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A global economic assessment of city policies to reduce climate change impacts

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Climate change impacts can be especially large in cities[1,2]. Several large cities are taking climate change into account in long-term strategies[3,4], for which it is important to have information on the costs and benefits of adaptation[5]. Studies on climate change impacts in cities mostly focus on a limited set of countries and risks, for example sea-level rise, health and water resources[6]. Most of these studies are qualitative, except for the costs of sea-level rise in cities[7,8]. These impact estimates do not take into account that large cities will experience additional warming due to the urban heat island effect[9,10], that is, the change of local climate patterns caused by urbanization. Here we provide a quantitative assessment of the economic costs of the joint impacts of local and global climate change for all main cities around the world. Cost–benefit analyses are presented of urban heat island mitigation options, including green and cool roofs and cool pavements. It is shown that local actions can be a climate risk-reduction instrument. Furthermore, limiting the urban heat island through city adaptation plans can significantly amplify the benefits of international mitigation efforts.

The city scale is especially relevant for climate policy[11]. Although cities cover around 1% of the Earth's surface[12], they produce about 80% of gross world product, consume about 78% of the world's energy and produce more than 60% of all CO_2 emissions[13–15]. Moreover, 54% of the world's population live in cities, and this is expected to grow to about 66% by 2050[14,16]. When designing climate policy at the city level, the variety of risk mitigation measures at global and local levels have to be evaluated and compared[2,3], noting that cities typically have little control over energy and agricultural policies, key elements of greenhouse gas emission reduction. While the benefits of global mitigation strategies have been discussed, the benefits of improving local climate under global climate change (GCC) are largely unknown. Compared with global efforts, some local actions to improve urban climate offer the advantages of being politically easier to implement and of having short-term benefits.

Changes in long-term climate normals at the city level are to a large extent determined by human intervention at different scales: changes in the atmospheric concentrations of radiative active substances affect global and regional climate[1]; the conversion of natural land to urban land affects local-scale climate[17]. The economic impacts of climate change are commonly considered to be nonlinear functions of temperature. Therefore, the joint impacts of the urban heat island (UHI) and GCC—as well as the benefits of mitigation efforts—are likely to be greater than the sum of the parts. The UHI occurs when vegetation and water bodies are replaced by materials such as concrete and asphalt, which have higher heat capacities and thermal conductivity. This urbanization process alters the local energy balance and produces changes in the local climate, such as higher temperatures, and changes in precipitation and wind patterns. According to the Environmental Protection Agency[18], the most important negative impacts of the UHI are increased energy use for cooling, higher emissions of air pollutants, human health risks and discomfort, and lower water quality. The UHI effect can exacerbate heat waves, which, among other impacts, have been shown to cause economic losses because of reduced labour productivity[19]. The impacts of GCC in cities are likely to be amplified by those of the UHI. These local impacts can be limited by city level adaptation policies[20], such as cool pavements, cool and green roofs and expanding vegetation in cities[18,21–23].

Figure 1 shows an estimate of the UHI effect for the 1,692 largest cities in the world for the period 1950–2015 (see Methods). Between 1950 and 2015, 27% of cities and 65% of the urban population warmed more than the world average (about 0.6 °C) as denoted by the black line in Fig. 1. Moreover, during this period, about 60% of the urban population experienced warming twice as large as the world.

Figure 2 shows the cumulative distributions of changes in local temperature (2015, 2050 and 2100 relative to 1900) exclusively due to GCC and for combined local and global climate change (see Methods). This illustrates the importance of the UHI in enhancing the effects of GCC. For the most populated cities (that is, the top 5%), the effects of UHI add 1.72 °C, 2.08 °C and 2.35 °C to the temperature increase due to GCC in 2015, 2050 and 2100, respectively. These estimates are 0.70 °C, 0.84 °C and 0.93 °C for the median cities. About 20% of these cities could experience a total warming higher than 4 °C in 2050 and about 25% could warm more than 7 °C by the end of this century.

The percentage of city gross domestic product (GDP) that would be lost for the median city in 2050 due to GCC alone is relatively small: 0.9% and 0.7% for the RCP8.5 and RCP4.5 emission scenarios, respectively (Supplementary Table 1). At the end of the century these impacts increase to 3.9% and 1.2%. As an illustration of the size of the economic impacts of GCC, the accumulated costs of climate change during this century comprise between 1.29%/0.59% (RCP8.5) and 0.60%/0.37% (RCP4.5) of the sum of all the cities' net present value of GDP between 2015 and 2100, using a 3% and a 7% discount rate, respectively (Table 1; Methods). However, these estimates neglect local climate change.

The accumulated impacts due to changes in local climate alone would be about half of those produced under the RCP8.5 (Table 1), and about the same size if a higher discount rate is used (Methods). These large impacts underline the importance of UHI mitigation strategies in large cities. The main threat to cities is that the UHI will amplify the impacts of GCC. Once the effects of the UHI are

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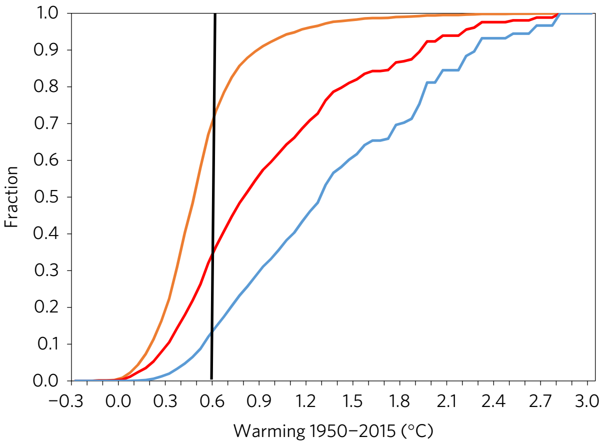

Figure 1 | Estimates of the UHI effect on the annual mean temperature for the 1,692 largest cities in the world for the period 1950–2015. Three cumulative density functions are shown: the black line represents the approximate observed increase in the global mean temperature between 1950 and 2015; the orange line shows the number of cities for different increases in temperature; the red line shows the number of people for different increases in temperature and the blue line shows the population-weighted mean temperature.

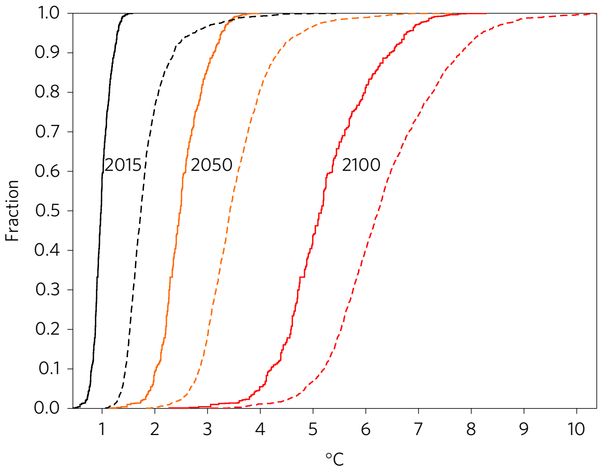

Figure 2 | Cumulative density functions of temperature changes of the 1,692 most populated cities in the world. The continuous lines show the estimated temperature increase for 2015 (black), 2050 (orange) and 2100 (red) under the RCP8.5 emissions scenario. Dashed lines include the estimated temperature increase from the UHI effect.

considered, the percentages of GDP lost for the median city are 1.4% and 1.7% in 2050 and 2.3% and 5.6% in 2100 for the RCP4.5 and RCP8.5, respectively (Supplementary Table 1). For the worst-off city, losses could reach up to 10.9% of GDP by 2100. The accumulated total costs of the urban impacts of global and local climate change for all cities during this century could be about 2.6 times those without UHI effects (Table 1). Moreover, even for the lowest emissions scenarios (350 ppm/RCP3PD), the accumulated costs would be 30% larger than those of the RCP8.5 when the UHI is ignored. The effects of uncontrolled UHI could more than offset the avoided impacts in large cities achieved by global mitigation efforts.

Another consequence of the joint effect of global and local climate change is that if local action to reduce the effects of the UHI is not implemented, GCC mitigation would be significantly less effective in reducing climate impacts. While a 350 ppm stabilization scenario would reduce the accumulated impacts of GCC (RCP8.5) by about 75%, when the effects of the UHI are added it would reduce them only by half.

Table 2 shows a cost–benefit analysis of four different local policies for combating the UHI: A—Large-scale cool roofs and cool pavements; B—Moderate-scale cool roofs and cool pavements; C—Moderate-scale green and cool roofs and cool pavements; D—Small-scale green and cool roofs and cool pavements (Methods and Supplementary Table 2). The results depend on the range of GCC scenarios (Methods). All of the strategies for mitigating the UHI produce a global positive net present value, even when GCC is not considered. Importantly, reducing the UHI is a desirable investment under all global warming scenarios, and substantially so under the worst. This is illustrated by the ratio of avoided impacts (benefits) to costs, which in all cases reaches its highest value under the RCP8.5 scenario. In this sense, investing in mitigating the UHI constitutes a risk-reduction instrument that will give the largest payoff when the worst outcomes occur, such as when no international greenhouse gases emissions reduction is implemented. Moreover, cities have control over measures for reducing the UHI through local planning and climate adaptation initiatives.

Of the options considered for mitigating the UHI, Policy B has the largest benefit–cost ratio (BCR)—that is, what Policy B would payoff for each dollar invested—ranging from US$6.00 without GCC to US$15.24 under RCP8.5. The aggregated costs of implementing this policy are 1.5% of the global urban product (GUP) and it could reduce the total accumulated losses between 9.7% to 18.3% depending on the GCC scenario. Policy A produces the largest net benefits of all policies considered. However, its costs are about twice as large as those of Policy B, leading to a lower BCR. Policies C and D have the lowest BCR. For example, between US$1.59 and US$3.96 for Policy D. Policy D yields lower BCR than other policies due to the inclusion of relatively expensive green roofs. Although the aggregate BCR values are larger than one, the distributional aspects of implementing policies C and D

Table 1 | Accumulated economic impacts of global climate change (GCC) and urban heat island (UHI) separately and combined under different emission scenarios.

	RCP8.5	RCP6	RCP4.5	550 ppm	450 ppm	RCP3PD	350 ppm
GCC	$\$3.21 \times 10^{13}$ [38.9%]	$\$1.68 \times 10^{13}$ [28.8%]	$\$1.49 \times 10^{13}$ [26.9%]	$\$1.43 \times 10^{13}$ [26.4%]	$\$1.05 \times 10^{13}$ [22.3%]	$\$8.24 \times 10^{12}$ [19.3%]	$\$7.71 \times 10^{12}$ [18.6%]
UHI	$\$1.54 \times 10^{13}$ [18.6%] (0.48)	$\$1.54 \times 10^{13}$ [26.4%] (0.92)	$\$1.54 \times 10^{13}$ [27.9%] (1.03)	$\$1.54 \times 10^{13}$ [28.5%] (1.08)	$\$1.54 \times 10^{13}$ [32.7%] (1.47)	$\$1.54 \times 10^{13}$ [36.2%] (1.87)	$\$1.54 \times 10^{13}$ [37.1%] (2.00)
Total	$\$8.26 \times 10^{13}$ (2.57)	$\$5.84 \times 10^{13}$ (3.48)	$\$5.53 \times 10^{13}$ (3.71)	$\$5.41 \times 10^{13}$ (3.78)	$\$4.71 \times 10^{13}$ (4.49)	$\$4.26 \times 10^{13}$ (5.17)	$\$4.15 \times 10^{13}$ (5.38)

Figures in brackets represent the present value of losses due to GCC/UHI as a percentage of the present value of the total losses. Figures in parenthesis represent the present value of the losses due to UHI/Total as a fraction of the present value of the losses produced by GCC alone. The symbol $ denotes US dollars. A 3% discount rate was used. Figures are rounded to three significant digits.

Table 2 | Costs and benefits of urban heat island reduction policies under different baseline scenarios.

	Policy A	Policy B	Policy C	Policy D
Costs	$\$1.18 \times 10^{12}$ 3.12% GUP	$\$5.64 \times 10^{11}$ 1.49% GUP	$\$1.80 \times 10^{12}$ 4.75% GUP	$\$1.44 \times 10^{12}$ 3.81% GUP
Net present value				
RCP8.5	$\$1.60 \times 10^{13}$ 19.3% TL	$\$8.03 \times 10^{12}$ 9.72% TL	$\$9.16 \times 10^{12}$ 11.1% TL	$\$4.28 \times 10^{12}$ 5.18% TL
RCP6	$\$1.34 \times 10^{13}$ 23.0% TL	$\$6.79 \times 10^{12}$ 11.6% TL	$\$7.56 \times 10^{12}$ 13.0% TL	$\$3.47 \times 10^{12}$ 5.94% TL
RCP4.5	$\$1.32 \times 10^{13}$ 23.9% TL	$\$6.69 \times 10^{12}$ 12.1% TL	$\$7.43 \times 10^{12}$ 13.4% TL	$\$3.40 \times 10^{12}$ 6.15% TL
NGCC	$\$5.18 \times 10^{12}$ 33.6% TL	$\$2.82 \times 10^{12}$ 18.3% TL	$\$2.44 \times 10^{12}$ 15.8% TL	$\$8.53 \times 10^{11}$ 5.52% TL
Benefit–cost ratio				
RCP8.5	\$14.5 {\$5.37, \$9.12}	\$15.2 {\$6.0, \$9.25}	\$6.09 {\$2.35, \$3.73}	\$3.96 {\$1.59, \$2.37}
RCP6	\$12.3 {\$5.37, \$6.95}	\$13.1 {\$6.0, \$7.05}	\$5.2 {\$2.35, \$2.85}	\$3.4 {\$1.59, \$1.81}
RCP4.5	\$12.1 {\$5.37, \$6.76}	\$12.9 {\$6.0, \$6.86}	\$5.13 {\$2.35, \$2.77}	\$3.35 {\$1.59, \$1.76}
NGCC	\$5.37	\$6.0	\$2.35	\$1.59
Cities with net losses				
RCP8.5	6 (0.35%)	6 (0.35%)	135 (7.98%)	685 (40.5%)
RCP6	20 (1.18%)	12 (0.71%)	399 (23.6%)	808 (47.8%)
RCP4.5	20 (1.18%)	18 (1.06%)	462 (27.3%)	817 (48.3%)
NGCC	788 (46.6%)	701 (41.4%)	1,140 (67.4%)	1,250 (73.8%)
Net benefits for the median city				
RCP8.5	$\$2.01 \times 10^{9}$ $[\$1.39 \times 10^{8}, \$6.8 \times 10^{10}]$	$\$1.05 \times 10^{9}$ $[\$7.2 \times 10^{7}, \$3.4 \times 10^{10}]$	$\$8.64 \times 10^{8}$ $[-\$1.89 \times 10^{8}, \$3.8 \times 10^{10}]$	$\$2.06 \times 10^{8}$ $[-\$3.52 \times 10^{8}, \$1.82 \times 10^{10}]$
RCP6	$\$1.52 \times 10^{9}$ $[\$5.71 \times 10^{7}, \$5.73 \times 10^{10}]$	$\$7.97 \times 10^{8}$ $[\$3.23 \times 10^{7}, \$2.89 \times 10^{10}]$	$\$5.67 \times 10^{8}$ $[-\$2.62 \times 10^{8}, \$3.3 \times 10^{10}]$	$\$9.66 \times 10^{7}$ $[-\$4.45 \times 10^{8}, \$1.51 \times 10^{10}]$
RCP4.5	$\$1.46 \times 10^{9}$ $[\$4.55 \times 10^{7}, \$5.68 \times 10^{10}]$	$\$7.65 \times 10^{8}$ $[\$2.8 \times 10^{7}, \$2.87 \times 10^{10}]$	$\$5.19 \times 10^{8}$ $[-\$2.74 \times 10^{8}, \$3.26 \times 10^{10}]$	$\$7.17 \times 10^{7}$ $[-\$4.68 \times 10^{8}, \$1.49 \times 10^{10}]$
NGCC	$\$4.06 \times 10^{7}$ $[-\$2.41 \times 10^{8}, \$2.3 \times 10^{10}]$	$\$7.0 \times 10^{7}$ $[-\$1.01 \times 10^{8}, \$1.22 \times 10^{10}]$	$-\$1.92 \times 10^{8}$ $[-\$1.19 \times 10^{9}, \$1.19 \times 10^{10}]$	$-\$1.98 \times 10^{8}$ $[-\$1.51 \times 10^{9}, \$5.41 \times 10^{9}]$

GUP, global urban product. NGCC, a no global climate change scenario. TL, the net present value of the benefits of the different policies as a fraction of the present value of the total losses. Numbers in parenthesis show the percentage of cities with net losses and numbers in brackets show the benefits for the cities in the 2.5th and 97.5th percentiles. The symbol \$ denotes US dollars. Figures in braces show the benefit–cost ratio decomposed into the contribution of local policy and interaction effects of global and local climate change, in that order. Policies: A—Large-scale cool roofs and cool pavements; B—Moderate-scale cool roofs and cool pavements; C—Moderate-scale green and cool roofs and cool pavements; D—Small-scale green and cool roofs and cool pavements. Figures are rounded to three significant digits.

need to be considered, because the number of cities with net losses increases substantially under these options. However, the BCR excludes indirect benefits of green roofs such as reduced pollution and health risk and storm water retention[1]. Including these indirect benefits may yield higher net benefits[18] and may reduce significantly the number of cities with net losses.

The distribution of costs and benefits over the 1,962 cities is not uniform. For no or small warming the UHI mitigation policies could imply losses for a number of cities. In the case of Policy B the number of cities with net losses ranges from 1 (0.35% of the total number of cities) in the case of the RCP8.5 scenario to 18 (1.06%) under the RCP4.5 scenario. Under a no global warming scenario, about 42% of the cities would have net losses from implementing Policy B. These estimates are similar for Policy A, while policies that include green roofs (C and D) lead to net losses for more cities.

Supplementary Table 3 presents the reduction in urban economic damages that would be obtained from implementing different stabilization scenarios in comparison with the baseline emission scenarios RCP8.5, RCP6 and RCP4.5. As expected, the largest benefits (about 50% avoided impacts) occur for the combination of the baseline scenario RCP8.5 and the substantial international mitigation under 350 ppm/RCP3PD. A 450ppm stabilization scenario would have similar results. For the rest of the baseline scenarios (RCP6, RCP4.5), the avoided impacts are much smaller.

UHI mitigation offers comparable or larger reductions in urban economic impacts than would be obtained from some combinations of reference and policy greenhouse gases emission scenarios (Supplementary Table 4). Under the reference scenario RCP8.5, the UHI mitigation policies would provide at most about half of the benefits of the different stabilization scenarios. However, for the baseline scenarios RCP6 and RCP4.5, any of the UHI mitigation policies would offer much larger benefits than the 550 ppm stabilization scenario, which represents weak climate policy (between 1.74 and 12 times larger).

The largest benefits for reducing the impacts of climate change are attained when both global and local measures are implemented together (Supplementary Table 5). In particular, lower levels of international mitigation action are needed to achieve the reduction in impacts that would otherwise be attained only by the most stringent stabilization goals. For example, the combination of Policy A and a 550 ppm stabilization scenario would bring larger benefits than those of the RCP3PD/350 ppm scenarios in the absence of local UHI mitigation measures, while policies B and C plus a 450 ppm stabilization effort would produce higher benefits than those of the RCP3PD/350 ppm scenarios (Table 3 and Supplementary Table 3). The implementation of international actions to stabilize the atmospheric concentrations of greenhouse gases would make investing in local measures to control the UHI effect more attractive as it

Table 3 | Change in urban impacts from global stabilization scenarios and local urban heat island mitigation policies.

	RCP8.5	RCP6	RCP4.5
550 ppm			
Policy A	−51.60% [1.50]	−31.50% [4.34]	−27.60% [13.50]
Policy B	−43.10% [1.25]	−19.50% [2.69]	−15.00% [7.32]
Policy C	−45.50% [1.32]	−22.80% [3.15]	−18.50% [9.04]
Policy D	−40.20% [1.17]	−15.40% [2.13]	−10.70% [5.22]
450 ppm			
Policy A	−59.00% [1.37]	−42.00% [2.17]	−38.80% [2.60]
Policy B	−51.10% [1.19]	−30.90% [1.59]	−27.00% [1.81]
Policy C	−53.30% [1.24]	−34.00% [1.75]	−30.30% [2.03]
Policy D	−48.50% [1.13]	−27.00% [1.39]	−23.00% [1.54]
RCP3PD			
Policy A	−64.00% [1.32]	−48.70% [1.80]	−46.00% [2.00]
Policy B	−56.20% [1.16]	−38.00% [1.41]	−34.50% [1.51]
Policy C	−58.30% [1.20]	−41.00% [1.52]	−37.70% [1.64]
Policy D	−53.60% [1.11]	−34.40% [1.27]	−30.70% [1.34]
350 ppm			
Policy A	−64.80% [1.30]	−50.20% [1.73]	−47.40% [1.90]
Policy B	−57.40% [1.15]	−39.80% [1.37]	−36.40% [1.46]
Policy C	−59.50% [1.19]	−42.70% [1.47]	−39.50% [1.58]
Policy D	−54.90% [1.10]	−36.20% [1.25]	−32.60% [1.31]

Figures represent the percentage of reduction in impacts achieved by the implementation of the selected global and local policies with respect to the impacts produced under the different reference scenarios. Numbers in brackets express avoided damages of both local and global policies as a fraction of the avoided losses that would be obtained from stabilization scenarios alone. Policies: A—Large-scale cool roofs and cool pavements; B—Moderate-scale cool roofs and cool pavements; C—Moderate-scale green and cool roofs and cool pavements; D—Small-scale green and cool roofs and cool pavements. Figures are rounded to three significant digits.

would have a higher return on investment as revealed by the BCR (Supplementary Table 5). The decomposition of the BCR shows that the pure benefits of only local policy (that is, those of NGCC; Table 2) are the same irrespective of global policy. The interaction effects of joint implementation are positive and large, and therefore make local investment in reducing UHI more attractive when global policy more strongly reduces greenhouses. This result is largely due to nonlinearity of climate impacts. Moreover, UHI mitigation is often profitable even without GCC (Table 2) and there are important co-benefits such as improved air quality, health and amenities.

This study provides the first attempt to quantify the effects and interactions of global and local climate as well as of local and global climate policy. Studies that neglect local warming effects are likely to significantly underestimate climate impacts, since we find that local warming as a result of the UHI significantly increases temperatures as well as economic losses in addition to global warming. City-level adaptation strategies to limit local warming are shown to have important economic net benefits for almost all cities around the world. Furthermore, some of these local adaptation strategies are politically easier to implement than global or national mitigation policies. However, actions at global and local levels are complementary since we show that the largest benefits of these local measures are obtained when both local and global actions are taken. The benefits of local climate policy can significantly enhance the benefits of global mitigation agreements. Adaptation policies to reduce the UHI effects also reduce a significant part of the expected impacts in the case global mitigation efforts are not successful, which implies that they can be viewed as a risk-reduction instrument that acts as an insurance for bad climate outcomes.

Methods

Methods, including statements of data availability and any associated accession codes and references, are available in the online version of this paper.

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References

1. De Sherbinin, A., Schiller, A. & Pulsipher, A. The vulnerability of global cities to climate hazards. *Environ. Urban.* **19,** 39–64 (2007).
2. Rosenzweig, C., Solecki, W. D., Hammer, S. A. & Mehrotra, S. *Climate Change and Cities: First Assessment Report of the Urban Climate Change Research Network* (Cambridge Univ. Press, 2011).
3. Aerts, J. & Botzen, W. Adaptation: cities' response to climate risks. *Nat. Clim. Change* **4,** 759–760 (2014).
4. Rosenzweig, C. & Solecki, W. Hurricane Sandy and adaptation pathways in New York: lessons from a first-responder city. *Glob. Environ. Change* **28,** 395–408 (2014).
5. Aerts, J. C. J. H. *et al*. Climate adaptation. Evaluating flood resilience strategies for coastal megacities. *Science* **344,** 473–475 (2014).
6. Hunt, A. & Watkiss, P. Climate change impacts and adaptation in cities: a review of the literature. *Climatic Change* **104,** 13–49 (2010).
7. Hallegatte, S., Green, C., Nicholls, R. J. & Corfee-Morlot, J. Future flood losses in major coastal cities. *Nat. Clim. Change* **3,** 802–806 (2013).
8. Budiyono, Y., Aerts, J., Brinkman, J., Marfai, M. A. & Ward, P. Flood risk assessment for delta mega-cities: a case study of Jakarta. *Nat. Hazards* **75,** 389–413 (2014).
9. Oke, T. R. City size and the urban heat island. *Atmos. Environ.* **7,** 769–779 (1973).
10. Mills, G. Urban climatology: history, status and prospects. *Urban Clim.* **10,** 479–489 (2014).
11. Jordan, A. J. *et al*. Emergence of polycentric climate governance and its future prospects. *Nat. Clim. Change* **5,** 977–982 (2015).
12. Akbari, H., Menon, S. & Rosenfeld, A. Global cooling: increasing world-wide urban albedos to offset CO_2. *Climatic Change* **94,** 275–286 (2009).
13. Stern, N. *The Economics of Climate Change: The Stern Review* (Cambridge Univ. Press, 2007).
14. Munich Re Group *Megacities: Megarisks: Trends and Challenges for Insurance and Risk Management* (Münchener Rückversicherungs-Gesellschaft, 2004).
15. Dobbs, R. *et al*. *Urban World: Mapping the Economic Power of Cities* 1–49 (McKinsey Global Institute, 2011).
16. Revi, A. *et al*. in *Climate Change 2014: Impacts, Adaptation, and Vulnerability* (eds Field, C. B. *et al*.) 535–612 (IPCC, Cambridge Univ. Press, 2014).
17. Zhao, L., Lee, X., Smith, R. B. & Oleson, K. Strong contributions of local background climate to urban heat islands. *Nature* **511,** 216–219 (2014).
18. US EPA *Reducing Urban Heat Islands: Compendium of Strategies* Heat Isl. Reduct. Act. 1–23 (2008).
19. Zander, K. K., Botzen, W. J. W., Oppermann, E., Kjellstrom, T. & Garnett, S. T. Heat stress causes substantial labour productivity loss in Australia. *Nat. Clim. Change* **5,** 647–651 (2015).
20. Weber, S., Sadoff, N., Zell, E. & de Sherbinin, A. Policy-relevant indicators for mapping the vulnerability of urban populations to extreme heat events: a case study of Philadelphia. *Appl. Geogr.* **63,** 231–243 (2015).
21. Memon, R. A., Leung, D. Y. C. & Chunho, L. A review on the generation, determination and mitigation of urban heat island. *J. Environ. Sci. China* **20,** 120–128 (2008).
22. Akbari, H. & Konopacki, S. Calculating energy-saving potentials of heat-island reduction strategies. *Energy Policy* **33,** 721–756 (2005).
23. Rosenfeld, A. H., Akbari, H., Romm, J. J. & Pomerantz, M. Cool communities: strategies for heat island mitigation and smog reduction. *Energy Build.* **28,** 51–62 (1998).

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Author contributions

F.E., W.J.W.B. and R.S.J.T. designed the study, analysed the data and wrote the paper. These authors contributed equally to the study. All authors discussed the results and commented on the manuscript.

Additional information

Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Publisher's note: Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations. Correspondence and requests for materials should be addressed to F.E.

Competing financial interests

The authors declare no competing financial interests.

Methods

The basic features of the model that produces the estimates presented in this paper are described in the following paragraphs. As it is the case for most global-scale models aimed to provide first economic estimates of the consequences of complex environmental problems, assumptions and stylized specifications are necessary. All estimates presented here are indicative, but provide a valuable insight into the joint effect of local and global climate change.

Global climate change projections were obtained by means of the MAGICC software. The SCENGEN multi-model pattern scaling was used to obtain the temperature changes for the geographical coordinates where the cities in this study are located. We use the MAGICC/SCENGEN models (http://www.magicc.org) version 5.3 for the WRE550, WRE450 and WRE350 stabilization scenarios and version 6 for three baseline emissions scenarios[24,25]—high (RCP8.5), medium–high (RCP6) and medium–low (RCP4.5)—and one stabilization scenario—RCP3PD. The reason for using two versions of MAGICC is that the first three scenarios are not available in version 6. All temperature trajectories were modified to start in year 2015 (instead of 2000; Supplementary Fig. 1) to have a common temperature value in the first year of the analysis.

Most UHI studies[26,27] focus on quantifying various aspects of maximum instantaneous urban-to-rural temperature differences. These results are difficult to link to seasonal or annual temperatures. However, empirical methods have been developed to estimate the effect of urbanization on mean seasonal and annual temperatures (in terms of average, minimum, maximum and range)[28]. One of the existing applications of this method has been to remove the effects of increasing population (urbanization) in large-scale studies of climate change[29]. Here we use this empirical method to estimate and project the increase in temperature in the 1,692 cities due to the UHI. The general form of the equation for estimating the increases in urban temperature[9,10,28] is $a \times Pop^b$, where a is a parameter estimated by the least-squares method and b is a fixed parameter. The parameter values are taken from Table 5 in ref. 28, which are calibrated for cities with population greater than 100,000. That study[28] provides different parameter values for this equation for average, minimum and maximum temperature for seasonal and annual values. We use the annual average values because those are input values for the DICE damage function. The parameter values used in this study are $a = 0.00174$ and $b = 0.45$.

The urban population data used in this paper come from the United Nations World Urbanization Prospects[30] (1950–2030), which covers all urban agglomerations with 300,000 inhabitants or more in 2014. The UN urban population data were extended to 2100 using the country-level growth rates of the A2 population scenario. The GDP scenarios (1990 US$) are based on the A2 country level socioeconomic projections. The A2 population and GDP scenarios used are available at http://ciesin.columbia.edu/datasets/downscaled. The aggregated cities GDP represents about 80% of global output[15]. This proportion was used to approximate the contribution of cities to country GDP, and the resulting aggregated output was then scaled to individual cities using the proportion of the population in each city within a country. Note that both the population and GDP projections, which are based on the A2 scenario, are a consistent realization of the SSP3 storyline[25] and can be combined as the driver of the baseline emissions scenarios RCP8.5, RCP6 and RCP4.5 (refs 25,31).

The estimates of the urban impacts of local and global climate change presented here are based on an adjusted impact function based on the DICE model, which is one of the most widely used integrated assessment models of the economic impacts of climate change[32]. The DICE impact function estimates economic losses caused by temperature increase. It has been estimated[32] that 2.5 °C warming would lead to a welfare loss of 1.5% of GDP. Judging from their sectoral impacts, 60% of the welfare losses are urban impacts, and 40% are rural. Agricultural impacts are excluded. The sectors considered in this study can be summarized into six categories: human settlements, health, non-market amenity impacts, other market impacts (including energy and water systems, construction, outdoor recreation), sea-level rise and catastrophic impacts. Welfare losses are quadratic in warming.

Let $D(t)$ denote total impact at time t, D_{U} denote urban impact and D_{R} denote rural impact. Then $D(t) = D_{\mathrm{U}}(t) + D_{\mathrm{R}}(t)$. Let $T(t)$ denote global warming, and $U(t)$ denote the UHI effect.

The original study[32] ignored the urban heat island effect, $U(t) = 0$. Their impact function is

$$D(t) = 1.5\left(\frac{T(t)}{2.5}\right)^2 = D_{\mathrm{R}}(t) + D_{\mathrm{U}}(t) = 0.6\left(\frac{T(t)}{2.5}\right)^2 + 0.9\left(\frac{T(t)}{2.5}\right)^2$$

Introducing the urban heat island effect, the impact function becomes

$$D(t) = D_{\mathrm{R}}(t) + D_{\mathrm{U}}(t) = 0.6\left(\frac{T(t)}{2.5}\right)^2 + 0.9\left(\frac{T(t) + U(t)}{2.5}\right)^2$$

That is, once the urban heath island is considered, impacts are always higher than found by ref. 32. As has been discussed in the literature, the currently available impact functions for estimating the economic effects of climate change may underestimate the true impacts of this phenomenon. Several categories of climate change effects are not included in these estimates and this is the case of all quantitative global climate change economic impact studies (for a review, see ref. 33). Results of climate impacts may, therefore, be seen as lower bounds. However, the impact functions from integrated assessment models are the best available tools for estimating the aggregated impacts of climate change. Until now, and to the best knowledge of the authors, no similar functions have been developed for UHI effects that could be used to complement that of DICE. In spite of the limitations expressed above, the use of DICE impact function provides relevant insights and estimates that allow a better understanding of the joint effects of local and global climate change and policy, their interactions, and the importance of benefits from local adaptation measures as risk-reduction instruments. Moreover, this paper shows that the local adaptation policies are already cost-effective with the standard, perhaps conservative, DICE impact function. This implies that the main conclusions of this paper are not affected even if the DICE impact function underestimates the impacts of local and global warming and related benefits of adaptation measures that limit the UHI effect. For the results presented in this paper a 3% discount rate was used. Here we present a sensitivity analysis of the results using a 7% discount rate, which shows that our main conclusions are robust to using this higher discount rate[34]. All costs and benefits are expressed in 1990 US dollar values. The correspondence between tables using a 7% and 3% discount rate is as follows: Table 1, Supplementary Table 6; Table 2, Supplementary Table 7; Table 3, Supplementary Tables 9; 3, 8; 4, 10; 5 and 11.

Results show that the main conclusions in this study are robust to a much higher discount rate. A higher discount rate makes the present values of impacts from global and local climate change smaller, which could justify investing less in global/local mitigation efforts[34]. (Supplementary Tables 6 and 7). However, there are important differences regarding when large impacts from global and local climate change will manifest themselves as well as the moment the benefits of global and local mitigation actions are going to be felt. The impacts of global climate change are gradual and the most significant ones are expected to happen in the later part of this century. Similarly, the benefits of global mitigation efforts would occur towards the end of the present century. With a high discount rate, these impacts and benefits have a small contribution to the corresponding present values. On the contrary, in the case of large cities, significant impacts of UHI are already occurring and UHI reduction policies can produce benefits in the short term. Consequently, a higher discount rate makes investing in global mitigation policies relatively less attractive than in local policies to reduce UHI.

The present value of the impacts of UHI is less sensitive to the discount rate chosen than that of the impacts from global climate change. With a 3% discount rate the present value of the accumulated impacts of UHI is about 48% of that of the RCP8.5 scenario, while with a 7% discount rate, the present values of the impacts due to UHI and of those of the RCP8.5 scenario have approximately the same magnitude (Table 1 and Supplementary Table 6). At the global aggregation level and for almost all global climate change scenarios, all local policies considered here produce benefits larger than their costs of implementation, even when a 7% discount rate is applied (Supplementary Table 7). However, the number of cities that have net losses from implementing the local policies increases considerably. For policies A and B, the number of cities with net losses increases to about 50%, while for policies C and D this number can reach up to around 60% and 70%, respectively. Under the NGCC scenario the number of cities with net losses can be as high as 90%.

Using a 7% discount rate, the largest reduction in urban economic impacts that can be attained by global mitigation efforts alone is about 30% (RCP8.5/350 ppm combination; Supplementary Table 9). These benefits can be greatly increased when local and global policies are implemented jointly (Supplementary Table 9). A 500 ppm stabilization scenario plus any of the local policies analysed here can produce similar or larger benefits than those that would be obtained by implementing a 350 pmm stabilization scenario, independently of the reference scenario that is chosen. Furthermore, the benefits of jointly implementing local and global measures are more than proportional due to interaction effects (Supplementary Table 10). The BCRs of all local policies become much more attractive than when no global mitigation scenario is implemented and the number of cities with net losses decreases significantly for most of the local policy options considered. In particular, Policy B produces the largest BCR values and the percentage of cities with net losses for this policy is between 0.59% and 39.24%, depending on the combination of reference and stabilization scenarios (Supplementary Table 11).

A variety of measures have been proposed to reduce the UHI effect, including expanding urban forest and plant coverage, green roofs, cool roofs and pavements that reflect solar energy and release heat quickly[18]. These measures can be implemented by the local authorities, as private initiatives that may be incentivized by policy, or made compulsory, for example, through building codes and zoning regulations[18]. In addition to limiting city-wide air temperatures, the UHI mitigation measures can have other beneficial effects. For example, green roofs can cool the house and outside temperature, lower energy costs, reduce storm water runoff and have aesthetic value. Apart from generating positive externalities, the resulting energy savings of cool and green roofs and increased vegetation are an important direct benefit for homeowners[22,35]. Here we focus on the potential reductions in air temperature of which several estimates have been reported by the Environmental Protection Agency (EPA) and other studies and on their benefits in terms of avoided climate impacts. According to the literature[21], the range of the maximum temperature reduction that can be achieved by adopting different measures is between 1.2 °C and 3 °C. The highest value of 3 °C results from a combination of expanding vegetation, cool pavements and cool roofs[23]. The EPA[18] estimates that improving pavement reflection between 10% and 35% results in a reduction of air temperature by 0.6 °C and a 50% adoption of cool roofs on houses reduces city-wide average (all day) air temperatures with about 0.2 °C. An alternative to cool roofs are green roofs, which can significantly reduce city-wide air temperatures, especially if these roofs are well irrigated. In particular, creating green roofs on 50% of the available surfaces in a city is estimated to reduce air temperatures in the entire city between 0.1 to 0.8 °C and an additional temperature reduction of between 0.5 °C and 1.0 °C can be achieved through irrigation of these roofs[18]. Below we present a sensitivity analysis regarding the effects over our cost–benefit analysis of using the lower and upper bounds of temperature reduction values of green roofs provided by the EPA. Air temperatures can be reduced by expanding tree and plant coverage in a city. In particular, peak temperatures can be 5 °C cooler in tree groves compared with open terrain, suburban areas with tree coverage are 2 °C to 3 °C cooler than air over ground, and sport fields are 1 °C to 2 °C cooler than bordering areas[18]. These estimates suggest that expanding tree and plant coverage can reduce the UHI effect, but it is difficult to translate these into an estimate of how much city-wide area temperatures can be reduced by this measure. For this reason, the expansion of tree coverage is not included as a mitigation strategy in our analyses. Four strategies for mitigating the UHI are considered: Policy A, 50% change of the cities' total roof area to cool roofs (liquid applied coating) and 100% change of the paved area to cool pavement (hot mix asphalt with light aggregate); Policy B, 20% change to cool roofs and 50% to cool pavement; Policy C, 10% change to green roofs, 25% change to cool roofs and 50% change to cool pavement; Policy D, 10% change to green roofs, 10% to cool roofs and 20% to cool pavement. For this study, UHI reduction policies are assumed to be implemented immediately. This assumption may be unrealistic in practice but it is made to illustrate the potential of UHI reduction measures in the context of local and global climate change. The city area was estimated as a function of the average population density (7,506.25 inhabitants km^{-2}) in the largest urban areas in the world (http://www.demographia.com/db-worldua.pdf). Based on Akbari[12], the proportion of roof and paved surfaces is assumed to be 25% and 35% of the total city area, respectively.

The estimates of the cooling effect and costs of some of the most popular options for mitigating the UHI were obtained from the EPA[18]. Supplementary Table 2 presents a summary of the options, cooling effect (including the percentage of city area) and costs used for this paper. It is assumed that these costs are expressed as 1990 US dollar values. The costs of changing to cool roofs could be close to zero if a cool colour is selected whenever a roof is changed. However, since in this study it is assumed that the implementation of the UHI reduction measures occurs in the initial year, we use the reference cost reported by the EPA. The UHI is restricted in our analysis to non-negative values (that is, mitigation measures can at most reduce the UHI warming to zero). Since the cooling effect of different UHI mitigation options is typically given for a particular percentage of city area (for example, 50% of the city roof surface is converted to green roofs), we linearly interpolate these values for other percentages of implementation. As such, the estimates are more reliable for the percentage values reported by the EPA[18] and reproduced in Supplementary Table 2. These estimates correspond to Policy A. The benefits of adopting different UHI mitigation options are analysed in the context of global emissions trajectories based on the baseline and mitigation scenarios mentioned above. This set of emissions scenarios represents a wide range of possible future climates with different associated levels of mitigation effort.

The effects on our cost–benefit analysis of using the lower and upper bounds of temperature reduction from green roofs provided by the EPA are also explored (see Supplementary Table 2). All estimates use a 3% discount rate. The policies considered for this sensitivity analysis are C and D; both include 10% change to green roofs. Supplementary Tables 12 and 13 report the costs and benefits of implementing these policies for the lower/upper bound values for temperature reductions from green roofs and different global emissions scenarios.

The main results of this sensitivity analysis are: policies C and D produce BCR values larger than one regardless of the temperature reduction value that is assumed for green roofs; however, even under the upper temperature reduction value from green roofs, policies C and D still produce the lowest BCR values of the policies considered in this study. If the upper (lower) bound of temperature reduction value for green roofs is used, the BCR values for Policy C are at most about US\$0.80 (RCP8.5) larger (smaller) than the BCR obtained using the average temperature reduction. These differences are smaller for the RCP6 and RCP4.5 scenarios, due to smaller interaction effects. In the NGCC scenario, these differences amount only to about US\$0.30. In the case of Policy D, if the upper (lower) bound of temperature reduction value for green roofs is used, the BCR values are at most about US\$1.00 (RCP8.5) larger (smaller) than the BCR obtained using the average temperature reduction. These differences are smaller for the RCP6 and RCP4.5 scenarios. Under the NGCC scenario these differences are about US\$0.40.

The number of cities with net losses is very sensitive to the temperature reduction value that is assumed for green roofs. For Policy C and the RCP8.5 scenario, the lower bound estimate for green roofs temperature reduction produces an increase of about 86% more cities with net losses with respect to the estimates produced with the average value. Using the upper bound value instead, the number of cities with net losses decreases by about 30%. For the RCP6 and RCP4.5, the upper/lower bound values for green roofs temperature reduction produce a change in the number of cities with net losses of about 50% and 40%, respectively, compared with the average temperature reduction value. For policies C and D, these differences are smaller than 10% under the NGCC scenario.

The sensitivity analysis shows that the inclusion of green roofs produces lower BCR values than other policies based on cheaper UHI reduction options. However, the benefits provided by green roofs are not fully taken into account in these calculations. The BCR values do not include indirect benefits, such as reduced pollution, health risk and storm water retention. If these additional benefits were included, the BCR values could be closer to those of policies A and B.

Data availability. The urban population data and the population and GDP projections were downloaded from https://esa.un.org/unpd/wup/cd-rom/WUP2014_XLS_CD_FILES/WUP2014-F12-Cities_Over_300K.xls and http://ciesin.columbia.edu/datasets/downscaled. Alternatively, the data set is available at https://doi.org/10.6084/m9.figshare.4789072.

References

24. IPCC *Climate Change 2013: The Physical Science Basis* (eds Stocker, T. F. *et al*.) (Cambridge Univ. Press, 2013).
25. van Vuuren, D. P. & Carter, T. R. Climate and socio-economic scenarios for climate change research and assessment: reconciling the new with the old. *Climatic Change* **122,** 415–429 (2014).
26. Oke, T. R. The energetic basis of the urban heat island. *Q. J. R. Meteorol. Soc.* **108,** 1–24 (1982).
27. Oke, T. *Urban Climatology and its Applications with Special Regard to Tropical Areas: Proceedings of the Technical Conference Organized by the World Meteorological Organization and Co-sponsored by the World* (WMO Secretariat, 1986).
28. Karl, T. R., Diaz, H. F. & Kukla, G. Urbanization: its detection and effect in the United States climate record. *J. Clim.* **1,** 1099–1123 (1988).
29. Jones, P. D. *et al*. The effect of urban warming on the northern hemisphere temperature average. *J. Clim.* **2,** 285–290 (1989).
30. United Nations, Department of Economic and Social Affairs *Population Division: World Urbanization Prospects, the 2009 Revision: Highlights* (2010).
31. KC, S. & Lutz, W. The human core of the shared socioeconomic pathways: population scenarios by age, sex and level of education for all countries to 2100. *Glob. Environ. Change* **42,** 181–192 (2017).
32. Nordhaus, W. D. & Boyer, J. *Warming the World: Economic Models of Global Warming* (MIT Press, 2003).
33. van den Bergh, J. C. J. M. & Botzen, W. J. W. A lower bound to the social cost of CO_2 emissions. *Nat. Clim. Change* **4,** 253–258 (2014).
34. Arrow, K. *et al*. Determining benefits and costs for future generations. *Science* **341,** 349–350 (2013).
35. Hall, D. C. Albedo and vegetation demand-side management options for warm climates. *Ecol. Econ.* **24,** 31–45 (1998).