) the calculated WBGT may be too high. In a pilot analysis of hourly data, we noted that the differences between 24-hour averages and daytime means in subtropical climates were generally between 3°C and 5°C. As a compromise and in order not to overestimate the heat exposures, we assumed that the WBGT values calculated from 24-hour values would represent the daytime mean WBGT outdoors.

Using 24-hour average temperature and relative humidity from the global climate model,[25] we calculated daily work WBGT for the current climate (years 1961–1990) and 3 future 30-year time periods centered on the 2020s (2010–2039), 2050s (2040–2069), and 2080s (2070–2099). In order to take into account indoor heat exposures for industrial and service sector workers, we used the approximation that indoor WGBT = outdoor WBGT −4, based on a deduction of the radiation exposure factor 3.94 from the formula above.

The distributions of the number of days at different work WBGT values within each future time period were calculated. To provide a single estimate of the daily WBGT distribution for each world region, we combined the distributions for regional cells using population weighting. Figure 2 shows

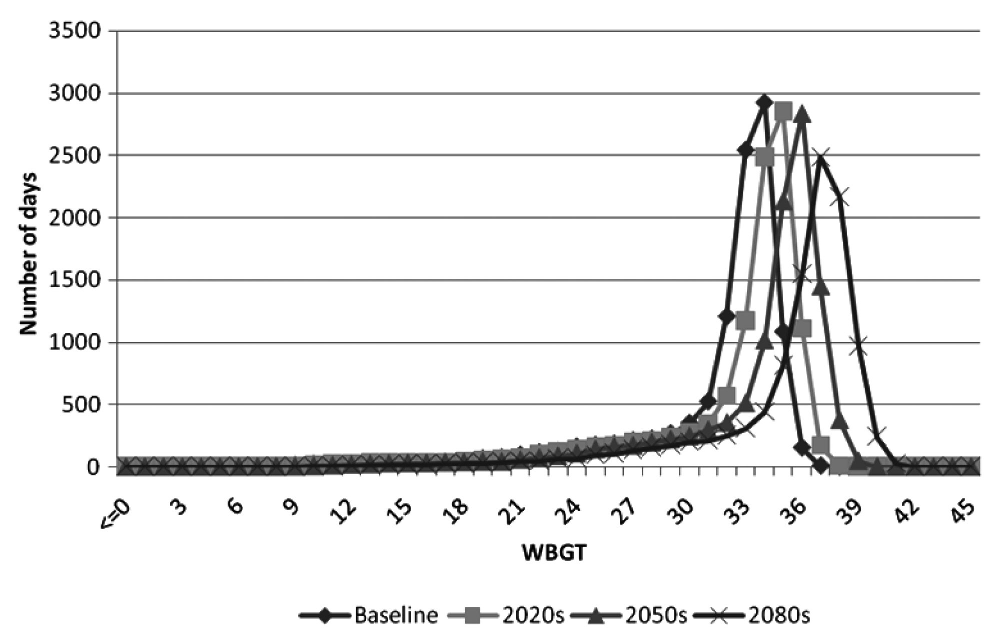

Fig. 2. Frequency distributions of estimated WBGT in Southeast Asia in current climate (1961–1990) and 3 future time periods under A2.

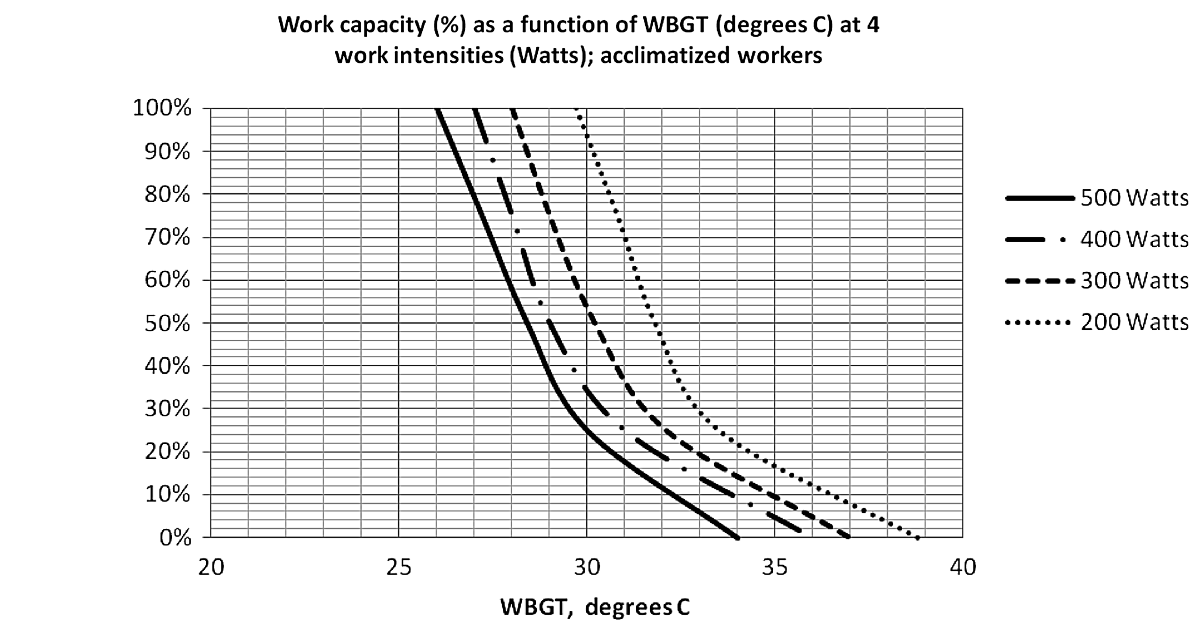

Fig. 3. Association between work capacity and WBGT for 4 work intensities. (First presented by Kjellstrom et al, 2009.[7] Based on the international standard[13] and recommendations by NIOSH, USA[20]).

the population weighted WBGT under the current climate and three future climates in Southeast Asia.

Using the ISO[13] and NIOSH[20] standards for acclimatized persons, Kjellstrom et al[7] produced a graph of "work capacity" as the maximum percentage of an hour that a worker should be engaged working (Figure 3). The 4 curves represent 4 different work intensities. We assume that 200 W corresponds to office desk work and service industries, 300 W to average manufacturing industry work, and 400 W to construction or agricultural work. Five hundred watts corresponds to very heavy laboring work and was not considered in this analysis. Work capacity rapidly diminishes within a 10- to 20-degree temperature range.

We then classified the working population of each region into 3 sectors: service, industry, and agriculture using World Bank data for 1990–2005.[31] In each region, any country without labor data was assumed to have the same distribution pattern as the country with the nearest gross domestic product (GDP) per capita for which labor data were available. Country data were combined using population-weighted averages to give estimates of labor distributions for each region.

Assuming the different work intensities for each sector (see above), we estimated regional labor productivity as a weighted average based on the distribution of work activities across the 3 sectors within each region. We assumed that labor patterns change over time, consistent with economic growth projected under the A2 and B2 emission scenarios[26,32] (Figure 4). North America was kept constant and all other regions converged towards this pattern as per capita income increased. Globally, GDP growth is higher under B2, and therefore more rapid convergence to the high-income distribution occurs under this scenario than under A2.

We then calculated the number of days with reduced work capacity for each day during each 30-year period using the WBGT work capacity relationships in Figure 3. The loss in work capacity for each day was added up for each 30-year period. The reductions in work capacity are presented for the baseline climate (we assume this to be 1961–1990 as it the standard period used for climate impact studies). For 2 climate-modeling scenarios and 3 future time periods, the additional reductions in relation to the reference period (no climate change) were calculated. As sensitivity analyses, we performed the same calculations assuming both constant climate and constant labor patterns over time.

RESULTS

Climate change is associated with a shift in the distribution of daily temperatures to include more hot days, and more days with WBGT exceeding the threshold for heat tolerance in individuals. Assuming trends towards less labor-intense work and no specific adaptation of workplace conditions to climate change, our model shows significant reductions in labor productivity due to climate warming in a number of regions, particularly in Africa (Table 2). In terms of absolute change in labor productivity (hence reflecting both current and future climate patterns) by the 2080s, the greatest losses (11.4% to 26.9%) are seen under A2 in Southeast Asia, Andean and Central America, Eastern Sub-Saharan Africa, and the Caribbean. Under the

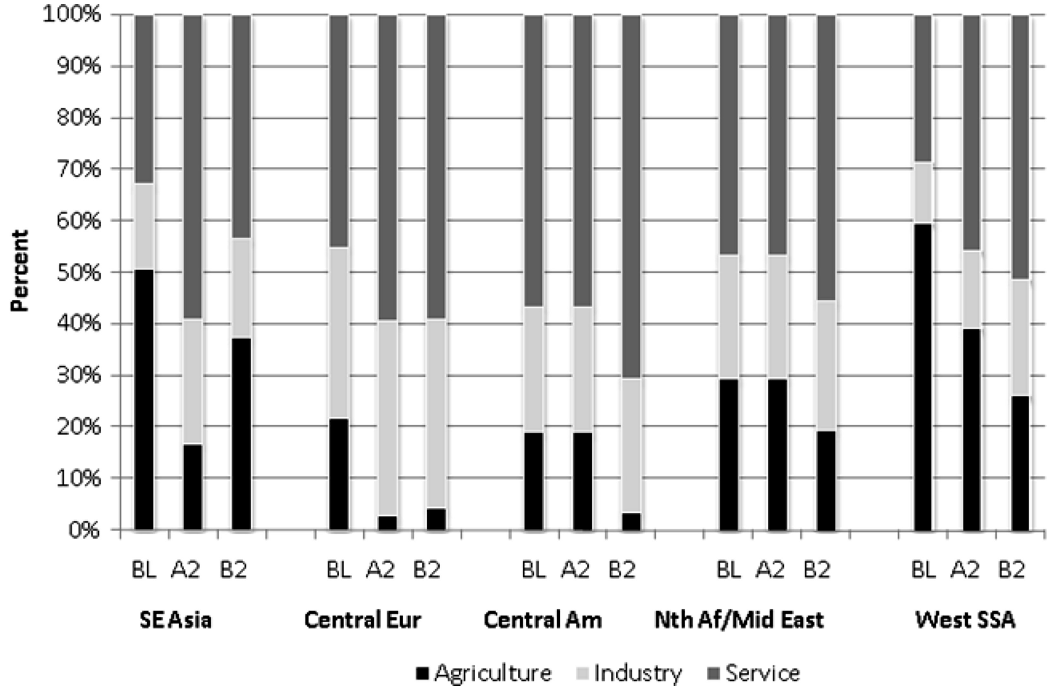

Fig. 4. Distribution of gross labor sectors, estimated for baseline and in the 2050s under the A2 and B2 scenarios, for selected regions. Regions are SE Asia = Southeast Asia; Central Eur = Central Europe; Central Am = Central America; Nth Af/Mid East = North Africa and Middle East; West SSA = Western Sub-Saharan Africa. Bars are BL = baseline; A2 = A2 in the 2050s; B2 = B2 in the 2050s.

A2 scenario, Eastern and Western Europe and Southern Latin America have the smallest losses (0.1% to 0.2%), with a gain seen in Tropical Latin America (3.0%). Under B2, the combined effects of less warming and greater wealth (meaning more people work in less labor-intense jobs) result in considerably smaller impacts in all regions (the greatest loss being 16% in Central America), and labor productivity gains in some regions (up to 6%).

The difference between impacts under the high- and low-emission scenarios is only apparent after the 2020s. This is due to the latency in the climate system, and any differences before the 2020s reflect natural climate variability and other uncertainties within the climate model. Ideally, an assessment should use a range of outputs from a range of climate models rather than a single time series.

Table 2 combines the impacts of a changing climate as well as projected changes of the labor force distribution within each region. In order to demonstrate the impact of each of these changes independently, we analyzed the percent working days lost due to high heat exposure in 2050 based on the A2 scenario in more detail (Table 3). The table shows that climate change creates losses of working days in all regions, which is expected because the temperature will go up everywhere. The impacts of assumed labor force changes vary between the regions, but all such changes reduce the workplace heat impacts. The impacts of the projected shifts of the workforce from agriculture to industry and services in 5 regions are particularly large (between 8.3% and 21.6%, Southeast Asia, Oceania, Western Sub-Saharan Africa, Central Sub-Saharan Africa, tropical Latin America). Thus, additional shifts of the working population from highly heat exposed to less heat exposed occupations can be an effective way of reducing this climate change impact in an area.

COMMENT

The climate change "attributable" effect is the difference between labor productivity (in terms of lost labor days) under the baseline climate and under the climate scenarios. The relationships in our model are theoretical and potential and may not reflect actual labor productivity losses as there will most likely be some adaptation measures in place, such as the space cooling of offices and factories. It is not possible to validate the labor productivity *loss* for the current climate because appropriate data are not available—but our measure of labor productivity is based on validated ergonomical guidelines.[13] However, adaptation measures will vary by country, with high-income countries having higher rates of adaptation, using more expensive methods, than low-income countries.

Countries and individual businesses will vary in their willingness or capacity to adapt to the projected climate change. There is a strong incentive to adapt. On average, the

Table 2.—Change in Labor Productivity

Region[a]	Impact	Baseline	2020s A2	2020s B2	2050s A2	2050s B2	2080s A2	2080s B2
Asia Pacific, High Income	% days lost	−0.3%	−0.2%	−0.5%	−0.5%	−0.9%	−2.0%	−1.7%
	Increment		+0.1%	−0.2%	−0.2%	−0.6%	−1.7%	−1.4%
Asia, Central	% days lost	−0.1%	−0.4%	−0.3%	−0.5%	−0.6%	−1.1%	−0.2%
	Increment		−0.3%	−0.1%	−0.4%	−0.4%	−0.9%	−0.1%
Asia, Eastern	% days lost	−10.1%	−9.7%	−11.3%	−10.5%	−7.7%	−16.4%	−10.4%
	Increment		+0.4%	−1.2%	−0.4%	+2.4%	−6.3%	−0.3%
Asia, South	% days lost	−25.2%	−30.1%	−22.9%	−29.6%	−22.8%	−32.7%	−28.4%
	Increment		−4.9%	+2.3%	−4.4%	+2.4%	−7.5%	−3.2%
Asia, Southeast	% days lost	−42.1%	−38.2%	−42.7%	−44.1%	−50.3%	−59.1%	−46.2%
	Increment		+3.9%	−0.6%	−2.0%	−8.2%	−17.0%	−4.1%
Australasia	% days lost	0.0%	−0.1%	−0.1%	−0.2%	−0.2%	−0.3%	−0.3%
	Increment		0.0%	0.0%	−0.2%	−0.1%	−0.3%	−0.3%
Caribbean	% days lost	−11.3%	−12.3%	−13.1%	−19.1%	−12.6%	−25.3%	−18.4%
	Increment		−1.0%	−1.8%	−7.7%	−1.2%	−14.0%	−7.1%
Europe, Central	% days lost	−0.1%	−0.2%	−0.4%	−0.1%	−0.1%	−0.4%	−0.3%
	Increment		0.0%	−0.3%	0.0%	0.0%	−0.3%	−0.1%
Europe, East	% days lost	−0.1%	−0.2%	−0.2%	−0.5%	−0.1%	−0.2%	−0.1%
	Increment		−0.2%	−0.2%	−0.4%	0.0%	−0.1%	−0.1%
Europe, West	% days lost	0.0%	0.0%	0.0%	0.0%	0.0%	−0.1%	0.0%
	Increment		0.0%	0.0%	0.0%	0.0%	−0.1%	0.0%
Latin America, Andean	% days lost	−1.8%	−2.8%	−2.7%	−5.0%	−2.9%	−13.2%	−6.7%
	Increment		−1.0%	−0.9%	−3.2%	−1.2%	−11.4%	−5.0%
Latin America, Central	% days lost	−15.5%	−23.0%	−22.9%	−34.1%	−19.9%	−42.4%	−31.5%
	Increment		−7.5%	−7.4%	−18.6%	−4.4%	−26.9%	−16.0%
Latin America, South	% days lost	−0.2%	−0.2%	−0.3%	−0.2%	−0.2%	−0.2%	−0.3%
	Increment		−0.1%	−0.1%	−0.1%	0.0%	−0.2%	−0.1%
Latin America, Tropical	% days lost	−11.9%	−13.0%	−13.3%	−5.8%	−3.6%	−8.9%	−6.0%
	Increment		−1.2%	−1.5%	+6.0%	+8.3%	+3.0%	+5.9%
North America, High Income	% days lost	−0.8%	−2.1%	−2.0%	−4.2%	−3.4%	−9.0%	−5.9%
	Increment		−1.3%	−1.2%	−3.4%	−2.6%	−8.2%	−5.1%
North Africa–Middle East	% days lost	0.0%	−0.2%	−0.1%	−0.6%	−0.3%	−0.5%	−0.1%
	Increment		−0.2%	−0.1%	−0.6%	−0.3%	−0.5%	−0.1%
Oceania	% days lost	−58.9%	−50.8%	−64.8%	−62.0%	−40.6%	−61.8%	−53.4%
	Increment		+8.0%	−6.0%	−3.1%	+18.2%	−2.9%	+5.5%
Sub-Saharan Africa, Central	% days lost	−33.6%	−41.1%	−40.9%	−34.5%	−22.6%	−38.2%	−30.3%
	Increment		−7.5%	−7.3%	−0.8%	+11.0%	−4.6%	+3.3%
Sub-Saharan Africa, East	% days lost	−7.0%	−10.4%	−10.4%	−11.9%	−9.8%	−19.2%	−11.0%
	Increment		−3.3%	−3.4%	−4.9%	−2.8%	−12.2%	−3.9%
Sub-Saharan Africa, South	% days lost	−2.2%	−3.4%	−3.3%	−1.8%	−1.2%	−3.1%	−1.9%
	Increment		−1.2%	−1.1%	+0.4%	+1.1%	−0.9%	+0.3%
Sub-Saharan Africa, West	% days lost	−40.3%	−47.0%	−47.1%	−43.8%	−32.1%	−49.6%	−42.0%
	Increment		−6.7%	−6.8%	−3.4%	+8.2%	−9.3%	−1.6%

Note. The change in labor productivity is expressed as percent work days lost and incremental change relative to baseline, by region for A2 and B2 scenarios, assuming changes in labor patterns. Negative numbers indicate days lost and positive numbers indicate days gained.
[a]For list of countries in each region, see Appendix.

elasticity of output to labor is 0.75.[33] This implies that, for every 1% reduction in labor productivity, income falls by 0.75%. Without adaptation, the economic losses of reduced labor productivity relative to baseline (Table 2) are up to 20% of GDP (Central America, A2, 2080).

There are several limitations to this study. The heat exposure (WBGT) is calculated with a simple formula that is approximate. The work capacity lost is based on international occupational health standards that may be exceeded in many workplaces. Further, we only look at one aspect of the effects of climate change on labor productivity. The number of days worked depends on the weather in both cold and hot countries. Working hours and work practices may change, and air conditioning may be put in place for some indoor jobs. Wages would respond to changes in the ability to work and to the costs to enhance that ability; this would determine

Table 3.—Sensitivity of Results to Assumed Labor Trends and Projected Climate Change

Region[a]	Change in available workdays compared to baseline for A2 in 2050s		
	Constant labor, changing climate	Changing labor, constant climate	Changing labor and climate[b]
Asia Pacific, High Income	−0.8%	+0.2%	−0.2%
Asia, Central	−0.7%	+0.1%	−0.4%
Asia, East	−7.0%	+5.1%	−0.4%
Asia, South	−11.5%	+6.7%	−4.4%
Asia, Southeast	−18.2%	+21.6%	−2.0%
Australasia	−0.2%	0.0%	−0.2%
Caribbean	−11.7%	+4.0%	−7.7%
Europe, Central	−0.6%	+0.1%	0.0%
Europe, East	−0.3%	0.0%	−0.4%
Europe, West	−0.1%	0.0%	0.0%
Latin America, Andean	−4.1%	+0.6%	−3.2%
Latin America, Central	−18.6%	0.0%	−18.6%
Latin American, South	−0.3%	+0.1%	−0.1%
Latin America, Tropical	−3.6%	+8.3%	+6.0%
North America, High Income	−3.4%	0.0%	−3.4%
North Africa–Middle East	−0.6%	0.0%	−0.6%
Oceania	−15.2%	+15.1%	−3.1%
Sub-Saharan Africa, Central	−15.4%	+11.5%	−0.8%
Sub-Saharan Africa, East	−8.9%	+2.0%	−4.9%
Sub-Saharan Africa, South	−2.8%	+1.6%	+0.4%
Sub-Saharan Africa, West	−15.8%	+13.0%	−3.4%

Note. The sensitivity is expressed as the incremental percent change in available workdays compared to baseline, for A2 in 2050s. Negative numbers indicate days lost and positive numbers indicate days gained. Because of the form of the relationship between labor sectors, heat exposures and available work days, columns 1 and 2 do not sum to give column 3.
[a]See Appendix for list of countries in each region.
[b]This equals the bottom line of the sixth column in Table 2.

whether the employer or the employee bears the brunt of the decrease in work capacity and it would shape the wider economic consequences. A more comprehensive analysis could address these outputs but is beyond the scope of this exercise. In addition, the climate model grid cell output may not accurately represent the observed temperature and humidity exposures for a given location, and only a limited number of climate data points are used. We therefore only report the aggregated regional changes in the labor productivity under climate warming. Humidity measures are likely to be more uncertain than the temperature projections.

The global burden of ill health from occupational exposures is large and often underestimated and under reported. The 2004 Global Burden of Disease assessment of occupational risk factors did not include the effects of heat or cold.[34] The direct effect of climate warming on direct [worker] productivity has not been investigated, as far as we are aware. Although some models have converted health impacts (mortality) into productivity losses, this is based on the assumption that mortality due to climate-sensitive diseases in adults will affect productivity at the regional level.[35]

We did not assess changes in productivity due to reduced cold stress because the relation between cold and productivity differs to that between heat and productivity. In general, for outdoor work, fewer too cold days could result in some productivity gains, but appropriate clothing protects against cold. For outdoor workers in polar regions, there may be labor productivity implications, but the numbers affected (in polar and subpolar regions) are very small compared to workers in temperate, tropical, and subtropical regions. Considering indoor cold, exposures tend to already be better regulated as they generally occur in high-income countries, meaning future productivity gains are likely to be small.

We are not addressing performance based on comfort and other issues in the environment (eg, motivation) that may also affect work behavior. We also do not address days lost due to illness (either heat-related or cold-related or other climate-sensitive illnesses), which are an additional climate change cost.

Assumptions about adaptation are key in all assessments of impacts on human systems due to climate change. As with many outcomes, there is a currently insufficient adaptation to climate factors in areas of limited economic development in terms of occupational exposures. There is an identifiable cost of climate change in terms of climate-proofing industrial and commercial buildings.[36] However, this is not always possible or may be prohibitively expensive, and it potentially increases greenhouse gas emissions. Further, there are limited adaptation options for outdoor work other than changes to hours worked. Nonetheless, this approximate analysis highlights an important potential climate change impact. Future research should study the productivity impacts at local and country level, as well as the adaptation to climate change in labor practices.

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Appendix: List of Countries by Region

ASIA PACIFIC, HIGH INCOME
Brunei Darussalam
Japan
Republic of Korea
Singapore

ASIA, CENTRAL
Armenia
Azerbaijan
Georgia
Kazakhstan
Kyrgyzstan
Mongolia
Tajikistan
Turkmenistan
Uzbekistan

ASIA, EAST
China
Democratic People's Republic of Korea
Hong Kong
Macao
Taiwan

ASIA, SOUTH
Afghanistan
Bangladesh
Bhutan
India
Nepal
Pakistan

ASIA, SOUTHEAST
Cambodia
Christmas Island
Cocos Islands
Indonesia
Lao People's Democratic Republic
Malaysia
Maldives
Mauritius
Myanmar
Philippines
Reunion
Seychelles
Sri Lanka
Thailand
Timore Leste
Viet Nam

AUSTRALASIA
Australia
New Zealand

CARIBBEAN
Anguilla
Antigua and Barbuda
Aruba
Bahamas
Barbados
Belize
Bermuda
British Virgin Islands
Cayman Islands
Cuba
Dominica
Dominican Republic
French Guiana
Grenada
Guadeloupe

CARIBBEAN (Continued)
Guyana
Haiti
Jamaica
Martinique
Montserrat
Netherlands Antilles
Puerto Rico
Saint Barthelemy
Saint Kitts and Nevis
Saint Lucia
Saint Martin
Saint Vincent and the Grenadines
Suriname
Trinidad and Tobago
Turks and Caicos Islands
US Virgin Islands

EUROPE, CENTRAL
Albania
Bosnia and Herzegovina
Bulgaria
Croatia
Czech Republic
Hungary
Montenegro
Poland
Romania
Serbia
Slovakia
Slovenia
The Former Yugoslav Republic of Macedonia

EUROPE, EAST
Belarus
Estonia
Latvia
Lithuania
Republic of Moldova
Russian Federation
Ukraine

EUROPE, WEST
Akrotiri and Dhekelia
Aland Islands
Andorra
Austria
Belgium
Channel Islands
Cyprus
Denmark
Faeroe Islands
Finland
France
Germany
Gibraltar
Greece
Greenland
Guernsey
Holy See
Iceland
Ireland
Isle of Man
Israel
Italy
Jersey
Liechtenstein
Luxembourg
Malta
Monaco

EUROPE,WEST (Continued)
Netherlands
Norway
Portugal
San Marino
Spain
Svalbard
Sweden
Switzerland
United Kingdom

LATIN AMERICA, ANDEAN
Bolivia
Ecuador
Peru

LATIN AMERICA, CENTRAL
Colombia
Costa Rica
El Salvador
Guatemala
Honduras
Mexico
Nicaragua
Panama
Venezuela

LATIN AMERICA, SOUTH
Argentina
Chile
Falkland Islands (Malvinas)
Uruguay

LATIN AMERICA, TROPICAL
Brazil
Paraguay

NORTH AFRICA / MIDDLE EAST
Algeria
Bahrain
Egypt
Iran (Islamic Republic of)
Iraq
Jordan
Kuwait
Lebanon
Libyan Arab Jamahiriya
Morocco
Occupied Palestinian Territory
Oman
Qatar
Saudi Arabia
Syrian Arab Republic
Tunisia
Turkey
United Arab Emirates
Western Sahara
Yemen

NORTH AMERICA, HIGH INCOME
Canada
United States of America
Saint Pierre et Miquelon

OCEANIA
American Samoa
Cook Islands
Fiji
French Polynesia
Guam
Kiribati
Marshall Islands

OCEANIA (Continued)
Micronesia (Federated States of) Nauru
New Caledonia
Niue
Norfolk Island
Northern Mariana Islands
Palau
Papua New Guinea
Pitcairn
Samoa
Solomon Islands
Tokelau
Tonga
Tuvalu
Vanuatu
Wallis and Futuna Islands

SUB-SAHARAN AFRICA, CENTRAL
Angola
Central African Republic
Congo
Democratic Republic of the Congo
Equatorial Guinea
Gabon

SUB-SAHARAN AFRICA, EAST
Burundi
Comoros
Djibouti
Eritrea
Ethiopia
Kenya
Madagascar
Malawi
Mayotte
Mozambique
Rwanda
Somalia
Sudan
Uganda
United Republic of Tanzania
Zambia

SUB-SAHARAN AFRICA, SOUTH
Botswana
Lesotho
Namibia
South Africa
Swaziland
Zimbabwe

SUB-SAHARAN AFRICA, WEST
Benin
Burkina Faso
Cameroon
Cape Verde
Chad
Cote d'Ivoire
Gambia
Ghana
Guinea
Guinea-Bissau
Liberia
Mali
Mauritania
Niger
Nigeria
Saint Helena
Sao Tome and Principe
Senegal
Sierra Leone
Togo