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Climate change, heat stress and labour productivity: A cost methodology for city economies

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Abstract

Cities are particularly vulnerable to heat waves. Despite this, no comprehensive methodology has been developed to assess the costs of heat stress on city economies either currently or under future climate change scenarios. Here, we develop a cost methodology that integrates urban climate modelling with labour productivity and economic production. It is designed to be tailored by policy makers and transferable from one city to another. As such it provides a potentially powerful policy tool for assessing the exposure of different economic sectors and the key mechanisms resulting in urban production losses under climate change. Results show that the impacts of heat on the urban economy are highly variable and depend on characteristics of production, such as the elasticity of substitution between capital and labour, and the relative size of different sectors in the economy. We estimate that in a warm year in the far future (2081-2100), the total losses to the urban economy could range between 0.4% of Gross Value Added (GVA) for London and 9.5% for Bilbao in the absence of adaptation. The averted losses due to adaptation measures such as behaviour change, air conditioning, ventilation, insulation and solar blinds range from -€114 million to over €2.3 billion. The methodology demonstrates the substantial impact that climate change could have on different sectors of the city economy, such as the financial services industry in London.

Keywords: climate change, economic, heat, labour, productivity, worker

1 Introduction

The impact of temperature on economic productivity and output has been the subject of research for over a century (see, for example, Huntington 1915). More recently, global warming and the risk of climate change have generated renewed interest in the topic (see Dell et al. 2014; Heal and Park 2015 for reviews of the literature).

A wide range of studies at the micro level have demonstrated the impact of heat stress on the productivity of workers by reducing cognitive and physical performance in the workplace (e.g. Grether 1973; Wyon 1974; Ramsey 1995; Berger 2014). Research has also been undertaken at the macro level by estimating the impact of increased temperature on income per capita (e.g. Horowitz 2009). Heal and Park (2015) have provided a model of labour supply decisions under heat stress, as well as the willingness to pay for mitigation, which they test empirically. They use both country level data and household data.

Using a different approach, Burke et al. (2015) combined micro and macro evidence to examine total production in an empirical study for a panel of 166 countries for the period 1960-2010. They found that productivity increased with temperature until approximately 13 degrees Celsius, and then decreased from that point on. They estimated a reduction as high as 23% of global gross domestic product (GDP) due to climate change in 2100, based on the Representative Concentration Pathway (RCP) 8.5 scenario (IPCC, 2013).

While the macro level relationship between temperature and productivity has been studied mainly at the national level, cities are particularly vulnerable to increases in heat. Built surfaces in cities are composed of a high percentage of non-reflective and water-resistant construction materials. In addition, the lack of vegetation and moisture-trapping soils – that would otherwise provide shade and contribute to cooling the air – means that temperatures in cities tend to be higher than those of surrounding areas: the so-called urban heat island (UHI) effect. Furthermore, because urban areas concentrate people and productive activity, productivity losses in cities can be amplified. As the number of people living in cities continues to increase,[1] so does the potential for adverse effects of increasing temperatures.

Despite the importance of the urban heat island effect, very little research has been undertaken on the effects of heat waves on city economies (a notable exception is Sabbag 2013). However, if policy makers are to implement effective measures to support urban adaptation to heat waves, a stronger evidence base – combined with city-level policy tools - is needed on the scale of potential damages and the effectiveness of different adaptation strategies.

Here, we develop a cost methodology that allows researchers and policy makers to assess the costs of heat stress on the urban economy through reduced labour productivity, along with the cost effectiveness of different adaptation measures. Our model starts from the micro-level evidence that heat induces a decrease in productivity at the individual level and shows how this decrease aggregates into production losses at the macro/city level.

We first estimate hourly productivity loss functions for individual workers at different levels of work intensity based on ISO standards for recommended hourly work rates at different levels of Wet Bulb

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[1] The urban population is expected to grow by 1 billion people in less developed countries and by 70 million people in developed countries by 2030 (UN DESA Population Division 2012, as cited in IPCC 2014).

Globe Temperature (WBGT). Work intensities are then attributed to different sectors of the metropolitan economy depending on the energy levels needed by workers to perform different activities.

We then define constant elasticity of substitution (CES) production functions for each sector that specifically encompass the productivity loss functions. The production functions are calibrated and aggregated at the city level according to specific weights given to each sector. This approach allows us to assess various characteristics of urban production, including the flexibility of the productive system in terms of the degree of substitutability between labour and capital, its labour intensity, and the relative importance of different sectors in the economy.

Finally, we use results from Hooyberghs et al. (2016) on projected indoor climatic conditions in an example office building for the year 2005 and the periods 2026-2045 and 2081-2100. We use this in order to compute an estimate of future production costs in three case study cities: Antwerp, Bilbao, and London.

2 Urban heat cost framework

2.1 Climate models at the city level

We model the influence of urban built-up areas on hourly air temperatures, land surface temperatures, wind speeds and humidity values using the UrbClim model (see De Ridder et al. 2015; Hooyberghs et al. 2015).

UrbClim is an urban climate model designed to model the urban climate at a spatial resolution of a few hundred metres. The model scales large-scale weather conditions down to agglomeration-scale and computes the impact of urban development on the most important weather parameters. It is composed of a land surface scheme describing the physics of energy and water exchange between the soil and the atmosphere in the city, coupled to a 3D boundary layer module, which models the atmospheric dynamics above the urban agglomeration.

To study the future urban climate, UrbClim has been coupled with the output of an ensemble of eleven global climate models (GCMs) contained in the Coupled Model Intercomparison Project 5 (CMIP5) archive of the IPCC (IPCC, 2013). From the scenarios identified in the IPCC report, we consider only the RCP8.5 business as usual scenario. This scenario has a large warming potential, but still assumes emissions well below business as usual (Peters et al. 2013).

Indoor climate was modelled using an illustrative office building, both equipped with an active cooling system and without (‘free-running’). In reality, thermal properties of different building types such as offices, factories and industrial plants will vary greatly, and further research should focus on different building classes. The building was modelled using the open source EnergyPlus simulation software (v8.2.0, released September 2014), a building energy analysis software which is managed by USA National Renewable Energy Laboratory (Crawley et al. 2001). A detailed description of the modelling is provided in Hooyberghs et al. (2015).

2.2 Productivity loss functions

In order to estimate the reduction in productivity of individual workers due to physiological heat stress, we follow previous researchers working at the population level by using internationally agreed standards for the length of work breaks at different temperatures above a heat stress threshold (e.g. Kjellstrom et al. 2009; Jay and Kenny 2010). We use ISO standards as the recognised international benchmark (ISO, 1989). We then test the robustness of results by comparing the ISO standards with the US standard provided by the National Institute for Occupational Safety and Health (NIOSH).

These international standards, based on previous physiological studies, use Wet Bulb Globe Temperature (WBGT) (see Yaglou 1956). The WBGT is a combination of three measurements: the natural wet bulb temperature (Tnwb, measured with a wetted thermometer exposed to the wind and heat radiation at the site), the black globe temperature (Tg, measured inside a 150 mm diameter black globe) and the air temperature (Ta, measured with a normal thermometer shaded from direct heat radiation). For indoor settings, direct solar radiation to the individuals is negligible. Hence the formula WBGT = 0.7 Tnwb + 0.3 Ta is used for indoor WBGT, while for outdoors WBGT = 0.7 Tnwb + 0.2 Tg + 0.2 Ta is used (NIOSH, 1986).

We define worker productivity as the proportion of a working day that a worker can perform a job under different heat conditions (Kjellstrom 2000). The productivity of labour for a given work intensity is a monotonically non-increasing function of the Wet Bulb Globe Temperature between an upper and a lower bound. Above the upper WBGT bound, worker productivity is zero, while below the lower bound, productivity is 1. Hourly productivity loss from WBGT, for a given work intensity (WI) is given by:

$$\mathrm{P_{WI}} = \begin{cases} 1 & \mathrm{WBGT} < \mathrm{Min} \\ \mathrm{f(WBGT)} & \mathrm{Min} \leq \mathrm{WBGT} \leq \mathrm{Max} \\ 0 & \mathrm{WBGT} > \mathrm{Max} \end{cases} \qquad (1)$$

where f(WBGT) is a monotonically decreasing function of WBGT. These $\mathrm{P_{WI}}$ functions are then aggregated into annual productivity loss. Productivity loss for labour (L) in a given sector s, $a_{L,s}$, is a function of WBGT through its effect on hourly productivity loss across all working hours (h) and working regimes $\{1, \ldots, H\}$, that is, $a_{L,s} = \sum_h \sum_{WI=1}^{N} P_{WI,h}\,(WBGT)$.

We derive a productivity loss function for each sector of the economy, based on an estimate of the average work intensity (WI) required for work in that sector. Sectors are defined according to the NACE statistical classification of economic activities used in the European Union. More details on the estimation of these loss functions are provided in the Online Appendix.

2.3 Production function

We define constant elasticity of substitution (CES) production functions for each sector of the economy that specifically encompass the productivity loss functions. The CES function is a general form production function that assumes a constant percentage change in factor proportions from a percentage change in the marginal rate of technical substitution. We use the standard form (Arrow et al. 1960). Sectoral production in a given time period t is thus the result of a certain level of the inputs capital (K) and labour (L) in the following manner:

$$Y_{c,s,t} = \quad f\left(L_{c,s,t}, K_{c,s,t}\right) = A_{s,c}\left[\theta_s\left(a_{K,s}K_{c,s,t}\right)^{\gamma_s} + (1-\theta_s)\left(a_{L,s}L_{c,s,t}\right)^{\gamma_s}\right]^{\frac{1}{\gamma_s}} \tag{2}$$

where $Y_{c,s,t}$ is a measure of production in sector *s* in city *c* at year *t*, $A_{s,c}$ is total factor productivity by sector and city, θ_s is the share of capital in sector *s*, γ_s measures the degree of substitution between production factors and $a_{K,s}$ and $a_{L,s}$ are, respectively, the productivity of capital and labour in sector *s*. For simplicity we normalise $a_{K,s}$ to 1, and $a_{L,s}$ is the function of WBGT defined in Section 2.3. The elasticity of substitution in each sector *s* is given by $\rho_s = \frac{1}{(1-\gamma_s)}$.

City production is a sum of sectoral production across all *N* sectors of the urban economy, and given by:

$$Y_{c,t} = \sum_{s=1}^{N} Y_{c,s,t} \tag{3}$$

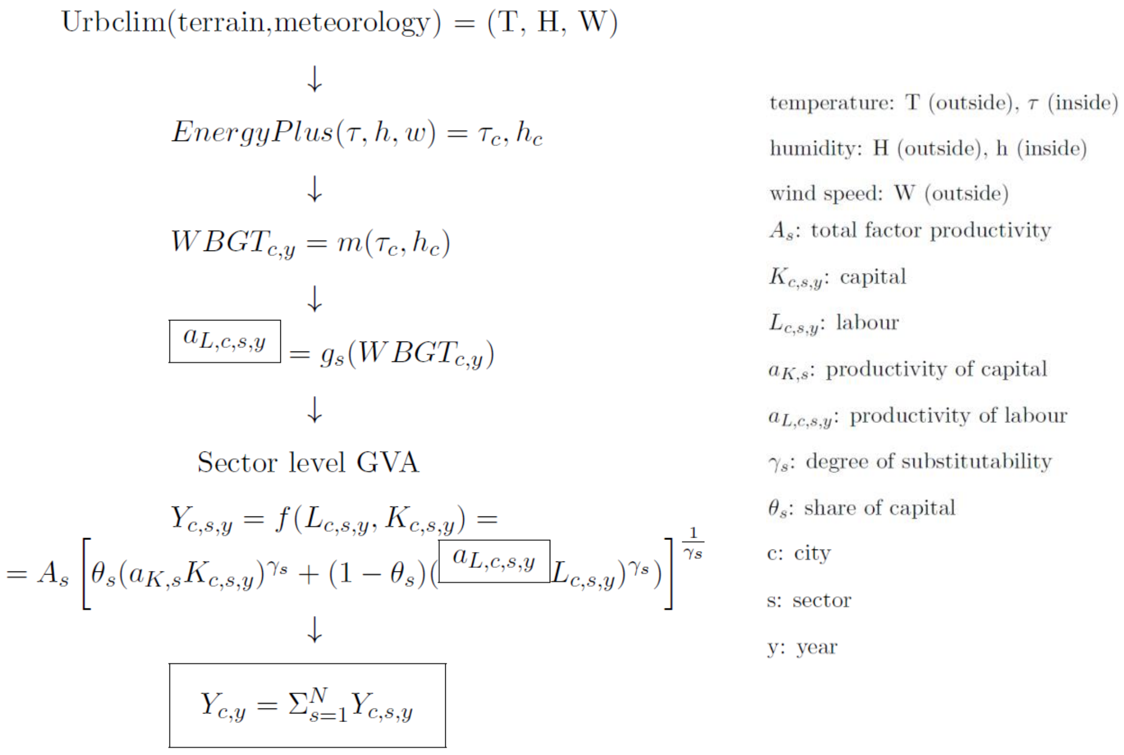
Thus equation (2) can be rewritten as:

$$Y_{c,t} = \sum_{s=1}^{N} A_{s,c}\left[\theta_s\left(a_{K,s}K_{c,s,t}\right)^{\gamma_s} + (1-\theta_s)\left(a_{L,s}(WBGT_h)L_{c,s,t}\right)^{\gamma_s}\right]^{\frac{1}{\gamma_s}} \tag{4}$$

which gives us city production as a function of WBGT. Because $a_{L,s}(WBGT)$ is a decreasing function of WBGT, and WBGT is increasing in temperature, city production is a decreasing function of workplace temperature. Precisely how production varies with WBGT depends both on the weight of each sector on total production, as well as on the parameters of each sector's production function.

The use of an explicit production function for each sector that is aggregated into city Gross Value Added (GVA) enriches the analysis, as it allows us to track the impact of different economic structures on the final effect of heat stress on the urban economy. An overview of the full model is presented in Figure 1.

Figure 1 Model Overview



3 Calibration

We calibrate the model to the economies of Antwerp (Belgium), Bilbao (Spain), and London (United Kingdom. The cities were chosen as case studies by the European RAMSES consortium, of which this work is part. By comparing three cities of different sizes, economic structures, and location, we are able to explore the impact of heat waves in different settings. To reduce the computational costs, only one reference year and four future years are considered in the economic analysis. We use the year 2005 as the reference year, and for each future period (2026-2045 and 2081-2100) and for each city, we choose a "cool" year (the year with the minimum productivity loss) and a "warm" year (the year with the maximum productivity loss).

We use the NACE statistical classification of economic activities used in the European Union. To measure production we use Gross Value Added (GVA) at the sector level. GVA measures the value of goods and services produced in each sector of the economy minus intermediate consumption. The total GVA for the reference period for each of the cities varies from €26 billion in Bilbao to €472 billion in London. The distribution of GVA between sectors also varies considerably. For example, the manufacturing sector accounts for 21.4% of the GVA of Antwerp but only 5.7% of that of London, while financial and insurance activities account for 38.6% of the GVA of London but only 18.9% of that of Bilbao.

We examine a range of adaptation measures most likely to be effective, based on Floater et al. (2014) and Kallaos et al. (2015). First, we estimate losses under behavioural adaptation, in the form of changing working hours. We use three regimes in which work is performed later in the evening, three in which work is performed earlier in the morning, and one extreme regime that includes early morning and late afternoon work.

Second, we estimate the effect of an increase in the rate of mechanical ventilation (from $22m^3$/h/p, the legal minimum in Belgium, to $50m^3$/h/p, corresponding to "Medium Indoor Air Quality" according to the European standards (EN 13779:2007)). In this scenario, the air in the office building is refreshed twice an hour.

Third, we examine the use of solar blinds on the outside of the building. These blinds are sun blocking screens that automatically lower if the irradiance on the windows is higher than a certain threshold value (in this example set to 75 W/m^2), thereby effectively reducing the incoming solar radiation affecting the building.[2] Both the external shading and the increased ventilation rates were previously suggested by Jentsch et al. (2008).

Finally, we examine the effect of an increase in insulation. We assume a reduction in the heat transfer through the glazing by decreasing the standard U-value of $1.2W/m^2/K$ to $0.8W/m^2/K$.

For a detailed description of the calibration of the production functions and the productivity loss functions please refer to the Online Appendix.

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[2] Although solar radiation affecting the employees directly is negligible for those working indoors, radiation to the outside of the building increases indoor temperature.

4 Results

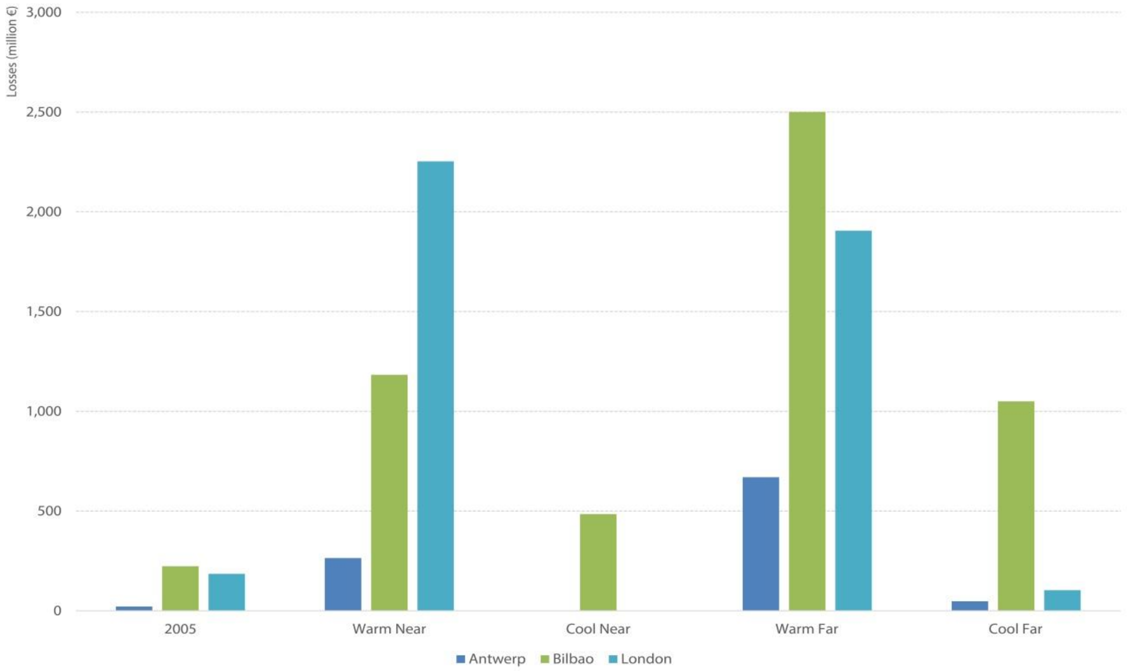
4.1 Relative size of losses

Based on the assumptions set out in the methodology, estimated losses due to heat stress and productivity are non-negligible. In a warm year in the far future (2081-2100) they are estimated to be around 0.4% of GVA in London, 2.1% in Antwerp, and 9.5% in Bilbao. These correspond to total losses of around €1.9 billion for London, €670 million in Antwerp, and €2.5 billion in Bilbao, in 2005 prices.

Losses vary greatly across sectors, according to each city's structure. For example, while in Antwerp losses in the manufacturing sector amount to 24% of all losses, in London they are only 6%. The construction sector accounts for only 4% and 6% of losses in Antwerp and Bilbao, respectively, while it accounts for 18% in London. Losses in the financial sector amount to 24% of total losses in London, 20% in Antwerp and 19% in Bilbao.

Even though the loss to the London economy is substantial, in relative terms it is the lowest. This is due to a combination of lower temperatures and an economic structure that is less vulnerable to heat stress (e.g. London's large financial sector combines low labour intensity and lower impacts of heat due to lower work intensities). Figure 2 presents losses in the five years for the three cities.

Figure 2 Heat related GVA losses across time



Note: Warm(Cool) Near(Far) years correspond to the warmest(coolest) years in time periods 2026-2045(2081-2100)

4.2 Comparative statistics

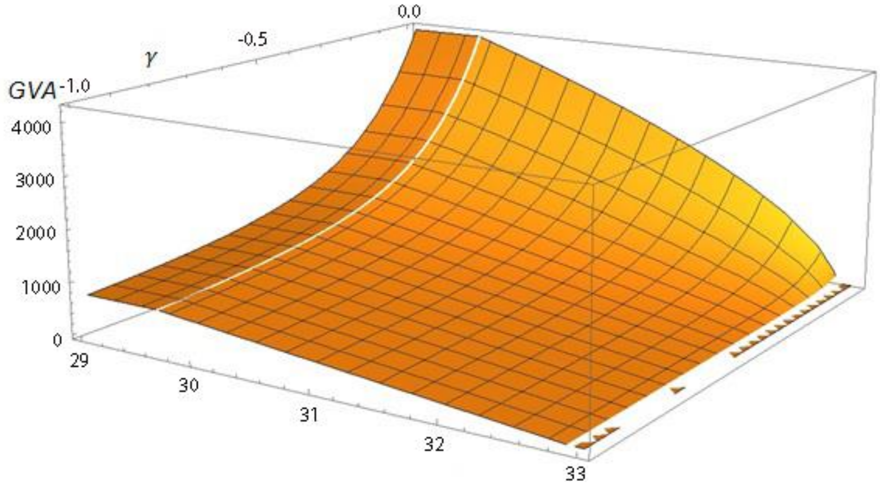
Production is monotonically non-increasing in WBGT. However, for constant labour and capital levels (that is, assuming capital and labour are at their optimal level), the shape of the relationship changes depending on the capital/labour shares (θ) and the elasticity of substitution (measured by γ).

As an example, Figure 3 depicts GVA for a sector of intensity $WI_2=240W$ as a function of WBGT and elasticity, assuming the same temperature is observed for all working hours within each day. GVA is depicted on the y-axis, WBGT on the x-axis and γ on the z-axis. For expositional purposes, the production function is calibrated to mimic the manufacturing sector in Antwerp. The first graph uses capital/labour share $\theta = 0.4$ and the second $\theta = 0.7$. For low values of γ (high elasticity), a decrease in capital shares reduces the concavity of the function, thereby causing higher decreases in GVA as temperature increases.

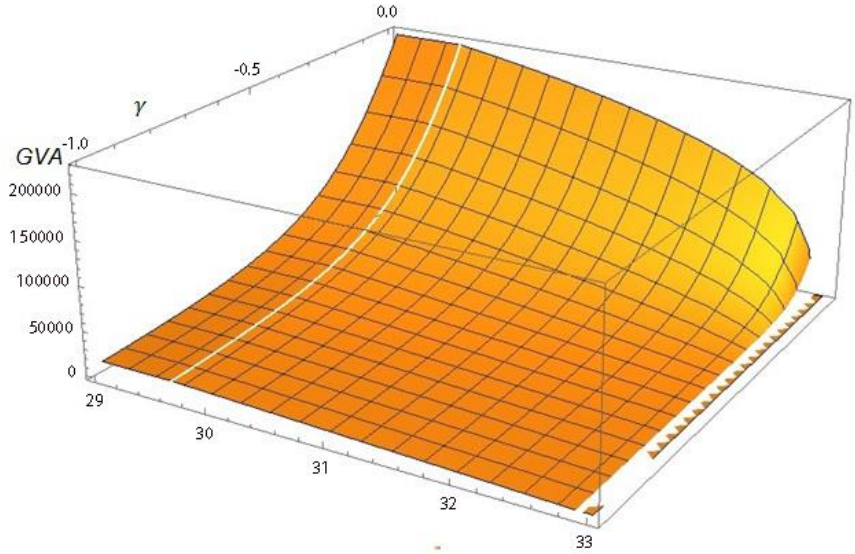
Intuitively, this means that the higher the share of labour input in a given sector, the larger the costs of heat stress through productivity losses. For a given capital/labour share, decreasing the elasticity of substitution (i.e., increasing γ) has the same effect. This is intuitive and means that if it is difficult to substitute labour with capital in production, as labour become less productive, losses increase more rapidly. This is clear in both figures when comparing the inclinations of the functions at $\gamma = -1$ and $\gamma = 0$. Finally, for high values of γ (low elasticity), increasing the share of capital decreases the responsiveness of GVA to a marginal increase in WBGT for low levels of the latter, but increases the responsiveness for high levels of WBGT.

Figure 3 GVA as a function of WBGT and elasticity; θ=0.4 and θ=0.7

θ=0.4



$\boldsymbol{\theta}$=0.7



Notes: GVA for a sector of WI_2=240W as a function of interior WBGT and γ.
The values for A, L, and K are set to mimic the manufacturing sector in Antwerp.

Finally, we study how losses to GVA vary across sectors when we change the parameters of the production function. Figure 4 depicts losses to GVA for each of the sectors of the London economy.[3] The baseline uses the actual London calibration of the function, in a warm year in the far future (2081-2100). We compare this with the baseline calibration, first with a θ_s that is 20% smaller, and second with a ρ_s that is 20% smaller (where $\rho_s = \frac{1}{(1-\gamma_s)}$), for each sector *s*.

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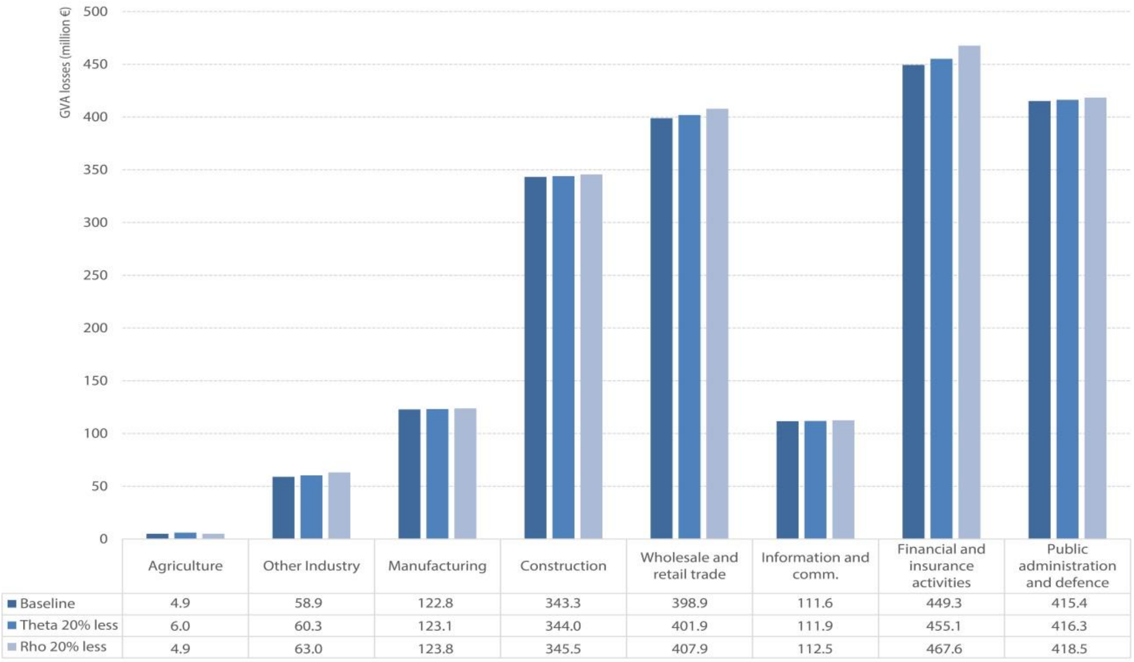
[3] The analogous figures for the other two case study cities are available from the authors upon request. The results and are not presented here due to constraints on space.

Figure 4 Losses to GVA for different parameters; London



	Agriculture	Other Industry	Manufacturing	Construction	Wholesale and retail trade	Information and comm.	Financial and insurance activities	Public administration and defence
■ Baseline	4.9	58.9	122.8	343.3	398.9	111.6	449.3	415.4
■ Theta 20% less	6.0	60.3	123.1	344.0	401.9	111.9	455.1	416.3
■ Rho 20% less	4.9	63.0	123.8	345.5	407.9	112.5	467.6	418.5

Notes: Losses to GVA for the baseline scenario, for a θ_s that is 20% smaller, and a ρ_s that is 20% smaller in each sector. Results for the London economy in a warm year in the far future (2081-2100).

As expected, in all sectors, decreasing capital shares increase losses. Additionally, for all sectors except agriculture, a decrease in elasticity has an even larger impact on increasing losses. This highlights the importance of a higher elasticity of substitution in coping with the impact of heat waves on labour productivity.

The weight of the manufacturing, construction, and public administration and defence sectors in the total amount of losses decreases for both scenarios, while the weight of all the other sectors increases. The former are the sectors with the lowest elasticities of substitution, which makes them more responsive to both changes in capital shares and elasticity itself, as can be inferred from Figure 3.

4.3 Impact of adaptation measures on averted losses

We first focus on behavioural adaptation by estimating the impact of changing working hours in terms of averted losses for labour productivity. In all three cities, schedules that avoid early afternoon work tend to result in higher productivity compared to the afternoon schedules. The schedule with the highest productivity is 7h-11h; 17h-20h for Antwerp and London, and 6h-13h for Bilbao.

Figure 5 presents averted losses from alternative adaptation measures for the three case study cities, for a warm year in the far future (2081-2100).[4] The behavioural change presented is the most efficient working schedule for each of the three cities. Under the assumptions used, air conditioning, increased

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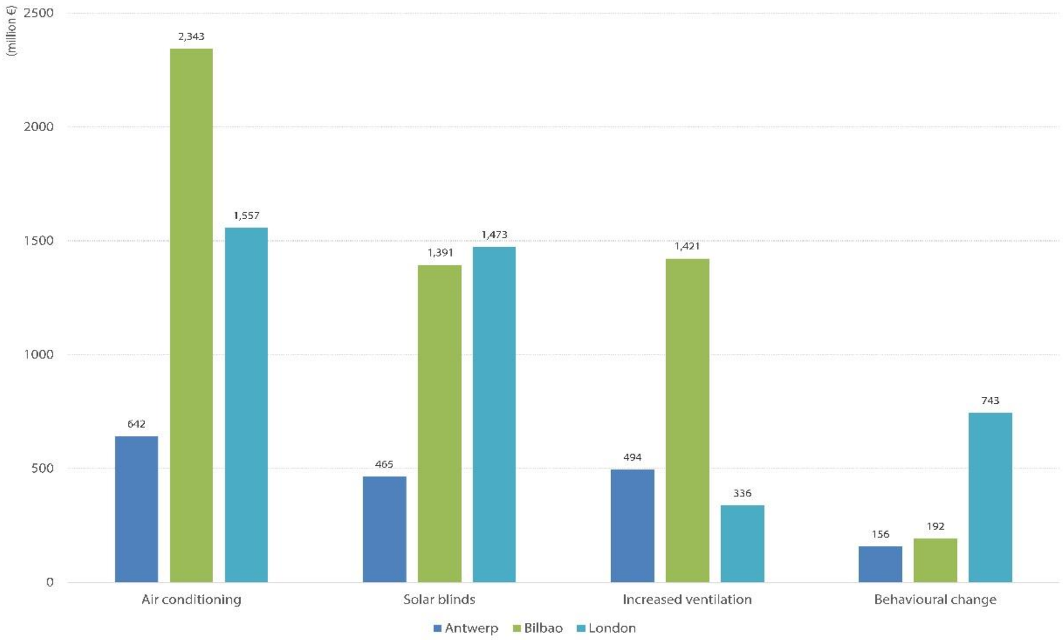
[4] Increased insulation resulted in negative benefits (losses) of 114 million euros for Antwerp, and so were left out of the remainder of the analysis.

ventilation and solar blinds all resulted in substantial reductions in productivity losses from heat stress. It should be noted that the implementation and operating costs of measures have not been included in these analyses, and these would need to be included if policy makers aimed to examine cost effectiveness. It is likely that air conditioning, being highly energy intensive, has large operating costs, in addition to being costly in terms of CO^2 production and contribution to further increases in urban temperature.

For London, solar blinds seem to have almost the same effect of air conditioning without many obvious drawbacks. For both Antwerp and Bilbao, solar blinds provide similar benefits to those of increased ventilation, without requiring energy. Furthermore, behavioural change presents itself in London as a viable alternative to the other measures, as it is able to protect both indoor and outdoor workers. However, its costs are more difficult to measure than those of other adaptation measures.

Figure 5 Averted losses under alternative adaptation

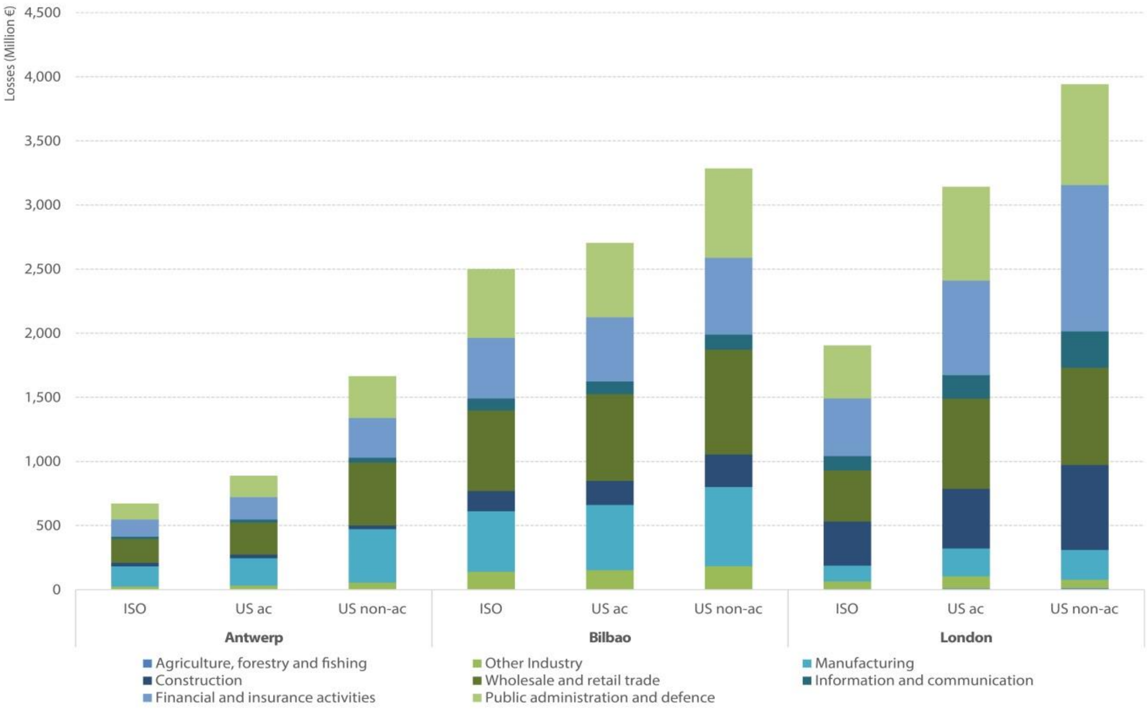


Note: Warm year in the far future (2081-2100). Values in million €.
Gross averted losses not including implementation costs.

4.4 Robustness: alternative productivity losses

The losses estimated for London in a warm year in the far future (2081-2100) for non-acclimatized workers are more than twice as high when using US standards than for ISO standards. Figure 6 presents the losses for the three cities and for the three standards, in a warm year in the far future, across all sectors of the economy. This shows that labour productivity losses are affected substantially by the standards used. Consequently, further research is required to determine which standards represent the more realistic estimate of losses.

Figure 6 Losses with different heat stress standards



Note: Losses estimated for a warm year in the far future, 2081-2100 (see Section 3 for details). ISO stands for worker productivity using ISO standards for an average acclimatised worker wearing light clothing, US ac using US standards for acclimatised workers, and US non-ac using US standards for non-acclimatised workers

5 Discussion

The analysis of the three case study cities demonstrates the substantial impact that climate change could have on the urban economy. It highlights the exposure of different economic sectors to heat waves, which result in different magnitudes of costs to the city economy, and the key mechanisms affecting production losses.

We find that sectors with lower elasticity between labour and capital and those that are more labour intensive are more exposed to heat waves. This means for example that cities that are highly dependent on the construction sector, which combines both low elasticity with large labour shares, could face larger costs.

Furthermore, the methodology allows for a comparison of averted losses from alternative adaptation measures in the city. An important question arising from the current study is whether effective adaptation that does not compromise climate mitigation can be designed and implemented. Air conditioning, for example, can increase outdoor urban temperature when used at a large scale, further exacerbating the impact of heat stress and potentially further increasing its costs. What is more, unless the electricity supply is decarbonised, the increase in energy demand will lead to increased carbon emissions, creating a trade-off between climate adaptation and climate mitigation. This paper can be used as a basis for further research on these topics.

Our analysis points to behavioural change as a potentially important adaptation measure for the case of London. Unlike air conditioning, this measure protects both indoor and outdoor work, providing benefits for cities with large construction sectors. However, an analysis of the costs of behaviour change in the wider economy could be substantial, and while it is beyond the scope of this paper, further research should be undertaken on the wider costs.

Our results also provide insights into climate impacts on inequality. Poorer individuals tend to provide non-skilled labour, often in sectors that are more sensitive to temperature stress. Assuming that the labour market operates with only minor frictions, then wages are set based on worker productivity. This implies that heat stress could in the long term decrease labour income, in particular where it already tends to be lower.

Finally, we perform our analysis for cities in Europe with a predominantly oceanic climate. According to Verisk Maplecroft (2016) the region with the most urban labour at risk due to heat stress over the next three decades is South East Asia, where they predict 16% of lost labour capacity, followed by the Caribbean and West Africa. Our methodology to measure the impact across sectors could have even higher significance in the context of these regions.

If policy makers are to use the cost methodology, it will require tailoring to specific city circumstances. Assumptions should be refined based on more detailed data held by municipal governments; examples include more detailed assessments of building types, acclimatisation of workers over time, and general equilibrium effects across the economy. In addition, the results of the methodology on labour productivity costs should be combined with other heat-related costs in the economy, such as direct health costs from mortality and morbidity (Kingsley et al. 2016) and transport disruptions due to infrastructure damage (Acero et al. 2014). These could have interlinkages and second order impacts.

In conclusion, the methodology is designed to be accessible to policy makers, readily transferable from one city to another, and able to be tailored to specific city circumstances with relatively modest data requirements. As such the methodology provides a potentially powerful policy tool for assessing the exposure and adaptation options for cities facing increased heat stress from climate change in the future, both by municipal and regional policy makers, as well as national policy makers who wish to compare adaptation strategies across different cities.

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