

# Heat stress and the labour force

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## Abstract

Heat stress affects the health of workers through physiological and behavioural responses, in turn, affecting the labour force through impacts on labour supply, labour productivity and labour capacity. In this Review, we explore the extent to which heat stress affects the labour force and discuss the corresponding occupational health and economic impacts. The relationship between labour force outcomes and temperature is largely nonlinear, declining sharply beyond peak thresholds. Observed and projected labour losses are heterogeneous across regions, sectors and warming levels. High-exposure sectors such as agriculture and construction are projected to experience the greatest losses under future warming, with ~33%, ~25% and ~18% declines in effective labour across Africa, Asia and Oceania, respectively, under a 3 °C warming scenario. Labour losses are also expected in low-exposure sectors such as manufacturing and utilities, but Northern Europe tends to benefit in the short run. These collective heterogeneous labour impacts lead to considerable reductions in global gross domestic product (GDP) and welfare, with projected GDP losses of 5.9% in South Asia and 3.6% in Africa. Improved local-scale exposure–response functions and incorporating adaptation into economic models are required to advance understanding of heat stress impacts on labour.

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## Introduction

Heat stress occurs when the human body is unable to maintain and regulate its internal temperature, the thresholds of which vary depending on the occupational setting and work intensity. It is generally associated with exposure to high temperatures, often combined with humidity, physical exertion or insufficient hydration<sup>1,2</sup>, and affects cardiovascular and respiratory systems, and physical capacity (Fig. 1). The risk of heat stress is greatest during heatwaves, the rising frequency and intensity of which has, in turn, caused an increase in heat stress incidence<sup>3</sup>. Projected warming – including global average increases of 1.5 °C by 2050 and 2–4 °C by 2100 – is further expected to increase future heat stress globally, particularly in sub-Saharan Africa, South Asia and parts of the Arabian peninsula<sup>4</sup>.

Through its impacts on human health (Fig. 1), extended exposure to heat stress can lead to negative and usually nonlinear effects on labour (Fig. 2a,b). These labour impacts encompass labour supply, labour productivity and labour capacity<sup>5</sup> (Fig. 2a), and they are driven by both physiological and behavioural responses. Labour effects are strongly heterogeneous<sup>6</sup> and are generally largest in outdoor working sectors such as agriculture and construction, particularly for low-income workers in sub-Saharan Africa, South Asia and Southeast Asia<sup>5,7–12</sup>.

As a result, labour impacts can cause (predominantly) negative impacts on economic output, economic growth and the health of workers. For instance, extreme heat-related impacts on manufacturing labour productivity reduced gross domestic product (GDP) in India by 3.5% from 1998 to 2009 (ref. 11). Heatwave impacts on labour similarly reduced European Union (EU) GDP by 0.3–0.5% over 2003–2018 (ref. 13). In extreme cases, heat stress can also lead to worker deaths, as reported in many nations<sup>3</sup> (Fig. 2c). For example, more than 550 workers died in Qatar from 2009 to 2019, and more than

10,000 workers are estimated to die every year in the Gulf countries<sup>14</sup>; these worker deaths are seemingly on the rise in places such as China, India and the Middle East<sup>15</sup>.

With ongoing anthropogenic warming, all these impacts tend to increase<sup>5,8,16</sup>. Therefore, a better understanding of the effects of warming on labour, as well as subsequent economic and worker health impacts, is needed, especially beyond short-term weather shocks. Through improved knowledge, individuals, firms and governments can undertake effective measures to protect workers. These actions might include implementing maximum temperature thresholds, early warning systems to provide information on high risk and/or heat stress days, mandatory breaks including water breaks, or decision-support tools<sup>17</sup>. Currently, however, there is very little information on the effectiveness of such measures.

In this Review, we outline how heat stress affects the labour force. We begin by examining the observed and projected impacts of warming on labour force outcomes, including labour supply, labour productivity and labour capacity. We subsequently focus on the economic impacts and implications for occupational health. Finally, we explore the adaptation opportunities and end with priorities for future research.

## Labour supply

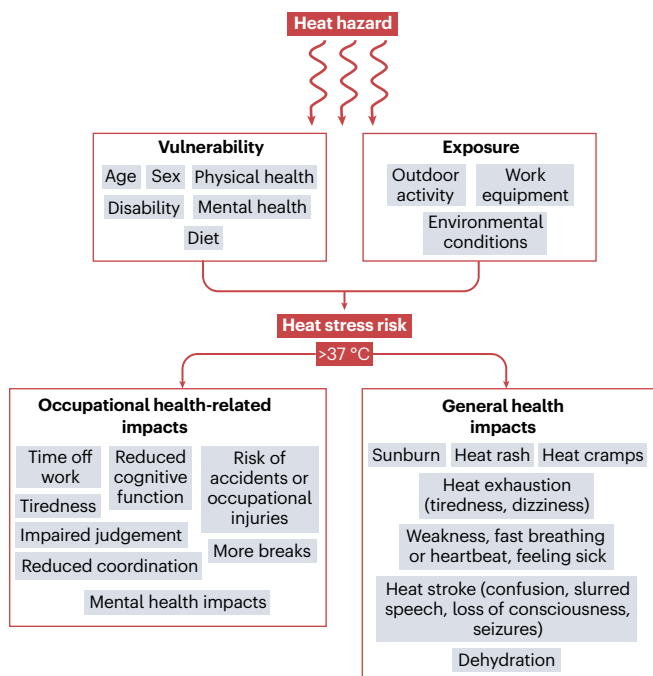
Labour supply refers to the amount of labour offered for hire per unit time. It is linked to high heat stress through involuntary or conscious reductions in working time, either by spending fewer hours at work or by taking more unpaid, irregular breaks<sup>5,18</sup>. The geographical and sectoral heterogeneity of heat stress impacts on labour supply, as well as projected future changes, are now discussed.

## Relationship with heat stress

The relationship between heat stress and labour supply is nonlinear<sup>5,10,19–22</sup> (Fig. 2b). Rising temperatures tend to increase labour supply up to a threshold, after which it falls rapidly. Although contrasting methodologies make comparison of these thresholds difficult, clear geographic and sectoral variability is evident, particularly between high-exposure (work taking place outdoor in the sun, such as agriculture and construction) and low-exposure (work taking place outdoors in the shade or indoors, such as manufacturing) sectors.

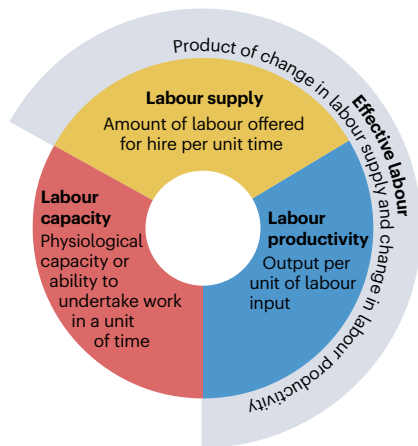
Labour supply in high-exposure sectors exhibits the strongest sensitivity to heat stress. Indeed, peak labour supply typically occurs at lower temperatures compared to low-exposure sectors<sup>5</sup>, with labour supply declining more sharply beyond this peak (or threshold)<sup>5,10,20,21</sup> (Fig. 2b). These thresholds vary by location (Fig. 3a). For example, labour supply peaks in high-exposure settings at mean temperatures of 21.3 °C in Africa, 20.2 °C in Asia, 20.6 °C in Central and South America, 14.3 °C in the USA and 11.2 °C in Europe<sup>5</sup>. By contrast, low-exposure optimum temperatures occur at 25.2 °C in Africa, 21.5 °C in Asia, 24.7 °C in Central and South America, 14.8 °C in the USA and 14.1 °C in Europe<sup>5</sup>. Thus, warmer countries tend to exhibit higher thresholds, possibly owing to worker adaptation<sup>5,10,11,19–21,23,24</sup>.

In addition to geography and sector, heat stress thresholds also differ by sex. For instance, the mean temperature at which labour supply peaks is 1 °C lower for female workers in high-exposure sectors of South Africa compared to male workers<sup>21</sup>. Lower temperature thresholds are also apparent for female agricultural workers in China who, in turn, experience ~2 h loss in work hours for an additional day above 26.5 °C compared to 1 h for men<sup>25</sup>; similar evidence is found in India<sup>26</sup>.

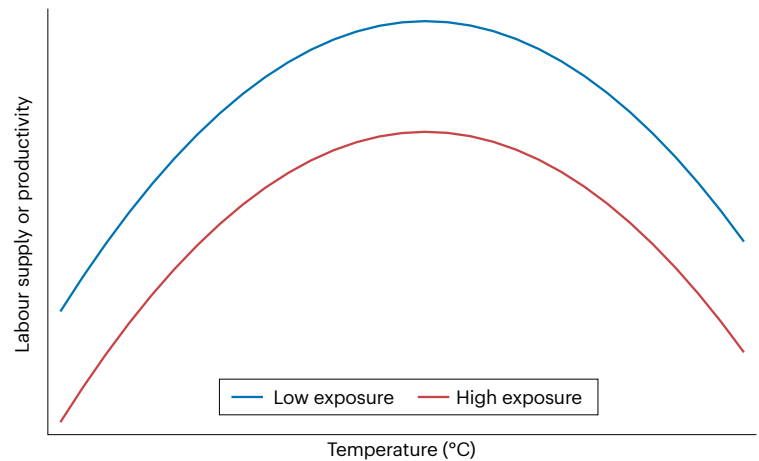


**Fig. 1 | Heat impacts on occupational health.** The factors influencing heat stress risk and the corresponding general health and occupational health impacts. Heat stress has multifaceted health impacts that influence labour.

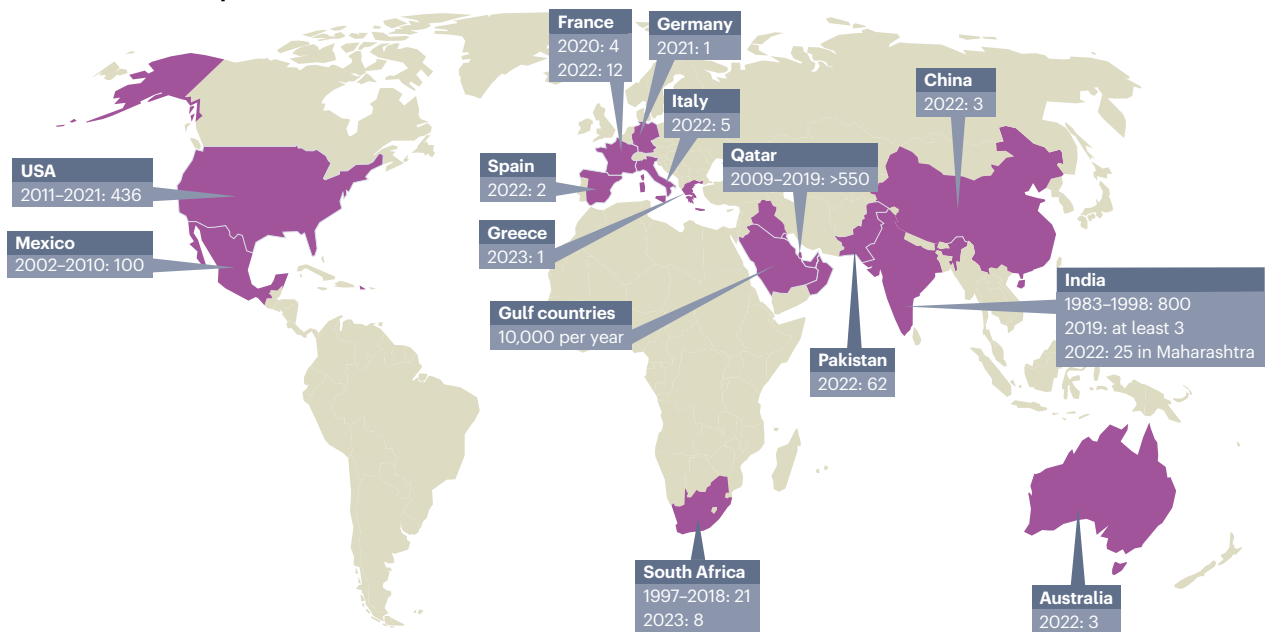
## a Definitions of labour force outcomes



## b Nonlinear impacts of heat stress



## c Recorded heat-related occupational deaths



**Fig. 2 | Labour force outcomes, temperature–labour relationship, and heat stress-induced occupational mortality.** **a**, The four measures of labour force outcomes. **b**, Representative nonlinear relationship between heat stress and labour supply or productivity for low-exposure and high-exposure sectors.

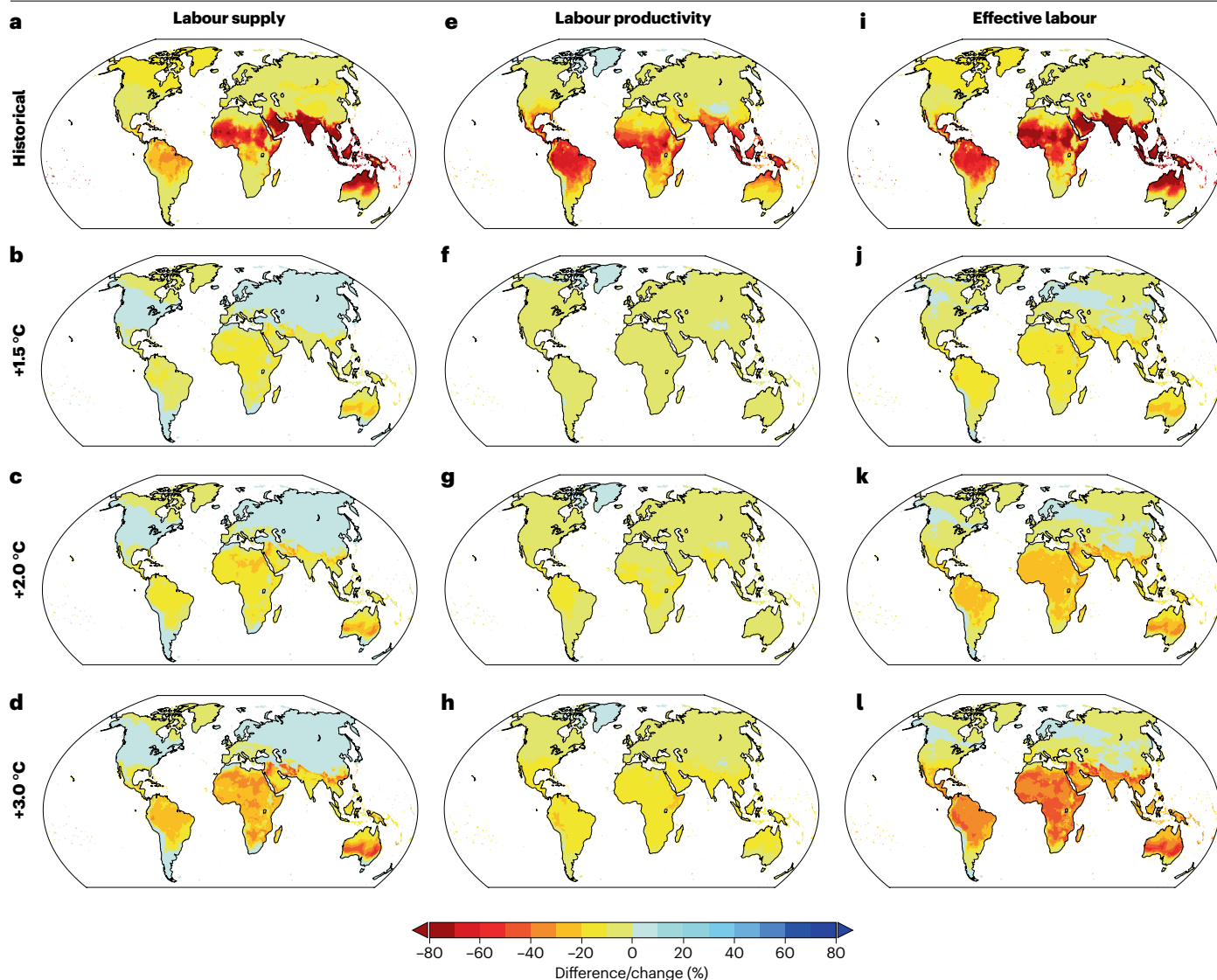
**c**, Recorded incidences of heat stress-related labour deaths, probably linked to direct heat impacts such as heat exhaustion, dehydration and heat stroke. Heat stress-induced occupational deaths are on the rise.

These differences relate to contrasting physiological thermoregulation between women and men<sup>21,27,28</sup>.

### Observed changes and influences

As temperatures and heat stress continue to increase, optimal temperature conditions are increasingly being exceeded, resulting in a reduction in labour supply. However, there is little direct evidence attributing observed labour changes to longer-term warming. Of that evidence, higher mean temperatures reduced total labour supply in high-exposure sectors of Europe by 1.05% in 2016–2020 compared to the 1964–1995 baseline, reflecting a loss of 17 h per worker per year (ref. 29).

Other empirical evidence from specific events or documenting heat stress–labour relationships from individual countries also offers insights, the findings reflecting geographic heterogeneities (Fig. 4a). In the USA, for instance, daily maximum temperatures >35.5 °C reduced labour supply by 4% in low-exposure sectors and 13% in high-exposure sectors<sup>30,31</sup>. Similarly, additional days with temperatures >26.5 °C reduced labour supply by 3% in China (ref. 25). Elsewhere in Asia, a maximum daytime temperature >37.7 °C reduced labour supply in India by 7% in 2011–2012 (ref. 32); and in Indonesia, the majority (66%) of workers in East Kalimantan report fewer work hours on days with Wet Bulb Globe Temperature (WBGT) > 27.5 °C (ref. 33).



**Fig. 3 | Historical and future heat stress impacts on the high-exposure labour force.** **a–d**, Historical and projected changes in high-exposure labour supply. **a**, Historical (1986–2005) impact (percentage point difference from optimal temperature conditions). **b–d**, Projected changes refer to changes under 1.5 °C, 2.0 °C and 3.0 °C warming scenarios relative to pre-industrial period.

**e–h**, As in panels **a–d** but for labour productivity<sup>62,65,75,78,85</sup>. **i–l**, As in panels **a–d** but for effective labour<sup>5</sup>. Heat stress is already negatively affecting the labour force, the effects of which are spatially heterogeneous and are expected to be substantially higher with future climate warming.

The numbers of hours worked also declines in Uganda, falling by -1 h per week for every 1 °C increase above weekly mean temperatures of 21.3 °C (ref. 20).

Relatedly, rising heat stress also increases absenteeism and sectoral reallocation of employment across the globe. In Brazil, for instance, one additional day with mean temperatures >30 °C increases the probability of absenteeism by 2% compared to the 18–21 °C reference bin<sup>34</sup>, whereas for garment and steel workers in India, any days with temperatures >35 °C beyond an initial 6-day period increase the probability of absenteeism by 0.5% (ref. 11). To minimize health impacts and maintain salaries, workers exposed to heat stress might be encouraged to pursue other opportunities in

low-exposure environments. For instance, at temperatures >30 °C, the probability of working in the agricultural sector in China is reduced by 1% (ref. 35).

### Projected changes

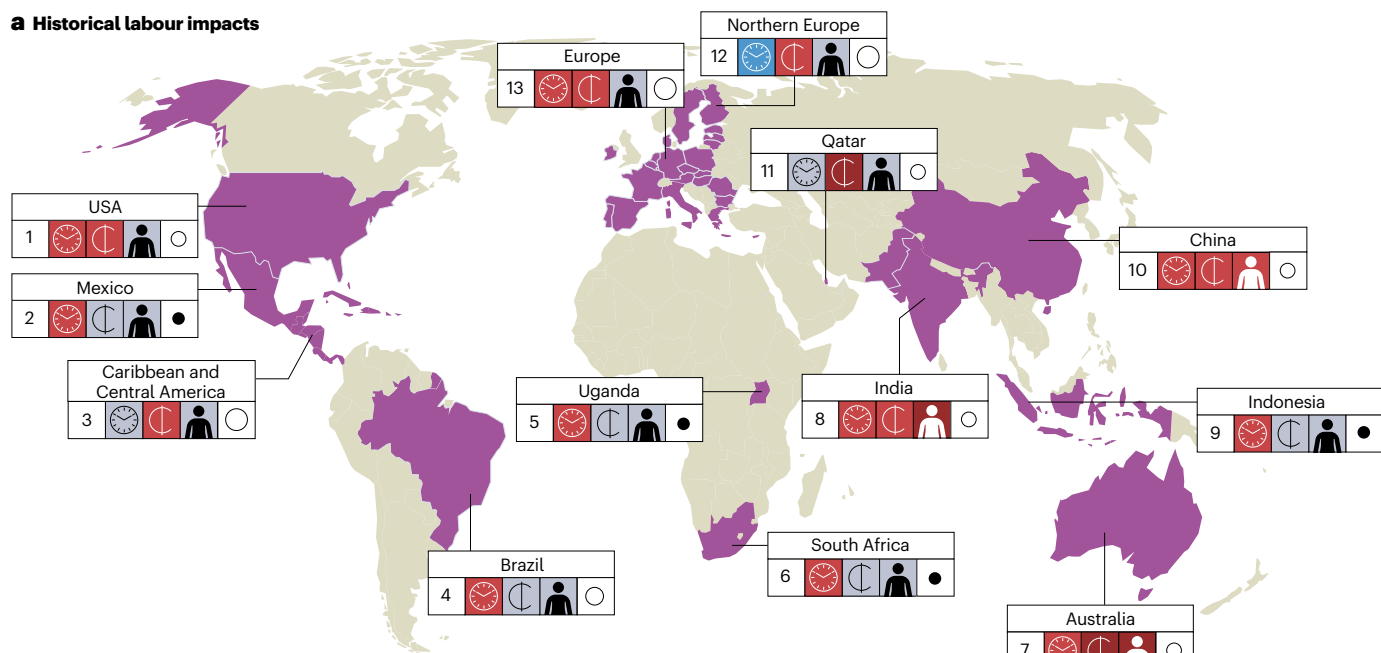
As with historical climate change, future warming is projected to generally have negative effects on labour supply (Fig. 4b). Any projections, however, are limited in that they assume that the labour force distribution across sectors remains fixed, most do not control for adaptation, and only the number of hours worked, and not worker effort, is affected by heat stress. Furthermore, changes in technology and labour market institutions might also lead to biased estimates in unknown directions.

# Review article

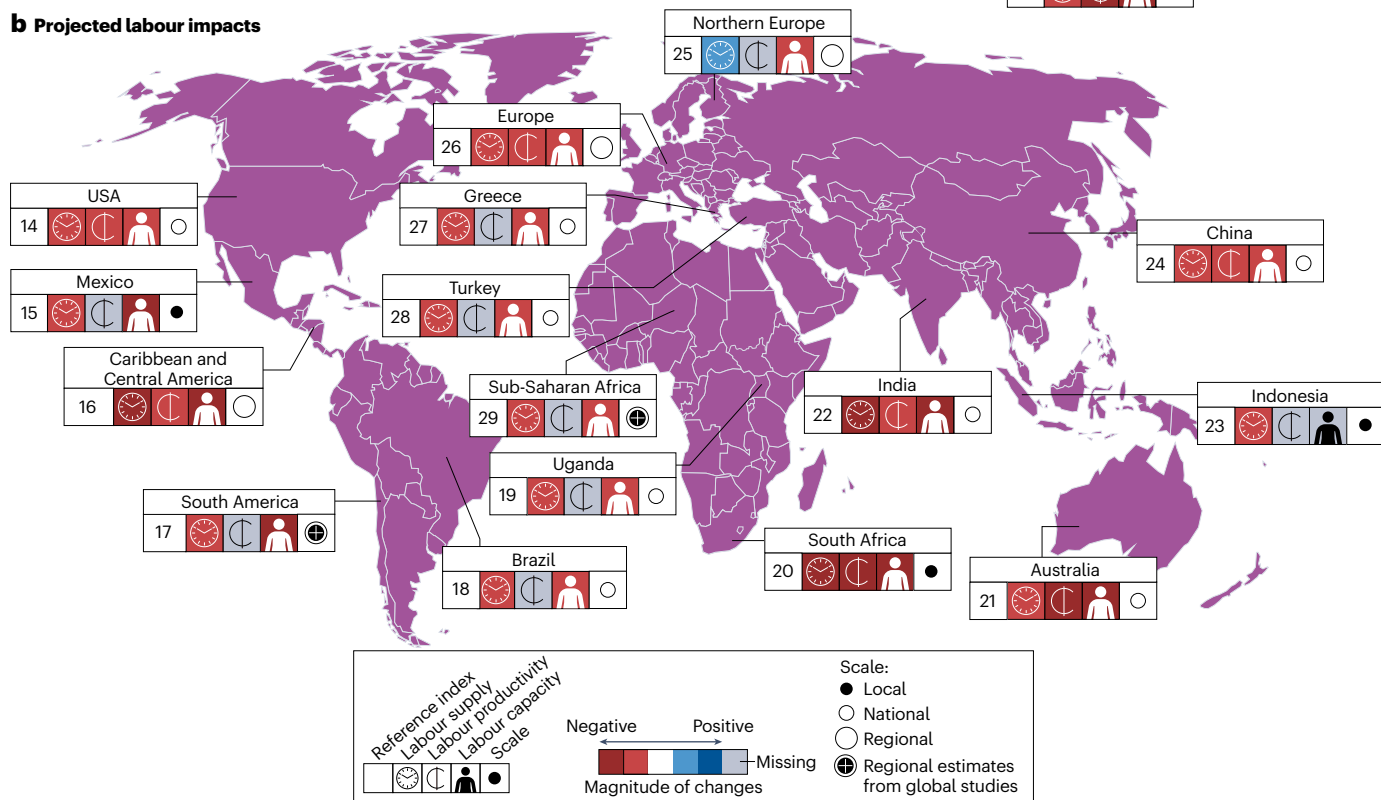
Nevertheless, projections indicate that labour supply effects vary geographically and by sector, exhibiting sensitivity to the level of warming (Table 1, Fig. 3b–d).

Total labour supply losses are projected to be highest in Africa, Asia, and Central South America. These losses are particularly prominent in high-exposure settings such as agriculture and

## a Historical labour impacts



## b Projected labour impacts



**Fig. 4 | Observed and projected labour impacts.** **a**, Summary of the sign and magnitude of historical impacts of heat stress on labour supply, labour productivity and labour capacity from published literature (Supplementary Table 1). The historical period broadly encompasses 1971–2020. **b**, As in panel **a**

but for future impacts of heat stress, broadly encompassing 2030–2100. Future climate change is projected to have large negative impacts on the labour force in Southeast Asia, sub-Saharan Africa and parts of Latin America, whereas positive impacts are projected only in Northern Europe.

**Table 1 | Percentage-point change in labour force outcomes by warming level relative to pre-industrial period**

Warming level (°C)	Africa		Asia		Central and South America		North America		Oceania		Europe	
	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High
<b>Change in labour supply<sup>a</sup> (percentage points)</b>												
1.5	-5.2	-7.8	-2.4	-5.4	-4.2	-5.1	-1.9	-2.6	-2.7	-4.6	0.4	-0.4
2.0	-8.0	-11.7	-3.8	-8.0	-6.2	-7.9	-2.7	-4.2	-4.3	-6.4	0.5	-1.0
3.0	-14.5	-20.1	-7.5	-13.0	-10.1	-14.1	-4.2	-6.4	-8.4	-11.7	0.7	-2.5
<b>Change in labour capacity<sup>b</sup> (percentage points)</b>												
1.5	-5.0	-6.2	-4.4	-5.3	-3.9	-4.0	-1.5	-2.7	-2.5	-4.4	-0.5	-1.2
2.0	-6.2	-9.2	-8.2	-8.2	-5.8	-7.6	-2.8	-4.4	-3.8	-5.7	-1.9	-1.9
3.0	-13.8	-16.0	-12.3	-14.2	-9.9	-14.3	-4.3	-6.0	-8.1	-11.2	-2.7	-3.4
<b>Change in effective labour (percentage points)<sup>a</sup></b>												
1.5	-9.9	-13.5	-6.7	-10.4	-6.5	-10.1	-1.3	-2.4	-4.8	-6.7	-0.1	-1.6
2.0	-14.9	-19.8	-10.4	-15.4	-10.1	-14.4	-2.2	-3.7	-7.6	-10.4	-0.3	-2.8
3.0	-25.9	-32.8	-18.6	-25.1	-13.6	-17.7	-4.5	-6.8	-13.8	-18.1	-1.0	-5.8

<sup>a</sup>From ref. 5. <sup>b</sup>Multi-model estimation using refs. 62,64,65,75,78.

construction which have the highest employment share in these regions. Indeed, at 1.5 °C warming, high-exposure labour supplies are projected to decline by 7.8, 5.4 and 5.1 percentage points for Africa, Asia, and Central and South America, respectively. These losses are substantially higher at 20.1, 13.0 and 14.1 percentage points for a 3 °C warming scenario<sup>5</sup> (Table 1). Labour supply losses in low-exposure sectors are relatively lower: 5.2 and 13.4 percentage points for Africa at 1.5 °C and 3 °C warming, respectively, 2.4 and 7.5 percentage points for Asia, and 4.2 and 10.1 percentage points for Central and South America (Table 1). There is clear regional variability in these future impacts, with the largest labour supply declines projected for sub-Saharan Africa, South Asia and Southeast Asia<sup>5,36,37</sup> (Fig. 3b–d).

Labour supply losses are comparatively smaller in the USA and Europe. In the USA, for instance, projected labour supply decreases by 2.6 and 6.4 percentage points in high-exposure sectors at 1.5 °C and 3 °C warming, respectively, and 1.9 and 4.2 percentage points for low-exposure settings (Table 1). In Europe, losses in high-exposure settings are even smaller at 0.4 percentage points for 1.5 °C warming and 2.5 percentage points for 3 °C warming (Table 1). For low-exposure settings, labour supply is actually projected to increase in northern Europe (including Sweden and Finland) and mountainous countries (including Austria) (Figs. 3b–d and 4b), largely owing to temperature still being below the optimal. Indeed, low-exposure sector labour supply is projected to increase by 0.4 percentage points at 1.5 °C and 0.7 percentage points at 3 °C warming (Table 1). However, these benefits tend to be short-lived as warming increases.

Along with these labour supply changes are labour reallocations from high-exposure to low-exposure sectors. Indeed, every 1 °C increase in mean temperature is expected to decrease district-level employment in high-exposure sectors by 7.1% in India, with corresponding increases in share of manufacture and service industries by 2% and 3.4%, respectively<sup>38</sup>. Relatedly, employment in low-exposure sectors in South Africa is projected to increase by 11.8% by 2100 under RCP8.5 (ref. 10) and 35.9% in China<sup>39</sup>. This heat stress-induced labour reallocation might result in migration and displacement within countries if workers find it difficult to find work. Alternatively, it could limit employment, as in rural Mexico where 0.3% and 1.4%

reductions are projected under RCP4.5 and RCP6.0 by 2075, respectively<sup>40</sup>.

## Labour productivity

Labour productivity is defined as the output per worker per hour worked<sup>41,42</sup> (Fig. 2a). Changes are driven by heat stress-induced fatigue, affected by environmental conditions, personal adaptive capacity and physical workload<sup>43</sup>. However, difficulties in collecting productivity data limit quantification of these relationships and influences. Using available evidence, the relationships between heat stress and labour productivity are now discussed, followed by observed and projected influences.

## Relationships with heat stress

Similar to the heat stress–labour supply relationship, the effect of heat stress on labour productivity is nonlinear<sup>11,44</sup> (Fig. 2b). Productivity tends to peak at an optimum temperature and decrease thereafter. This optimum temperature varies by location<sup>11,45</sup>, sector<sup>46</sup>, exposure<sup>47,48</sup> and intensity of required physical activities<sup>49</sup>, and it is typically 20–30 °C (ref. 45). As with labour supply, optimum temperature at which labour productivity is maximized is relatively lower in high-exposure sectors such as agriculture and construction<sup>5,8,49–52</sup>.

Epidemiological modelling and International Organization for Standardization standard risk functions show that labour productivity loss as a function of temperature for moderate intensity work (300W) follows a sigmoid curve, starting to pick up from 0% loss around 25 °C and surpassing 90% loss at around 32–38 °C (ref. 53). Compared to thermoneutral conditions, WBGT greater than 22 °C or 24.8 °C (depending on work intensity) causes about a four times higher environmental heat stress on the body, and the core temperature of workers increases by 0.7 °C on average<sup>37</sup>.

## Observed and projected influences

Empirical evidence offers insight into shorter-term influences of heat stress on labour productivity across the globe (Fig. 4a). In China<sup>54</sup>, India<sup>11</sup>, Europe<sup>46</sup>, and the Caribbean and Central America<sup>48</sup>, for example, a 1 °C increase in average temperature is associated with

3.5–6%, 2–4%, 3% and 2.5% reductions in industrial and/or manufacturing productivity or output, respectively; a 1 °C increase in WBGT in Hong Kong also reduces construction productivity by 0.33% (ref. 47). Compared to baseline temperatures, temperatures >37°C lowered the productivity of blueberry pickers by 12% in the USA<sup>55</sup>; temperatures >35°C lowered paper cup manufacture productivity by 8.5% in China<sup>44</sup>; temperatures >28°C lowered garment factory productivity by as much as 8% in India<sup>11</sup>; and temperatures >35°C lowered construction sector productivity by 18–35% in Chennai, India<sup>56</sup>. Evidence also demonstrates heat stress effects for less explicit thresholds, including Australia (35% declines in productivity during days perceived to have been affected by heat stress<sup>49</sup>) and Qatar (up to 50% declines in productivity in high-exposure sectors in summer compared to winter<sup>57</sup>). Micro-level survey data similarly provide supporting evidence of heat stress reducing productivity<sup>58,49–51</sup>.

Future warming is projected to affect labour productivity further. However, limited projections are available owing to the lack of historical data<sup>17</sup>. As with labour supply, future changes to labour productivity are dependent on sector, geography and warming level (Figs. 3f–h and 4b). Without adaptation, productivity losses will be highest in high-exposure and high-intensity sectors of Asia and Africa. Country-level analyses support these findings, revealing productivity losses in Southeast Asia, Central America and the Caribbean<sup>5,7,58</sup> (Fig. 4b). Furthermore by 2080, labour productivity in the Indian manufacturing sector is projected to fall 8.9% under RCP8.5 relative to 2005–2010 (ref. 11). Productivity losses are consistently lower in Europe and North America (Fig. 3f–h and 4b). In Europe, for example, 2.5% and 3.75% losses are projected in the agricultural sector under 1.5 °C and 2.0 °C warming, respectively, reaching 5% in Mediterranean and Southern European countries under 2 °C warming<sup>46</sup>.

## Effective labour

Although labour productivity and labour supply offer useful insights, they do not provide the broader picture of labour force changes as a whole. Effective labour – the product of changes in labour supply and labour productivity – offers a more comprehensive assessment of the impact of heat stress on the labour force<sup>5</sup>.

Given that effective labour is a composite of labour supply and labour productivity, the patterns of projected changes are largely consistent. Changes are largest in sub-Saharan Africa, South Asia and Oceania (Fig. 3j–l), increase with rising temperature, and are larger for high-exposure settings than for low-exposure settings (Table 1). Effective labour losses are highest in Africa, reaching 13.5 and 32.8 percentage points for high-exposure settings at 1.5 °C and 3 °C warming, respectively, and 9.9 and 25.9 percentage points for low-exposure settings. By contrast, losses are smallest in Europe at 1.6 and 5.8 percentage points for high-exposure settings at 1.5 °C and 3 °C warming, respectively, and 0.1 and 1.0 percentage points for low-exposure settings (Table 1).

## Labour capacity

Labour capacity considers the physiological ability to undertake work under prevailing environmental conditions per unit time. However, the metric is often used inconsistently<sup>59</sup> and/or interchangeably with labour productivity<sup>58,60,61</sup>. Physical capacity<sup>6,62,63</sup>, level of work achieved at different work intensities<sup>64</sup>, the ability to conduct work safely<sup>35</sup> and cognitive function of workers<sup>65–67</sup> have also been used. These inconsistencies impede robust comparisons, not least because capacity changes are reported as a percentage<sup>62</sup> or as a loss of labour hours<sup>78,68,69</sup>. Labour capacity can be estimated using an empirical approach or a standards

approach<sup>61,70</sup> (using relationships developed by the National Institute for Occupational Safety and Health<sup>71</sup> and the International Organization for Standardization<sup>72</sup>), each with their advantages and disadvantages. The relationships between heat stress and labour capacity are now discussed, as are the observed and projected impacts.

## Relationships with heat stress

Heat-related changes in labour capacity vary in different environmental and professional settings depending on the nature of the work (outdoor versus indoor, and intensity of work) and exposure to environmental factors such as temperature, humidity, wind speed and shade conditions. Most exposure–response functions do not account for regional differences. Because climate change effects are localized, global-level response functions, as commonly used in climate change impact assessments, have probably resulted in biased estimates. The empirical approach estimates labour capacity from observations of human performance at different temperatures in either idealized environments such as climatic chambers or treadmills<sup>73,74</sup>, or in real-world work environments<sup>56,62,75,76</sup>. These methodological differences have resulted in a large range of estimated reductions in labour capacity linked to increases in WBGT, from as low as 15% (ref. 77) to as high as 70% (ref. 78) (Fig. 3).

The range of estimates varies considerably, depending on the climate conditions, type of work, fitness level of workers and the workload. Empirical models find a range of 20–40% reduction in work capacity at a WBGT of 30 °C, depending on the fitness level of the workers<sup>79</sup>. Labour capacity loss appears to be greatest among agricultural workers followed by workers employed in the construction sector<sup>7,8,36,60,80–82</sup>. The largest declines in labour capacity owing to heat stress have been found in South, East, and Southeast Asia, the Middle East, and South and Central America<sup>7,8,68,69,78</sup>, regions with a relatively high share of working-age population working in the agriculture sector<sup>5,8</sup>. In terms of countries, the highest declines in labour capacity owing to heat stress are in Bangladesh, China and India<sup>60,82</sup>. Some higher-income countries have also experienced reduced labour capacity as a result of increasing temperatures<sup>83</sup>.

## Observed changes and influences

Similar to labour supply and productivity, rising heat stress has caused declines in labour capacity. At the global scale, these losses are thought to total 490 billion potential labour hours in 2022 (ref. 7). These hours lost represent capacity changes of –9%–20% since –2000 (refs. 8,78,80,83) or 11% of full work capacity over 1990–2010 based on physical work capacity (the maximum physical work output that can be reasonably expected from an individual performing moderate to heavy work over an entire shift)<sup>79,84</sup>. There is also evidence of short-term capacity losses from heat stress for specific occupational settings such as factories, mines and farms (Fig. 4a). For example, rice farmers in India experienced a 5% decline in labour capacity per 1°C increase in WBGT between 26 °C and 32 °C (ref. 62). In China, direct work time decreased by 0.57% when WBGT increased by 1 °C in 2014 (refs. 50,62,75,76).

## Projected changes

Future warming is expected to reduce labour capacity further (Table 1, Fig. 4b). However, these projections must be treated with caution as many are based on exposure–response functions that use a small number of observations from specific locations but are computed at the global level<sup>62,78</sup>. Also, uncertainties have often also been overlooked or under-estimated<sup>58,64,70,78,85</sup>, although assessments now routinely

quantify effects using multiple climate models, emissions scenarios and labour capacity models<sup>5,45,86–89</sup>. To date, there are no probabilistic projections or assessments that have used the latest IPCC Shared Socioeconomic Pathways emission scenarios<sup>4</sup>.

Labour capacity losses are expected at the global, continental and national levels. For instance, at the global scale, heat stress is projected to reduce total labour capacity by 2.2% by 2030 (ref. 24). Similar to other measures of labour force, the magnitude of changes varies depending on the sector, and is greatest for high-exposure outdoor settings<sup>84,90</sup>. For instance, global labour capacity is projected to decrease by 13.6% for high-exposure settings and 11.5% for low-exposure settings at 3 °C warming relative to pre-industrial period<sup>5</sup>. Relatedly, outdoor labour capacity is projected to decline to 54% of the theoretical maximum by the 2090s under RCP8.5; for comparison, labour capacity was estimated to be at 82% of the maximum during 2001–2010 owing to warming-induced increases in heat<sup>91</sup>.

Consistent with labour supply and labour productivity, the highest impacts are expected in Africa, Asia and Oceania<sup>5,92</sup> (Table 1, Fig. 4b). For instance, at 1.5 °C warming, high-exposure labour capacity losses compared to pre-industrial period are 6.2, 5.3 and 4.4 percentage points for Africa, Asia and Oceania, respectively; these reductions increase to 16.0, 14.2 and 14.3 percentage points, respectively, at 3.0 °C warming (Table 1). Changes in low-exposure sectors are lower: losses reach 5.0 and 13.8 percentage points for Africa at 1.5 °C and 3 °C warming, respectively, 4.4 and 12.3 percentage points for Asia, and 2.5 and 8.1 percentage points for Oceania (Table 1); note, however, that the uncertainty for these estimates is high<sup>5</sup>. At the national level, these losses can be much higher, especially in sub-Saharan Africa and Southeast Asia<sup>80,93</sup>. Elsewhere, annual heat-related work hours lost in China is projected to increase by 11% under RCP4.5 and 121% under RCP8.5, compared to 1986–2005 (ref. 94), and in Bahrain, Cambodia, Pakistan, Qatar and the UAE, 11%–15% declines in annual labour capacity are expected with 3 °C warming<sup>95</sup>.

Labour capacity losses tend to be consistently lower in North America and Europe (Fig. 4d). Losses reach 2.7 and 1.5 percentage points for high-exposure and low-exposure settings in North America at 1.5 °C warming, respectively, increasing to 6.0 and 4.3 percentage points for 3 °C warming (Table 1). In Europe, by contrast, capacity losses are 1.2 and 0.5 percentage points for high-exposure and low-exposure settings at 1.5 °C warming, respectively, and 3.4 and 2.7 percentage points for 3 °C warming (Table 1); uncertainty is lowest here also, reflecting greater confidence in regional warming magnitudes. Thus, the least-negative impacts are expected in Europe, consistent with labour supply and labour productivity. Nevertheless, high changes are expected in some regions. In Turkey, for instance, potential working hours are projected to decline by 8% in 2071–2100 under a high-warming scenario, with losses in some regions as high as 52% (ref. 96). In Greece, 5%–10% declines are also expected by the 2080s under a high-warming scenario<sup>87,88</sup>.

## Macroeconomic impacts

Impacts on the labour force provide a key transmission channel through which heat stress causes economic damages. Various approaches can be used to quantify historical and projected impacts, including simplistic methods that multiply lost working hours by sectoral income or average value added per worker<sup>78,24</sup>, primarily to assess observed impacts; econometric or statistical methods that use observed data to quantify the historical impacts of heat stress on the economy through labour force damages; or structural modelling such as with

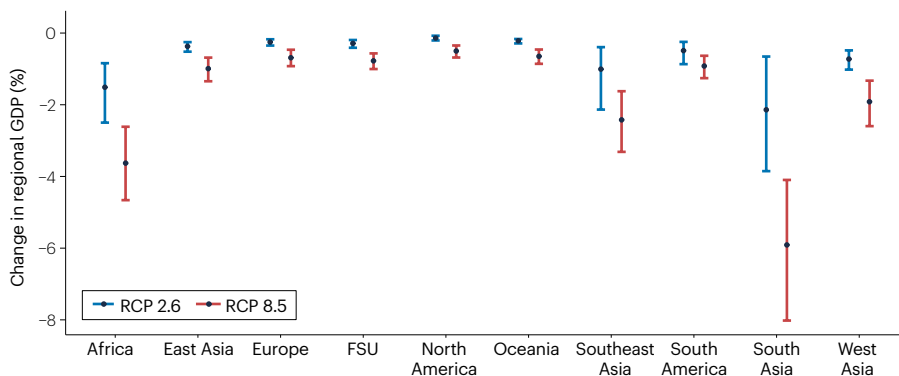
computable general equilibrium models (CGE, calibrated with heat stress-induced labour outcome shocks to estimate their spillover effects on potential changes in terms of trade, competitiveness, household income and GDP<sup>97</sup>) or integrated assessment models (IAMs, represented through aggregated or reduced-form damage functions in IAMs<sup>98</sup>) that are primarily used for projected impacts. These methods all have weaknesses, limiting inter-method comparisons and emphasizing that any results should be interpreted with caution.

Specific heat events – through effects on labour – have had various observed impacts on macroeconomic indicators such as GDP, GDP per capita and income per capita. Indeed, heat stress impacts on labour caused losses equivalent to 1.7% of global GDP in 2017 (ref. 8). In Europe, the 2003, 2010 and 2015 heatwaves resulted in losses of US\$59–90 and US\$41–72 per agricultural and construction worker, respectively<sup>86,99</sup>; the largest losses per worker were in Cyprus, Italy and Spain. These heatwave events, plus that of 2018, also contributed to total annual European Union GDP losses of 0.3–0.5% (ref. 13). In Spain, the estimated annual economic burden of work hours lost owing to heat stress is €370 million (0.03% of Spain's GDP) during 1994–2013 (ref. 100). The 2013–2014 heatwave in Australia caused a 0.4% decline in GDP, equivalent to US\$6.2 billion (ref. 49), and the 2013 heatwave in China resulted in a 0.7% direct output loss and 4.4% of indirect output loss in the manufacturing sector in Nanjing<sup>101</sup>.

Projections of these economic impacts vary substantially depending on the methodology and the region. For example, global GDP losses by end of the century are estimated to be 0.3% using IAMs<sup>12,91</sup> and 0.1% using CGE models<sup>16,86</sup> under RCP2.6. Under RCP8.5, these losses are projected to be 2.6% for IAMs<sup>12,91</sup> and 1.4% for CGE models<sup>86</sup>. Under RCP8.5, the largest GDP losses are expected in South Asia (5.9%), Africa (3.6%), Southeast Asia (2.4%) and South America (0.9%)<sup>102</sup> (Fig. 5), but there is considerable country-level variability. Specifically, losses of 20% GDP per capita are projected in Uganda and South Africa by the end of the century under RCP8.5 (refs. 10, 20, 21) and 32% and 27.5% in India and Indonesia under a 3 °C warming scenario<sup>103</sup>, respectively.

High-income countries also experience economic damages owing to heat stress-induced labour productivity losses. For example, under RCP8.5, these losses are projected to be US\$1.16 billion in Switzerland by 2050 (ref. 104) and US\$150 billion in the USA by 2080–2099 (ref. 105). There are also potential international spillover effects of labour productivity shocks owing to heat stress<sup>106</sup>. For instance, declines in labour productivity in trading partners outside the EU are projected to result in GDP losses of up to €80 billion (0.63% of GDP) under a high-warming scenario<sup>61</sup>.

Sectoral impacts are also substantial. Given that agriculture is an important sector through which heat stress-induced impacts on the labour force are transmitted, countries with a relatively higher share of agriculture GDP and a higher share of workers in the agricultural sector tend to be particularly vulnerable, both in terms of income and distributional implications, as these workers generally are some of the lowest earners<sup>107</sup>. Indeed, climate change induced labour capacity decline in the agricultural sector could result in a global welfare loss of US\$136 billion under a 3 °C warming scenario, with crop prices increasing by 5%, relative to 1986–2005 (ref. 80). Moreover, the manufacturing output of China is projected to decline by 12% by 2050, equivalent to a loss of US\$39.5 billion, under a 4 °C warming scenario<sup>108</sup>, whereas a 1 °C increase in future temperature is projected to reduce manufacturing output in India by 3.5%–5% (ref. 11).



**Fig. 5 | Future impacts of heat stress on the labour force.** Reductions in regional gross domestic product (GDP) in 2100 compared to a 'no climate change' scenario for representative concentration pathway (RCP) 2.6 (blue) and RCP 8.5 (red)<sup>86</sup>. Error bars indicate uncertainties in the estimates arising from climatic and socioeconomic scenarios. Economic costs resulting from heat-induced reductions in worker productivity vary geographically and are projected to increase. FSU, former Soviet Union.

## Implications for occupational health and safety

In addition to impacts on various labour outcomes, heat stress also affects occupational health and safety<sup>83,109–115</sup>. These occupational health concerns emerge through heat stress-related reductions in cognitive function, judgement, motor performance and coordination<sup>83,109–111</sup>, which in combination with dehydration<sup>79,116</sup>, dizziness and muscle cramps all reduce safety and increase the risk of injuries in the workplace<sup>117,118</sup> (Fig. 1). In extreme cases, heat stress can also cause congestive heart failure, acute kidney injury<sup>119–124</sup>, heatstroke and death (Fig. 2c).

Similar to labour force outcomes, occupational health impacts vary markedly by sector. Risk is largest in high-exposure and high-intensity sectors such as construction<sup>111</sup>, mining, agriculture<sup>119,125–127</sup> and manufacturing<sup>75,100,112,128</sup>. For example, a 1 °C increase in minimum temperature during 2011–2012 is associated with 1.7% increase in daily injury claims among manufacturing sector workers in Guangzhou, China<sup>112</sup>.

Occupational health impacts are also geographically heterogeneous. Heat stress effects on occupational health are largest in Asia, Africa and South America where high-exposure employment dominates. In China, for example, a 1 °C increase in maximum temperatures above 33.8 °C is associated with a 41.6% increase in medical costs and a 74.8% increase in days lost owing to occupational injuries<sup>129</sup>. During 2011–2012, 4.1% of insurance payouts were attributable to heat stress when WBGT > 25°C (ref. 74). Health impacts on workers are also increasingly prevalent in high-income countries (Fig. 2c). Work-related injuries in Australia<sup>83</sup> and Spain<sup>100</sup>, for instance, increase for indoor and outdoor workers during periods of moderate or extreme heat stress. In the case of Spain, 2.4% of all injuries from 1994 to 2013 were associated with heat stress, resulting in 0.58 million person-days lost and an economic cost of €320 million (ref. 100). In Italy, 1.7% of the occupational injuries during 2014–2019 can be attributed to high temperatures (mean temperature above the 75th percentile)<sup>111</sup>. Similar connections are also evident in the USA, where 36% of deaths amongst construction workers from 1992 to 2016 are linked to heat<sup>130</sup> and where injury compensation claims against the Washington State Fund have also increased owing to rising heat stress<sup>125</sup>.

Generally, risk is greatest for older and inexperienced workers who are more physiologically vulnerable<sup>111</sup>. However, younger workers also tend to be at risk owing to lack of heat stress acclimatization in the work place.

In line with rising heat stress, the risk of heat-related injuries and illnesses is increasing across occupational and income settings.

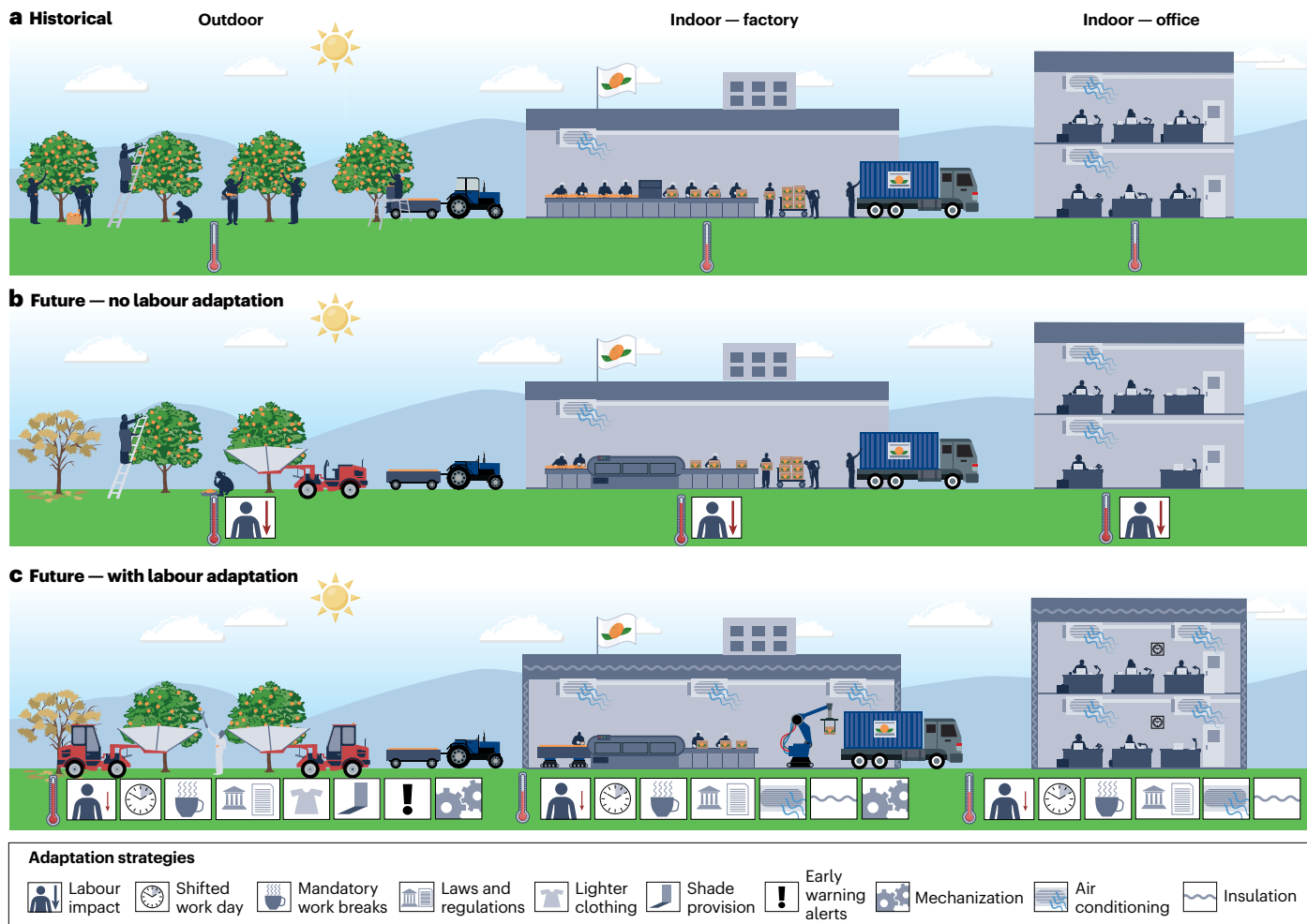
This heightened risk is found in outdoor<sup>119,125–127</sup> and indoor settings<sup>111</sup> for low-income<sup>128</sup> and high-income countries<sup>111,130</sup>. According to the International Labour Organization, an estimated 22.85 million occupational injuries, 18,970 deaths and 2.09 million disability-adjusted life years can be attributed to excessive heat at the global level<sup>15</sup>. Any such heat-related injuries also have corresponding compensation, medical and rehabilitation costs<sup>100,129,131</sup>, with workers increasingly claiming compensation for medical expenses, lost wages and, in extreme cases, disability or impairment benefits. Furthermore, the risk of heat stress-related occupational injuries tends to increase in the future. By 2100, on average nearly 6 h of work time will need to be shifted from current daytime work schedules to offset labour losses<sup>91</sup>.

## Adaptation opportunities

Given the negative health and economic impacts of heat stress on workers in most countries, adaptation efforts are necessary and will become increasingly so as heat stress and its impact on labour continue to rise (Fig. 6). These efforts are designed to change the relationship between heat stress and labour force impacts. Full adaptation implies that labour-related damages do not increase while heat stress increases, whereas partial adaptation reduces the gradient of the temperature–labour outcome damage curve. There is likely already a gap between actually implemented adaptation and the adaptation required to meet social and humanitarian objectives, that will probably grow unless more explicit adaptation action is taken<sup>87,116,132,133</sup>. Adaptation efforts can be autonomous actions by workers, employer driven, or government legislated and enforced<sup>116</sup> and can take place in outdoor or indoor environments (Fig. 6).

Autonomous heat adaptation measures by workers are those that occur without explicit employer or government intervention and are largely behavioural or practice responses<sup>134</sup>. These actions might include workers changing what they wear<sup>133</sup>, taking additional breaks<sup>33</sup>, working more slowly<sup>116</sup>, increasing hydration<sup>17,133</sup>, shifting working hours<sup>91,135</sup> or even seeking employment in a location or sector with less heat exposure<sup>10,20,21,136</sup> (Fig. 6c) – there is a lack of evidence on the effectiveness of adaptation actions. The ability of workers to adapt to increasing temperatures can be constrained by regulation, employment rules, information asymmetries or lack of unionization. For example, some workers might be able to choose to work during cooler hours of the day when others cannot. Moreover, the extent to which and how a worker adapts will also be influenced by their contract type, such as whether they are paid a salary, paid according to output, or are subcontracted<sup>10,17,133,136</sup>.

# Review article



**Fig. 6 | Heat stress impacts and adaptation opportunities.** **a**, Historical temperatures and working conditions across outdoor, factory and office environments in the food sector. **b**, As in panel **a** but for a future scenario with no labour adaptation. Comparison of thermometers and icons indicates changes in temperature and labour compared to historical temperatures and working conditions, respectively. **c**, As in panel **b** but for a future scenario with labour

adaptation. Icons also reveal adaptation strategies available for the specific working environment. These environments are only to indicate the range and benefits of adaptation opportunities across a work environment. Introduction of early warning systems, mandatory breaks and shifting work hours could be particularly effective in reducing outdoor exposure during the hottest times of the day.

Employers might also adopt heat stress adaptation strategies in an effort to minimize labour and economic losses. These strategies can include shade provision for outdoor workers<sup>33,53,137</sup>, adjusting formal hours of work from hotter to cooler parts of the day<sup>24</sup> (including night-time working), use of exoskeletons (mechanical structures that workers can wear to help increase their strength and endurance)<sup>87</sup>, use of light-coloured or light clothing, mechanization, rest and recovery spaces<sup>132</sup>, and climate control (such as air conditioning)<sup>11,12,87</sup> (Fig. 6). These approaches have known benefits. In Florence, for example, a 1 h earlier start reduced productivity loss by 18% amongst agricultural workers<sup>53</sup>. Moreover, light-coloured clothes can reduce the skin temperature of workers by 12–13% compared to darker-coloured clothes<sup>138</sup>. In manufacturing plants in India, climate control has also been found to reduce the negative effect of temperature above 30 °C on labour productivity<sup>11</sup>. However, there is often a lack of robust empirical evidence regarding the costs and benefits

of various adaptation options<sup>5,17,116</sup>, particularly in economically relevant settings.

In addition to these employee and employer strategies, some adaptation efforts are also government legislated and enforced (Fig. 6). These laws largely involve maximum temperature thresholds at which work can take place and limiting certain types of work during extreme heat<sup>139</sup>. Several governments have enacted new laws and regulations as an adaptation response to increasing heat: in Puglia, Italy, farm work is prohibited between 12:30 and 16:00 on ‘high-risk’ days between June and September; in Qatar, outdoor work is prohibited when WBGT > 32.1 °C in the summer<sup>77</sup>; in China, worker protection plans limit continuous work when the daily maximum temperature is 35–37 °C and suspend outdoor work when WBGT > 40 °C, although the enforcement of these regulations appears to vary between local provinces<sup>140</sup>. However, many countries do not have a legal maximum temperature, although the European Commission has communicated

that additional worker protection action on climate risks will be considered<sup>141</sup>. Government-mandated or implemented early-warning systems and accurate weather forecasts can also protect workers from the adverse effects of heat stress<sup>142</sup>.

Lack of information is a limiting factor for adaptation across worker, employer and government efforts. There are several market imperfections that could affect adaptation decisions, where governments might have an important role. One possibility is that workers, employers and government might have asymmetric and incomplete information concerning the effects of heat stress on the health of workers, leading to a gap between what a social planner might implement and what is actually realized in the labour market. For example, it is only relatively recently that the incidence of kidney disease in agricultural workers is being linked to increased heat stress<sup>123,143</sup>. To the extent that workers and/or employers are not fully cognizant of heat-induced health effects (including slower onset illnesses such as chronic kidney disease), better information on the health and economic impacts of climate change can comprise an important input to effective and efficient adaptation measures. Lack of awareness among workers and employers (as high as 41% reported in some surveys<sup>144</sup>) regarding adaptation strategies and their effectiveness might also be a major barrier to implementing adaptation in the workplace<sup>29,30</sup>.

Adaptation efforts are anticipated to reduce heat-related losses in labour supply and productivity, and their associated economic impacts. Indeed, it has been suggested that labour productivity losses under future warming could be 10%–40% lower with adaptation<sup>96</sup>. Accordingly, up to 70% of economic losses are thought to be preventable using effective adaptation measures such as shifting working hours, installing air conditioning and mechanization<sup>145</sup>. Shifting the work day by up to 3 h alone can reduce global GDP loss by 0.3%, 0.4%, 0.5% and 0.7% at 1.5 °C, 2.0 °C, 3.0 °C and 4.0 °C warming, respectively, by 2090 (ref. 146). Labour productivity losses owing to climate change impacts on health (vector-borne, respiratory, and gastroenteric diseases) are also estimated to cost just 0.1% of GDP in 2050 in lower-income countries if adaptation measures to protect workers are adopted, with a key assumption that adaptive capacity improves with income levels<sup>97</sup>. However, there is still insufficient incorporation of adaptation into IAMs, in part because the definition and empirical measurement of adaptation remains contested, and in part because there is still insufficient understanding particularly of the long-term impacts of heat and heat stress on health.

Although adaptation efforts are designed to be beneficial, some measures can result in maladaptation when considered in the broader context of health, wellbeing and economic growth. For example, shifting working hours away from the hottest hours of the day becomes less effective as early morning and late evening heat exposure increases<sup>8</sup> and can adversely affect the health of workers owing to sleep disruption<sup>5,17,33</sup>. Furthermore, shifting the work day can expose workers to increased risks from some infectious diseases (including malaria, Lyme disease and dengue<sup>15</sup>), harming the physical and mental health of workers<sup>135,147,148</sup>. Cooling through the removal of protective clothing can expose workers to higher risks of injury<sup>134</sup>. Although air conditioning could reverse some of the effects of warming, it can be considered as an example of maladaptation if the electricity used is generated from fossil fuels. Efforts to protect health can come at the cost of productivity and the earnings of workers, or increased labour costs; in extreme cases, it can involve closure of a factory or movement to a cooler location, incurring costs and harming livelihoods. Despite these potential trade-offs, implementing adaptation measures to

protect the health of workers tends to be a win–win strategy if it also improves productivity and reduces absenteeism, resulting in improved profitability and output<sup>17,139</sup>.

## Summary and future perspectives

Rising heat stress is affecting the labour force, the impacts of which are heterogeneous across occupational settings, income groups, gender and location. Labour supply, productivity and capacity decrease during periods of heat stress, most notably in high-exposure outdoor sectors such as agriculture and construction in sub-Saharan Africa, South Asia and Southeast Asia. Through these impacts on labour, heat stress exposure also has negative effects on economic output, economic growth, the health of workers and occupational safety. Projections suggest these negative impacts on the labour force (including geographic and sector variability) will worsen as heat stress increases with rising temperatures. Mitigation efforts can deliver global health and economic co-benefits across all sectors and regions, but adaptation will probably be important for protecting workers from increased heat stress, even if warming is limited to 1.5 °C. However, there are still many unknowns about heat stress impacts on labour, necessitating continued research.

Much of the research on labour has focused on individual components such as labour supply or productivity. As such, understanding of the overall impact of heat stress on the labour force is lacking, providing a limited picture that overlooks cumulative and cascading effects. Composite metrics are therefore needed, of which effective labour is one example (Table 1, Fig. 3j–l). Such a metric would enable estimation of the impacts of heat stress on labour force as a whole. Furthermore, economic models that integrate these impacts can provide more realistic estimates of economic damages due to the effects of heat stress on the labour force. Such a complete picture would also contribute to the loss and damage debate in the historical context and allow more realistic identification of future heat–labour damage hotspots.

Global-level analyses suggest that some regions have higher tendency to experience larger labour impacts. However, deep-dive evidence that incorporates local contexts is often lacking, particularly from Latin America and most of Africa where some of the most vulnerable workers live<sup>21,149</sup>. Such evidence provides understanding of the dynamics between socioeconomic drivers and climatic stressors, critical for designing local adaptation policies and policy-relevant projections of future changes. Dedicated data collection can fill this gap, with a focus being on labour productivity and adaptation measures. Workers in the gig economy are particularly vulnerable to heat stress as they tend to have fewer protections than other workers, and they might have to trade off health and income during periods of heat stress. In the context of impacts on occupational health, a major gap is estimating the number of workers that are harmed by extreme heat. More data is also needed on occupational injuries and mortality in the context of heat stress, especially from countries in the underrepresented regions in South America and Africa (Fig. 1c).

Empirical evidence of the direct impact of climate change on labour productivity and labour capacity still also lacks a harmonized and standardized approach. In particular, exposure–response functions have, thus far, been based on a small number of observations from a limited number of locations and workers, leading to an insufficient empirical foundation for macroeconomic models. Many assessments are currently essentially numerical exercises that combine these unrepresentative response functions with gridded climatic data to estimate impacts of climate change on the labour force at the global

level. The potential biases and errors in such an approach often do not appear to be sufficiently clarified when used for policy-related work. One way forward involves the use of observational data such as labour force surveys, time use surveys and firm-level data on labour allocation and outputs to estimate sub-national-specific, country-specific or region-specific response functions, and using these to compute projections and reduce uncertainty<sup>5,10,11,20,21,26,30,34,38,150</sup>. Definitions and differentiation between labour capacity and productivity need to be harmonized to improve the estimates and comparability of results.

Another major caveat in current understanding is the choice of heat stress indicators. WBGT is often used, but this indicator tends to underestimate thermal stress conditions. As such, evidence using WBGT should be treated with caution<sup>5,151</sup>. Thermal comfort indices could be used as an alternative. These incorporate only temperature and humidity and, thus, do not require empirical estimation of meteorological variables<sup>152</sup>. Similarly, the heat index<sup>153</sup> could be a suitable alternative index given that it also incorporates humidity and temperature without requiring empirical estimation of other inputs<sup>154</sup>.

To date, little consideration of socioeconomic and sociodemographic factors has been given in the heat–labour impact literature. As a result, differences in vulnerability between workers and their occupational settings, such as those in manual labour or outdoor jobs, have not always been taken into account, potentially leading to inaccuracies in estimating the severity of heat stress and the effectiveness of adaptation policies. Prioritizing better knowledge in this area has high potential to generate a robust evidence base that can inform local labour policies. In particular, future research should focus on incorporating the interaction between socioeconomic characteristics (such as skill-level and education), occupational settings (exposure-level) and climatic stressors. New research should also focus on sub-sector levels such as agriculture, construction and manufacturing.

Early warning systems and collaborative research with relevant stakeholders in the labour force will be key to protecting workers from increasing heat stress. Future research in collaboration with occupational safety and health institutions, labour unions and regulators can help to create early warning systems that, when combined with heat health action plans and maximum temperature regulations, can safeguard workers from extreme heat. By delving into empirically estimated temperature thresholds and impact-based forecasts specific to industries and sub-sectors, research can enhance the efficacy of these early warning systems. Such research can also serve as the foundation for designing tailored plans to protect workers from extreme heat, requiring maximum temperature benchmarks to be implemented for work to safely occur. Potential differences in impacts by gender has also not been sufficiently addressed, including the impacts of heat stress on pregnant workers in outdoor sectors.

Macroeconomic assessments of the impacts of climate change on labour productivity are currently compromised because adaptation is not well incorporated. This limitation is linked to the complexity of modelling adaptation and insufficient attention. Macroeconomic models could be improved by explicitly allowing for climatic stressors to differentially affect workers across high- and low-exposure settings within the same sector, and for accommodating climate-linked labour substitutability. Improved modelling and assumptions over the cost and effectiveness of adaptation is similarly needed, that is, not constrained by assumptions of labour supply and demand reacting to productivity changes in perfectly competitive labour markets.

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## Author contributions

S.D. led the writing of the manuscript, coordinated all contributions and led the writing of 'Labour supply' section. E.J.Z.R. led the writing of 'Adaptation opportunities' section and led the editing and reviewing of the draft manuscript. S.N.G. led the writing of 'Labour capacity' section and co-designed the figures on health risks of heat stress for workers and the conceptualization of adaptation. S.S. led the writing of 'Labour productivity' section and co-designed figure on health risks of heat stress for workers. J.P. co-led the writing of 'Labour productivity' section. F.B. led the writing of 'Macroeconomic impacts' section. All authors discussed the content and contributed to the writing of the manuscript.

## Competing interests

The authors declare no competing interests.

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