Contrasting urban and rural heat stress responses to climate change

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[1] Hot temperatures in combination with high humidity cause human discomfort and may increase morbidity and mortality. A global climate model with an embedded urban model is used to explore the urban-rural contrast in the wet-bulb globe temperature, a heat stress index accounting for temperature and humidity. Wet-bulb globe temperatures are calculated at each model time step to resolve the heat stress diurnal cycle. The model simulates substantially higher heat stress in urban areas compared to neighboring rural areas. Urban humidity deficit only weakly offsets the enhanced heat stress due to the large night-time urban heat island. The urban-rural contrast in heat stress is most pronounced at night and over mid-latitudes and sub-tropics. During heatwaves, the urban heat stress amplification is particularly pronounced. Heat stress strongly increases with doubled CO2 concentrations over both urban and rural surfaces. The tropics experience the greatest increase in number of high-heat-stress nights, despite a relatively weak ~2°C warming. Given the lack of a distinct annual cycle and high relative humidity, the modest tropical warming leads to exceedance of the present-day record levels during more than half of the year in tropical regions, where adaptive capacity is often low. While the absolute urban and rural heat stress response to 2 × CO2 is similar, the occurrence of nights with extremely high heat stress increases more in cities than surrounding rural areas. Citation: Fischer, E. M., K. W. Oleson, and D. M. Lawrence (2012), Contrasting urban and rural heat stress responses to climate change, Geophys. Res. Lett., 39, L03705, doi:10.1029/2011GL050576.

1. Introduction

[2] Today more than half of the world’s population resides in urban areas with the percentage expected to increase rapidly within the next decades [Martine and Marshall, 2007]. However, the global climate models (GCMs) used for projections in the IPCC AR4 do not account for urban surfaces. As urban areas only cover a small fraction of Earth's surface, they play only a minor role for global mean temperature increase [Parker, 2006]. However, the differences in the surface energy budget of urban areas may substantially alter the climate change impacts on the local population.

[3] Recent major summer heatwaves in 2003 in Europe and 2010 in Russia caused tens of thousands of heat-related deaths [Robine et al., 2008; Barriopedro et al., 2011]. In both cases the mortality excess in absolute numbers was particularly high in the urbanized areas around Paris and Moscow, respectively. Apart from excessive temperature anomalies, confounding health risk factors such as humidity, radiation, low winds and air pollution may have played an important role. All these variables differ between urbanized and rural areas and tend to reach exceptional levels during heatwaves.

[4] Here we focus on two well-established risk factors: temperature and humidity. High ambient temperatures and humidity reduce the human body’s efficiency of transporting away the metabolic heat through evaporative cooling (sweating) and heat conduction [Sherwood and Huber, 2010]. Consequently, they lead to heat stress and can increase both morbidity and mortality [Basu and Samet, 2002].

[5] Urban air temperatures are substantially higher than corresponding temperatures in the surrounding rural areas. This so-called urban heat island (UHI) effect that arises from the different radiative, thermal, moisture and aerodynamic properties detailed below, is most pronounced for night-time minimum temperatures [e.g., Oke et al., 1991, and references therein]. Relative humidity tends to be lower over urban areas [Oke, 1987], which may offset some of the heat stress induced by warmer urban temperatures. The influence of these two competing effects and their response to increased greenhouse-gas concentrations has not been addressed in a GCM framework.

[6] Enhanced atmospheric concentrations of greenhouse gases are expected to result in global increases in heat stress indices along with rising temperatures [Delworth et al., 1999; Sherwood and Huber, 2010; Willett and Sherwood, 2012]. However, most of the available global projections on combined temperature-humidity measures are either based on seasonal mean changes obtained from climate models with a very coarse resolution, or assume spatially uniform warming and constant relative humidity.

[7] Regional scenarios for Europe based on a single regional climate model (RCM) [Diffenbaugh et al., 2007] and a comprehensive multi-model RCM experiment [Fischer and Schär, 2010] suggest a consistent pattern of heat stress changes. More frequent critical heat stress levels are expected particularly along the Mediterranean coasts, which have some of the highest population densities of southern Europe. However, these findings are based on models that do not account for the unique properties of urban surfaces.

[8] Here we use a GCM that includes an urban canyon model to explore the urban-rural contrast of heat stress indices and their response to a doubling of CO2. We focus on the following four zonal land regions: northern Europe (47–60°N, 0–30°E), southern Europe (36–47°N, 0–30°E),
northern Africa (20°–36°N, 0°–30°E), and tropical Africa (10°S–10°N, 0°–30°E). These regions are highlighted as they illustrate the latitudinal dependence of the urban-rural contrast for four distinct climatic zones.

2. Heat Stress Index and Climate Model

There are several commonly used heat stress indices that account for the effects of temperature as well as additional environmental factors. Here we use the Simplified Wet-Bulb Globe Temperature \( W \), with \( W = 0.567T + 0.393e + 3.94 \), where \( T \) is the temperature in °C, and \( e \) is the simultaneous vapour pressure in hPa (Figure 1). While \( W \) is often interpreted as a corrected temperature and given in °C, we will hereafter refer to it as a unitless index to avoid confusion with temperature. The \( W \) thresholds (see Figure 1) refer to the health risk for people working or training under heat conditions.

We have implemented the heat stress index \( W \) directly in the model code so that it is calculated online at every model 30-minute time step (archived hourly). Previous model studies calculated heat stress indices from daily or seasonal mean values or in some cases daily maximum temperatures and minimum relative humidity, implicitly

![Figure 1. Illustration of wet-bulb globe temperature (W) definition: W is shown as a function of temperature for different levels of relative humidity. It is illustrated that a 2°C warming yields larger W increases if humidity is high and/or temperatures are high. The levels to the right illustrate the risk level described by Willett and Sherwood (2012).](image-url)
assuming that they occur at the same time of day [Delworth et al., 1999; Diffenbaugh et al., 2007; Fischer and Schär, 2010]. Consequently, the diurnal minimum of W tends to be overestimated (Figure S1 in the auxiliary material) and maximum of W underestimated as the diurnal temperature maxima often do not coincide with the relative humidity minima. For the 99th percentile of daily W, the bias due to a non-accurate (i.e., not online) calculation regionally exceeds 1–2 units (Figure S1).

3. Present-Day Urban-Rural Heat Stress Contrast

[12] To evaluate how the urban environment affects heat stress, we assess the representation of a given model variable over the urban and the rural surface fraction of the same gridbox. The rural fraction is here defined as the area-average across all plant functional types and bare soil of a gridbox. Air temperatures in the urban canopy layer, defined as the portion of the boundary layer below the tops of the surface roughness elements (building height) [Oke, 1976], are here given at a height of 2m above the source height for the turbulent fluxes.

[13] The comparison of the present-day diurnal cycle of urban and rural temperatures during summer (JJA) (Figure 2, left, blue lines) reveals that the urban heat island (UHI) starts to build up during the second half of the day and typically reaches a maximum before sunrise. A north-south cross section showing four regions in Europe and Africa illustrates that the timing is similar with larger UHI for daily temperature minima (Tmin) than maxima (Tmax) at all latitudes, which is consistent with numerous observational studies [e.g., Arnfield, 2003, and references therein]. Urban Tmax is about 3–4.5°C warmer than rural Tmax in northern and southern Europe and northern and southern Africa and about 1°C warmer in tropical Africa. The urban-rural Tmax contrast is greatest over northern Africa. An urban cool island is actually seen in tropical Africa. The modelled UHI is broadly consistent with observed latitudinal dependence of UHI [Wienert and Kuttler, 2005], with a weak or even cool Tmax UHI found in some tropical regions [e.g., Roth, 2007].

[14] The night-time build-up of the UHI is to a large extent determined by the urban-rural contrast in daytime heat storage and subsequent night-time heat release from the ground [e.g., Oleson et al., 2011], which is consistent with observational studies [e.g., Oke et al., 1991]. The dominating surface property is the thermal admittance μ defined as μ = (kC)1/2, where k is the thermal conductivity and C is the heat capacity. Thermal admittance is high for most of the urban surfaces and saturated wet soils, and low for unsaturated to dry soils [Oke et al., 1991]. Given its high admittance, the city fabric stores more heat during the day than dry rural surfaces, and releases that stored heat through the night, allowing the urban canopy layer to stay relatively warm. Furthermore, the intensity of UHI is sensitive to longwave trapping - radiative cooling is less efficient in urban areas due to the smaller sky-view factor in urban canyons. This effect is most important in clear sky conditions when the rural fraction cools off efficiently but can be damped by downward longwave radiation resulting from clouds and the high tropospheric temperatures and humidity. Further potential factors contributing to the modelled UHI include the latent heat flux contrast (low in urban due to the large fraction of impervious urban surfaces), differences in longwave surface emissivity and anthropogenic waste heat flux from heating and air conditioning.

[15] The latitudinal dependence of the simulated nighttime UHI is to a large extent determined by differences in the night-time radiative cooling of the rural fraction, which is more pronounced in the extratropics than the tropics. In the tropics the rural areas do not cool off much more than urban areas due to the high downward longwave radiation resulting from the cloudiness and the high tropospheric temperatures and humidity. The downward longwave radiation, which in the model is about 50 W m−2 larger in tropical Africa compared to northern Africa, counteracts the radiative surface cooling more efficiently in the rural fraction due to the larger sky-view factor. A second potential factor for the low tropical UHI is the surface wetness that results in rural thermal admittance values similar to those seen in urban areas [Oke et al., 1991]. Nevertheless, in our simulations the simulated night-time urban surface storage heat release is substantially larger than the corresponding rural flux even in the tropics (Figure S2).

[16] The UHI of Tmax is largest in northern Africa where the rural surfaces, typically dry desert surfaces, are comparatively bright and have higher albedos than urban materials. As a result the absorbed shortwave radiation is lower for rural compared to urban surfaces (Figure S2), which contributes to the daytime UHI in the model. In contrast in forested regions rural albedos are often lower than urban albedos.

[17] The diurnal cycle of urban and rural relative humidity (RH) basically mirrors the temperature cycle over all four regions considered (Figure 2, middle left). In northern Europe and southern Europe simulated nighttime RHmax is lower over urban areas by more than 15% and 10%, respectively. The simulated patterns of urban-rural contrasts in RH provide a coherent picture, which is reasonably consistent with observed in-situ measurements in comparable cities of the northern mid-latitudes and subtropics [Ackerman, 1987; Robau, 2003; Unkašević et al., 2001]. The urban RH deficit mainly results from higher urban temperatures and lower latent heat flux. Due to the high fraction of impervious urban surfaces, the latent heat flux is 30−60Wm−2 lower than over the corresponding rural fraction in much of Europe and tropical Africa (Figure S2).

[18] The warmer urban temperatures and lower humidities have opposite effects on heat stress. Figure 2 (middle right) indicates that the net effect, expressed as the urban-rural contrast in W is mostly positive or in other words dominated by the warmer temperatures. The urban and rural W cycles are reminiscent of the temperature cycles in all regions. However, the urban-rural W contrast would be larger if it was not offset by the urban RH deficit at night. In northern and southern Europe Wmin is on average around 1.3 and 1.7 units, respectively, higher than over the corresponding rural fraction despite a pronounced urban RH deficit. The simulation of higher heat stress indices in urban areas compared to rural areas is supported by local observational evidence for cities in the US [Basara et al., 2010], Greece [Kamoutsis et al., 2007], Hungary [Unger,
1996] and tropical Africa [Balogun et al., 2010]. These zonal variation in urban-rural contrasts shown here for a north-south transect from northern Europe to tropical Africa are also valid for other longitudes. A north-south gradient is also found along the Americas with on average somewhat larger urban-rural contrasts and from northeastern to southeastern Asia with smaller contrasts (not shown).

Figure 2. Urban-rural contrast in diurnal cycle: Area-averaged summer (JJA) diurnal cycle in (left) temperature, (middle left) relative humidity, and (middle right) wet-bulb globe temperatures in northern Europe (47–60°N, 0–30°E), southern Europe (36–47°N, 0–30°E), northern Africa (20–36°N, 0–30°E), and tropical Africa (10°S–10°N, 0–30°E) (dashed line, rural; solid line, urban; blue for 1 × CO₂ and red for 2 × CO₂). (right) Correlation between daily mean temperature and corresponding daily mean UHI across all summer days in 1 × CO₂ (blue) and 2 × CO₂ (red).
The simulated urban-rural contrast in heat stress varies not only in space but also in time and reaches values 60–65% larger or smaller than the mean. Analysis of daily summer values reveals a highly significant correlation between background temperature (daily mean) and urban-rural heat stress contrast ($r = 0.45$ for northern Europe, $r = 0.56$ for southern Europe). The correlation is even stronger for daily mean temperature against UHI ($r = 0.64$ for northern Europe, $r = 0.70$ for southern Europe, Figure 2). This indicates that the urban heat stress amplification is greatest during the days with highest heat stress. The high UHI on hot days appears to mainly relate to low cloudiness associated with very warm days in the extratropics. The absence of clouds leads to more efficient rural radiative cooling at night and intensifies the UHI. The relation is consistent with observational studies suggesting increasing UHI with decreasing cloud cover [Morris et al., 2001; Steeneveld et al., 2011] and highest UHI at anticyclonic conditions [Arnfield, 2003; Unger, 1996, and references therein]. Note that the tropics show no or slightly negative correlations between background temperature and urban-rural contrast (Figure 2, bottom right). In summary, despite the absence of a daytime contrast, the overall urban heat stress is substantially exacerbated due to the large night-time contrasts, a crucial health factor that hampers human recovery from daytime heat loads and that may lead to sleep deprivation [Grize et al., 2005]. Note that here only the dominant urban density class in each grid cell, mostly medium density, is simulated. As a result the heat stress, in the higher density classes, such as central business districts, may be underrepresented in this study.

4. Urban and Rural Response to a Doubling of CO₂

Detailed comparison reveals that urban and rural areas respond similarly to a doubling of CO₂ (red curves in Figure 2). Consistent with Oleson [2012] urban temperatures warm slightly less than surrounding rural temperatures in tropical Africa and somewhat more in northern and southern Europe (only Tmin in the latter). However, the urban and rural $W$ response to a doubling of CO₂ is very similar in all regions.

For human comfort and health, changes in the number of days and nights of the year with high heat stress may be more relevant than the mean change. We here choose the daily 99th percentile ($1\times CO₂$) of rural heat stress ($W_{\text{min},99,1×CO₂}$) as a critical threshold, thereby accounting for adaptation of the population to current climate conditions.

Consistent with the mean urban–rural contrasts, the number of nights with exceptional heat stress ($W_{\text{min}} > W_{\text{min},99,1×CO₂}$, hereafter high-heat-stress nights) is substantially higher in urban areas (Figure 3, blue bars). In northern Africa the present-day number of high-heat-stress nights is around 10 times larger in the urban than the rural fraction. The occurrence of high-heat-stress days ($W_{\text{max}} > W_{\text{max},99,1×CO₂}$) differs less between urban and rural fraction and varies in sign across regions (Figure 3).

Increasing concentration of CO₂ lead both to substantially more high-heat-stress nights and days (Figure 3, red bars). The frequency changes for days and nights of exceptional $W$ are broadly consistent with the occurrence of hot days and warm nights (temperature-based only) of McCarthy et al. [2010] and Oleson [2012]. However, including the RH aspect of heat stress can amplify or mitigate the local response to enhanced CO₂ and therefore alter urban-rural heat stress contrasts. Despite similar urban compared to rural $W$ response to CO₂ doubling, the frequency increase of urban high-heat-stress nights can substantially exceed that in the corresponding rural fraction. The larger urban increase in night counts arises from the statistical non-linearity in the exceedance frequency: given more
 frequent present-day exceedance, the same mean shift in the \(W\) climatology in response to \(2\times CO_2\) yields a greater exceedance frequency change.

Interestingly, the occurrence of high-heat-stress days and nights increases strongly in tropical Africa both in urban and rural areas, which is remarkable since the tropics experience the weakest temperature change. This seemingly contradictory pattern is discussed in the following section in a global context.

5. Global Pattern of Heat Stress Response to a Doubling of \(CO_2\)

The doubling of atmospheric \(CO_2\) concentrations in our simulations leads to a global temperature increase of 2.9°C, which is close to the best estimate for climate sensitivity of 3°C [Intergovernmental Panel on Climate Change (IPCC), 2007]. The largest absolute change in the local 99th percentile of daily minimum temperatures (\(T_{min99}\)) is simulated in the subtropics and mid-latitudes, such as central North America, central Eurasia, southern Africa and Australia (Figure 4a). There \(T_{min99}\) warms by up to 5°C and exceeds the corresponding local mean summer warming by more than 50%. These areas typically experience a decrease in evapotranspiration arising from land surface drying or are dry even under present-day conditions. The \(T_{min99}\) change is comparatively weak in humid climates (i.e., along coasts and in tropical regions).

Interestingly, the response pattern for 99th percentiles of daily \(W\) minima (\(W_{min99}\), Figure 4b) is spatially much more uniform than \(T_{min99}\). All across the globe land regions tend to show similar \(W_{min99}\) response, irrespective of their distinct \(T_{min99}\) response (Figure 4c). The reason is that the weak warming over humid regions yields about the same \(W\) increase as the strong warming seen in comparatively dry regions (see illustration in Figure 1), except for the Sahara region. Mid-latitude regions with strong warming tend to dry even further, which mitigates the \(W_{min99}\) response to a doubling of \(CO_2\).

As highlighted in the previous section there is a remarkable contrast between the geographical response pattern for temperature (Figure 4a) and for the number of high-heat-stress nights (after a doubling of \(CO_2\)) (i.e., change in the exceedance frequency, Figure 4d). The former is smallest and the latter largest over the tropics. Despite the comparatively weak warming of around 2°C in tropical Africa and Asia (Figure 3a), more than half of all nights per year in the doubled \(CO_2\) climate experience heat stress exceeding extreme levels in present-day climate (Figure 4d). This is due to the virtual absence of a temperature seasonal cycle at present-day and low synoptic variability, which permits major changes in the frequency of occurrence of exceptionally warm nights, even with relatively weak mean warming. Even in extra-tropical regions the increase in occurrence of high heat-stress nights is very pronounced. Particularly in the southern United States, Mexico, around the Mediterranean, and in India and Southeast Asia present-day \(W_{min99}\) thresholds are exceeded on 50–100 more nights. This suggests that despite a comparatively small \(W\) response, some of the areas would experience unprecedented heat stress conditions on numerous days of the year, which requires strong adaptive measures. These results are independent of the
definition of heat stress indices and have been repeated for other measures of heat stress such as HUMIDEX [Masterson and Richardson, 1979] and heat index (apparent temperature) [Steadman, 1979].

6. Conclusions

[29] We explored urban amplification of heat stress in one of the first global climate models to include an urban model. Heat stress is defined here as the Simplified Wet-Bulb Globe Temperature (\(W\)). Consistent with local observational evidence, the model simulates strong urban-rural temperature and humidity differences at night and weak differences during the daytime. In northern mid-latitudes and subtropics, nights are up to 4°C warmer and 10-15% drier in urban areas compared to surrounding rural areas. The night-time urban temperature amplification and the associated humidity deficit are competing factors that counteract each other with respect to urban heat stress. However, all across the globe \(W\) is dominated by the higher urban than rural temperatures, which is consistent with local observational evidence from selected in-situ measurements. In northern and southern Europe urban Wmin on average exceeds corresponding rural values by 1.3 and 1.7 units, respectively, which may imply a higher threat level in the heat stress classification (see Figure 1). In northern and southern Europe as well as northern Africa the largest urban heat stress amplification occurs during the hottest days, when urban-rural contrasts exceed the mean by 60-65%. The daytime maximum heat stress (Wmax) exhibits less of a contrast.

[30] While the spatial patterns in urban-rural differences in temperature and combined heat stress are broadly consistent with observational records and are expected to be robust, the exact local quantification of the contrasts simulated by the model includes considerable uncertainties and should be interpreted as illustrative examples and not as a local assessment of urban-rural contrasts. While there may be substantial biases in the absolute numbers, the urban-rural contrasts discussed here are rather insensitive to such biases as they relate to percentile-based thresholds. Note that the urban surface properties in CLM4 mainly represent medium density urban areas. Heat stress in higher urban density classes, such as central business districts, may be underestimated in this study.

[31] We also show that heat stress increases at a similar rate in both urban and rural areas in response to a doubling of CO\(_2\). To provide a more direct link to human health and adaptation to climate change, we also quantified changes in the occurrence of high-heat-stress days and nights defined in relation to the daily 99th percentile (1 \(\times\) CO\(_2\)) of rural heat stress (Wmax\(_{99,1} \times\)CO\(_2\) and Wmin\(_{99,1} \times\)CO\(_2\)). Despite near-equal urban and rural warming in response to 2 \(\times\) CO\(_2\), the change in occurrence of high-heat-stress nights is greater in urban than rural areas, for all regions analysed here. The increase in the number of both urban and rural high-heat stress days and nights is extremely pronounced in the tropics, which is remarkable as these latitudes experience the weakest warming signal. This seemingly contradictory pattern results from (a) the difference between absolute \(W\) response and change in exceedance counts, which are highly sensitive to the present-day climatology, and (b) the difference in the temperature and heat stress response induced by humidity. Irrespective of the weaker warming, humid regions such as tropical Africa experience a similar heat stress response to comparatively dry regions in eastern Europe and the US Midwest.

[32] In tropical Africa and Asia, more than half of all nights each year in the doubled CO\(_2\) climate experience heat stress exceeding extreme levels in present-day climate. Even in extra-tropical regions such as around the Mediterranean, southern US, Mexico, India and southeast Asia, heat stress reaches unprecedented magnitudes in 50–100 nights of the year. If heat stress conditions that have never been experienced under present-day conditions become regular with increasing CO\(_2\) levels, significant adaptation efforts will be required, especially in the relatively poor tropical regions. The heat stress levels simulated here are still well below the potential adaptability limit postulated by Sherwood and Huber [2010].

[33] Note that our experiment does not account for urban humidity sources from combustion and potential future urban growth, two effects that typically increase the urban-rural contrasts [e.g., Oke, 1973, 1988]. Given these limitations and substantial uncertainties, the exceedance frequencies presented here are not suited for impact studies or local risk assessment but should rather provide a coherent global picture of critical features of urban heat stress amplification and heat stress changes due to increasing CO\(_2\) levels. Our findings emphasize the need for improved understanding of the urban and rural heat stress response to greenhouse-gas emissions in order to design well-informed adaptation strategies. A strong focus on the unique aspects of urban climate is vital as today more than half of the world’s population lives in cities with the percentage expected to increase rapidly within the next decades.

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