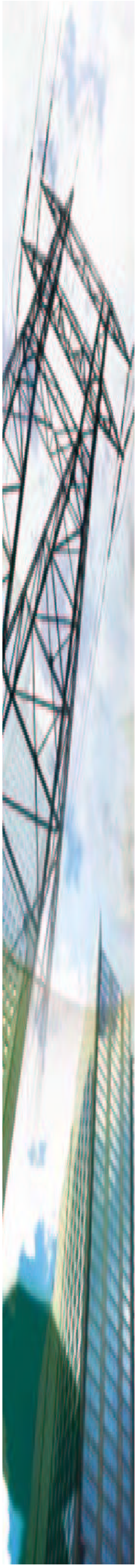
Building Knowledge for a Changing Climate



# *BETWIXT*
# *Built EnvironmenT: Weather scenarios for investigation of Impacts and eXTremes*

## BETWIXT Technical Briefing Note 6
## Version 1, September 2004

## RELATIVE IMPACTS OF RADIATIVE FORCING, LANDSCAPE EFFECTS AND LOCAL HEAT SOURCES ON SIMULATED CLIMATE CHANGE IN URBAN AREAS

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# CHANGES IN URBAN TEMPERATURE AND HUMIDITY DUE TO RADIATIVE FORCING, LANDSCAPE EFFECTS AND LOCAL HEAT SOURCES

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## 1. Introduction

Built-up areas exert significant influences on their local climates, with an "urban heat island" being observed in many cities (Figure 1). This is due partly to the influence of the urbanised landscape on the surface energy budget and local meteorology, and partly from sources of heat arising from human activities. The nature of the land surface is a key factor influencing the sensitivity of near-surface climates to radiative forcing by increasing greenhouse gas concentrations, so the responses of urban climates to radiative forcing may be different to those of non-urban climates. Moreover, increases in anthropogenic heat sources may exert an additional direct forcing of local climates.

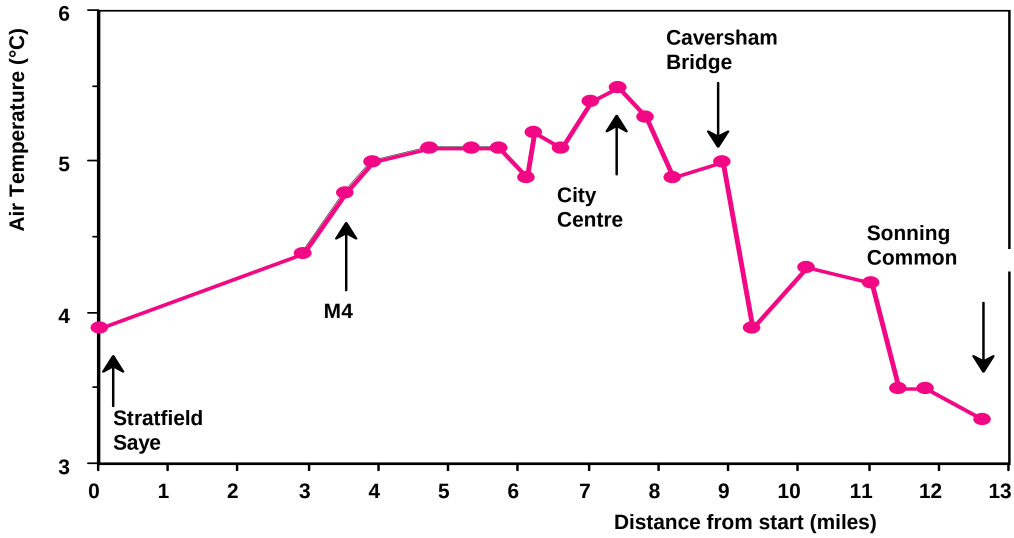


**Figure 1.** Observations of near-surface air temperature across Reading on 21/22 April 1989

However, scenarios of climate change do not consider the influences of urban areas on their own local climates. Consequently, it may not be appropriate to apply such scenarios to climate change impacts studies in the context of built-up areas. While this problem may be partially addressed by combining climate change scenarios with representations of present-day urban heat islands, this does not address the interactions between urban landscapes and radiative forcing nor account for increasing anthropogenic heat sources. Here we use a new land-surface parametrization in a General Circulation Model of climate to assess the potential bias in climate scenarios in the context of climate change in built-up areas.

A parametrization of urban land surfaces and anthropogenic heat sources (Best 1998) has been implemented in the land surface scheme of the Hadley Centre Atmospheric General Circulation Model HadAM3 (Essery et al 2003, Pope et al 2000) , in order to examine the potential importance of current and future urban heat island effects relative to the local effects of radiatively-forced climate change. The modelling methodologies have been previously described in BETWIXT Technical Note 3 (Betts and Best 2004). This technical report addresses the following questions regarding the simulation of climate and climate change in the London gridbox with this model:

1. Does the inclusion of the present-day extent of the urbanised portion of the landscape produce a heat island as a result of landscape effects?
2. How does this affect temperatures under a doubled-$CO_2$ climate?
3. Are feedbacks between the land surface and atmosphere important for the sensitivity of the local climate to doubling $CO_2$?
4. Does the inclusion of the present-day anthropogenic heat source add to the heat island?
5. What is the effect of a tripling of the anthropogenic heat source?
6. How does this compare with doubling $CO_2$?

## 2. Experimental design

### 2. 1 Comparing the effects of the urban land surface, anthropogenic heat sources and radiatively-forced climate change

The impacts of urban areas on their own local climate change were investigated with a number of simulations with the climate model. These simulations varied the following aspects of the model: atmospheric $CO_2$ concentration; the presence or absence of urban areas; the presence and extent of direct anthropogenic heat sources. The size of the current anthropogenic heat source was estimated as $20Wm^{-2}$ from information on energy consumption; details are given in BETWIXT Technical Note 3 (Betts and Best 2004). As a preliminary sensitivity study to assess the effects of future increases in anthropogenic heat sources in comparison with a doubling of $CO_2$, we considered a simple linear extrapolation of the projected fossil fuel consumption trend which gives a tripling of consumption around the approximate projected time of doubling of $CO_2$. We therefore considered a scenario of anthropogenic heat sources being increased by a factor of three to 60 $Wm^{-2}$.

The following simulations were performed including various combinations of $CO_2$ concentrations and urban influences:

U1N: Current $CO_2$ with current urban areas but no anthropogenic heat sources
U2N: Doubled $CO_2$ with current urban areas but no anthropogenic heat sources
U1C: Current $CO_2$ with current urban areas and current anthropogenic heat sources
U2C: Doubled $CO_2$ with current urban areas and current anthropogenic heat sources
U2T: Doubled $CO_2$ with current urban areas and tripled anthropogenic heat sources.

In simulation U1N, comparison of the temperatures simulated for the urban tiles with those for the non-urban tiles in the same gridboxes shows the extent of the urban heat island under the present-day climate. Since the urban tile is coupled to the atmosphere and influences the overlying meteorology through the fluxes of heat, moisture and momentum, the simulated urban heat island includes the effect of feedbacks between the atmosphere and land surface.

A similar comparison in U2N shows the extent of the urban heat under a doubled-$CO_2$ climate, giving an indication of the extent to which temperature extremes under global warming are modified in the urban area.

Comparison of simulations U2N and U1N shows the impacts of radiatively-forced climate change on temperatures on urban and non-urban areas, and hence, any changes in the character of the urban heat island as a result of radiatively-forced climate change.

Comparison of simulations U1C and U1N shows the impact of anthropogenic heat sources on the simulated present-day urban heat islands. Comparison of simulations U2C and U2N show the effects of anthropogenic heat sources on the character of the urban heat island under doubled $CO_2$. Further comparison with U2T shows the effect of tripling the heat source.

Comparison of U2T and U1C shows the overall warming due to doubling $CO_2$ and tripling anthropogenic heat sources relative to the present-day state.

## 2.2 Examining assumptions of stationarity in the climate system

An alternative method for assessing the potential effects of urban heat islands under a doubled-CO2 climate would be to assume stationarity of the heat island anomly (ie: that the character of the heat island is not affected by radiatively-forced climate change), and therefore to impose an present-day heat island pattern on a standard climate change simulation which neglected heat island effects. In order to compare this method with that of modelling the heat islands, a further pair of simulations at present-day and doubled-$CO_2$ was performed with no urban areas included:

N1N: Current $CO_2$ with no urban areas and no anthropogenic heat sources
N2N: Doubled $CO_2$ with no urban areas and no anthropogenic heat sources

An alternative representation of urban temperatures under doubled-$CO_2$ including landscape effects was therefore constructed with this by imposing the heat island anomalies from U1N on the radiatively-forced climate change pattern given by N2N-N1N:

A2N: Doubled $CO_2$ with present-day urban heat island (landscape effects only)

A further alternative representation of urban temperatures under doubled-$CO_2$ including both landscape effects and current anthropogenic heat sources was constructed by imposing the heat island anomalies from U1C on N2N-N1N:

A2C: Doubled $CO_2$ with present-day urban heat island (landscape effects and current heat sources)

Comparisons of A2N and A2C with U2N and U2C respectively test the validity of the assumption of stationarity for the urban heat island signal with respect to doubling $CO_2$.

Each simulation used a climatology for sea surface temperatures which was in balance with the atmospheric $CO_2$ concentration, hence minimising model spin up effects and constraining internal climate variability which can obscure the results.

All simulations were performed for 20 years after five years of spinup. The results presented here consist of daily temperatures throughout the 20-year simulations for the GCM gridbox covering south-east England (hereafter referred to as the “London gridbox”).

## 3. Results

### 3.1 Simulated urban heat islands due to landscape effects

In simulation U1N, In the London gridbox, the distributions of daily maximum and minimum temperatures throughout the 20 years of simulation showed fewer cool days and more warm days on the urban tile compared with the grass tile (Figure 2). In particular, the warmer ends of the distributions of both maximum and minimum temperatures were shifted more towards higher temperatures on the urban tile compared to the grass tile. Direct day-by-day comparison of urban and grass tile temperatures (Figure 4) shows that on the majority of days the urban tile was warmer than the grass tile, although on some days the reverse was true. A general urban heat island effect therefore did emerge from the parametrization of urban areas as a consequence of the physical properties specified for the land surface. Daily maximum temperatures exceeded 30ºC on 1.7% of days on the urban tile and 1.4% of days on the grass tile (Table 1). Night-time minimum temperatures exceeded 20ºC on 0.4% of nights on the urban tile compared to 0.2% of nights on the grass tile (Table 2). High night-time minimum temperatures can affect human health as they limit the usual night-time relief from heat stress during the day.

The distribution of maximum and minimum temperatures in simulation U2N also showed urban heat island effects, implying that high temperatures under a radiatively-forced climate will be increased further by heat islands. Cities may therefore experience more extreme high temperatures than rural areas. For example, in simulation U2N, maximum temperatures exceeded 30ºC on 4.6% of days compared to 3.7% of days on the grass tile (Table 1). Similarly, whereas the grass tile experienced approximately 1.1% of nights with minimum temperatures exceeding 20ºC, the urban tile exceeded this threshold on 2.0% of nights (Table 2).

Although the absolute temperatures were generally higher on the urban tiles than the non-urban tiles under the doubled $CO_2$ climate, the radiatively-forced climate change relative to the present-day climate was actually smaller on the urban tiles than the grass tiles in the London gridbox. This is because the urban heat island due to landscape effects was stronger under the present-day climate than the doubled-$CO_2$ climate. Betts and Best (2004) showed that the urban tile temperatures under doubled $CO_2$ were lower when the urban processes were explicitly included in the model (simulation U2N) rather than being constructed by adding a present-day urban heat island to a doubled-$CO_2$ climate change (A2N). The sensitivity of the urban area in the London gridbox to doubling $CO_2$ was therefore smaller than that of the non-urban area. Nevertheless, despite a smaller climate change in urban area relative to the present-day due to warmer present-day state, the absolute temperatures under the doubled-$CO_2$ climate are still simulated to be higher in urban areas.

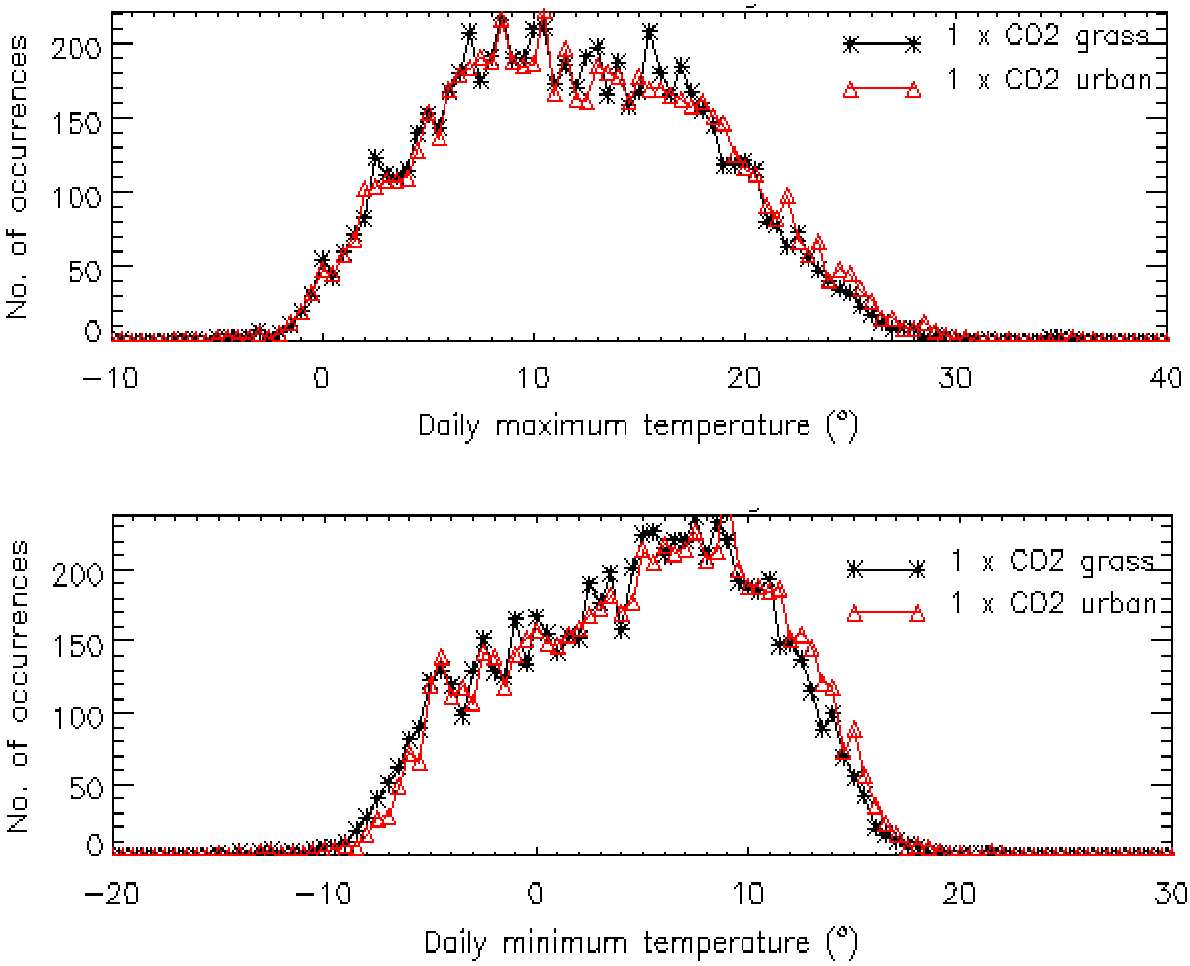


**Figure 2.** Simulated present-day distributions of daily maximum and minimum temperatures (simulation U1N) in the London gridbox

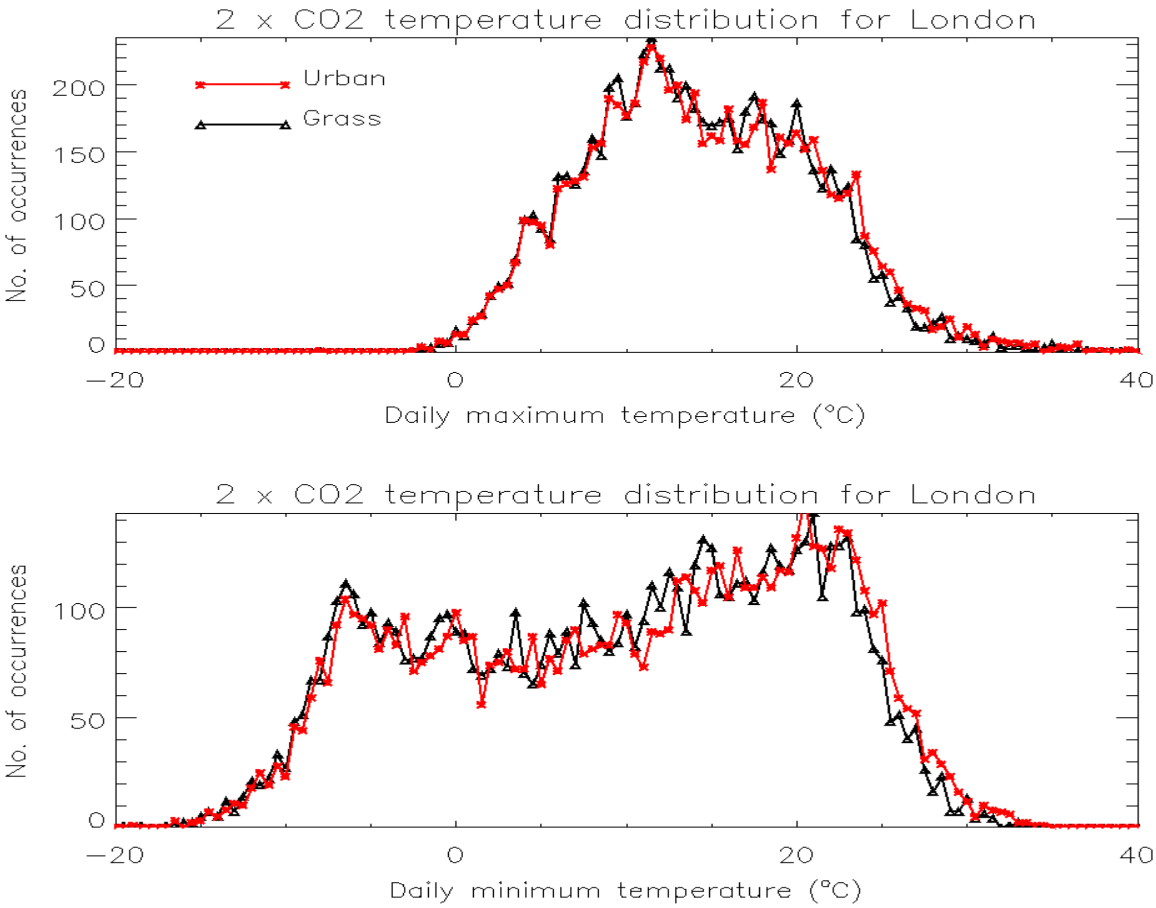


**Figure 3.** Simulated distributions of daily maximum and minimum temperatures under a doubled-$CO_2$ climate (simulation U2N) in the London gridbox

**Table 1.** Percentage of days with maximum temperatures exceeding $30^{oC}$

| Simulation | D | N1N | N2N | U1N | U2N | U1C | U2C | U2T |
|---|---|---|---|---|---|---|---|---|
| Urban | 5.1 | 2.0 | 4.9 | 1.7 | 4.6 | 2.9 | 4.1 | 5.2 |
| Grass | 4.4 | 1.6 | 4.1 | 1.4 | 3.7 | 2.3 | 3.1 | 4.2 |

**Table 2.** Percentage of days with minimum temperatures exceeding $20^{oC}$

| Simulation | D | N1N | N2N | U1N | U2N | U1C | U2C | U2T |
|---|---|---|---|---|---|---|---|---|
| Urban | 2.4 | 0.4 | 1.3 | 0.4 | 2.0 | 0.6 | 1.7 | 3.4 |
| Grass | 1.1 | 0.3 | 0.7 | 0.2 | 1.1 | 0.4 | 0.9 | 1.6 |

### 3.2 Effects of anthropogenic heat sources on urban heat islands

In simulations U1C and U2C, the present-day anthropogenic heat source imposed a small further warming influence on the urban tile in addition to the landscape effect, with U2C showing an increased occurrence of heat islands greater than 0.5ºC and decreased occurrence of less intense heat islands and “negative” heat islands (Figure 4). Simulation A2C, the construction of doubled-$CO_2$ urban temperatures using heat island anomalies from U1C, showed a very similar temporal distribution of heat islands to U2C. This suggests an increased validity of the assumption of stationarity for the heat island character including present-day anthropogenic heat source effects.

The tripling of the anthropogenic heat source (U2T) induced significant further warming (Figure 5), increasing the frequency of daily maximum and minimum urban temperatures exceeding the 30ºC and 20ºC thresholds to 5.2% and 3.4% respectively. The frequency of warm maximum and minimum grass temperatures also increased, suggesting an effect of the increased anthropogenic heat source beyond the immediate confined of the urban area.

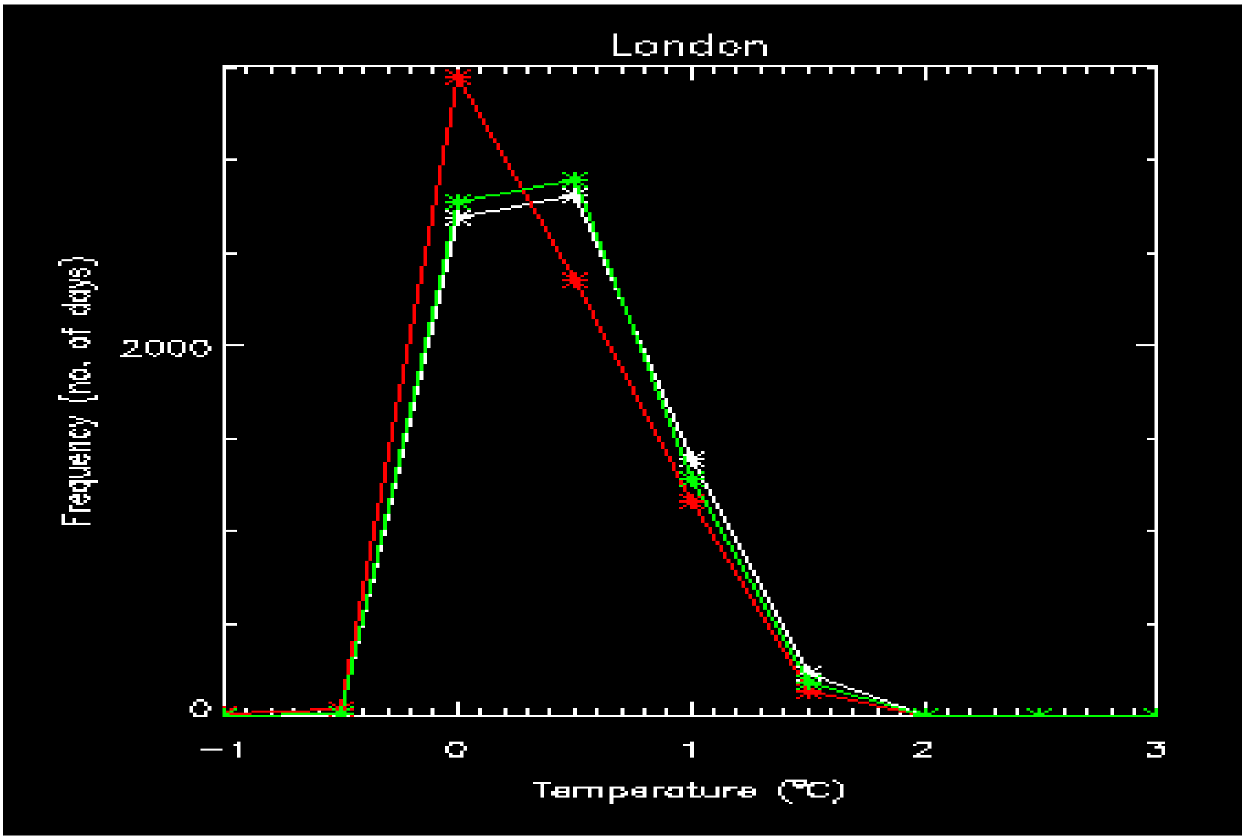


**Figure 4**. Distributions of heat island magnitudes in the London gridbox in simulations U2N (red line), U2C (green line) and A2C (white line).

Comparing the shifts in maximum and minimum temperature distributions due to doubling $CO_2$ and tripling the anthropogenic heat source (Figure 6) suggests that the heat source forcing exerts a smaller effect but is not insignificant. The additional warming effect of the tripled heat source on minimum temperatures is approximately 50% of that due to doubling $CO_2$. This suggests that plausible increases in anthropogenic heat release could exert a significant additional influence on urban climates, with particular implications for impacts on human health through unrelieved heat stress overnight.

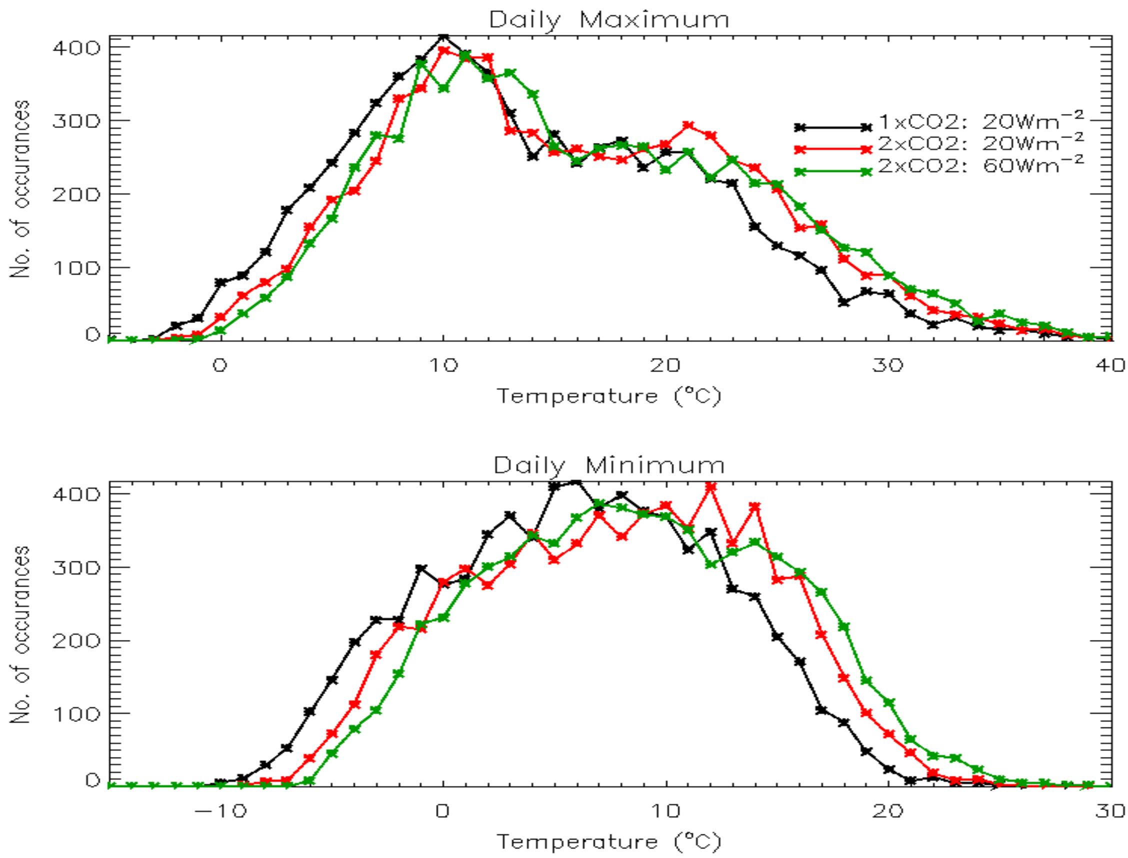


**Figure 5.** Relative impact of doubling CO2 and tripling anthropogenic heat release on maximum and minimum urban temperatures in the London gridbox.

Although a doubling of CO2 does not significantly change the character of the heat island distribution, the character does change markedly as a result of a tripling of the heat source (Figure 7). Large heat islands become more frequent, particularly at the time of the night-time minimum. This indicates that while the assumption of stationarity under radiatively-forced climate change may be valid for heat islands induced by the present-day heat source, the assumption may not be valid for increases in the anthropogenic heat source. This implies that the changes in temperature in urban areas due to increasing $CO_2$ and increasing anthropogenic heat release will be more reliably estimated by the explicit modelling of urban heat islands within climate models.

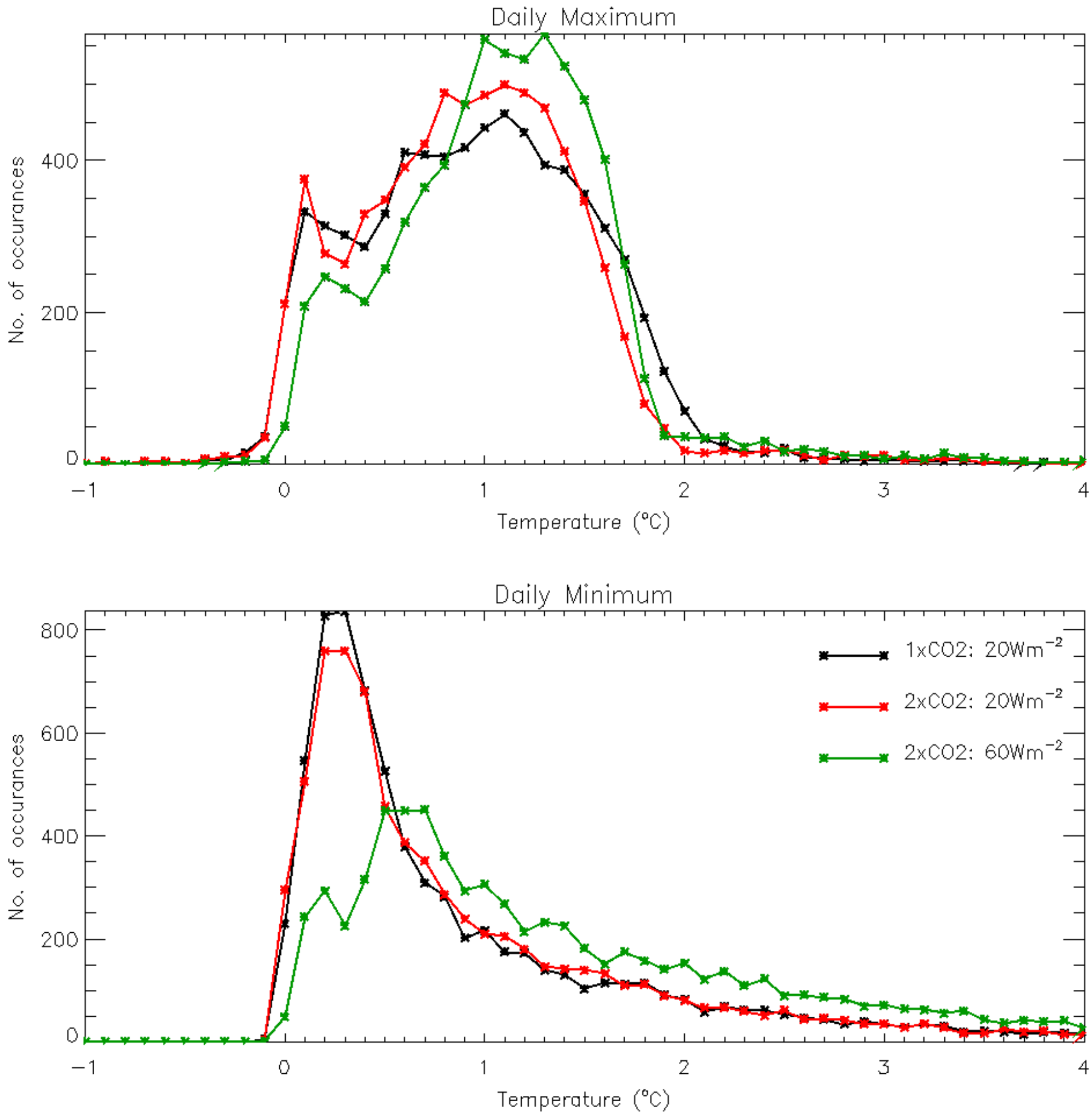


**Figure 6:** Changes in the urban heat island distribution due to doubling $CO_2$ and tripling the anthropogenic heat source

### 3.3 Effects of urban land and anthropogenic heat sources on humidity

As well as being warmer than their surrounding rural land, urban areas can be less humid as a result of reduced evaporation from the less-porous ground surface. In simulation U2N, the London gridbox showed a general urban "dry island" with relative humidity on the urban tile being lower than the grass tile on the majority of days (Figure 7). In simulation U2C and U2T, the dry island became progressively more pronounced as the heat island increased. The effects of tripling the anthropogenic heat source on the relative humidity "dry island" were greater than those of doubling CO2 (Figure 8), suggesting that future changes in relative humidity in urban areas may be dominated by direct urban effects rather than those of radiatively-forced climate change.

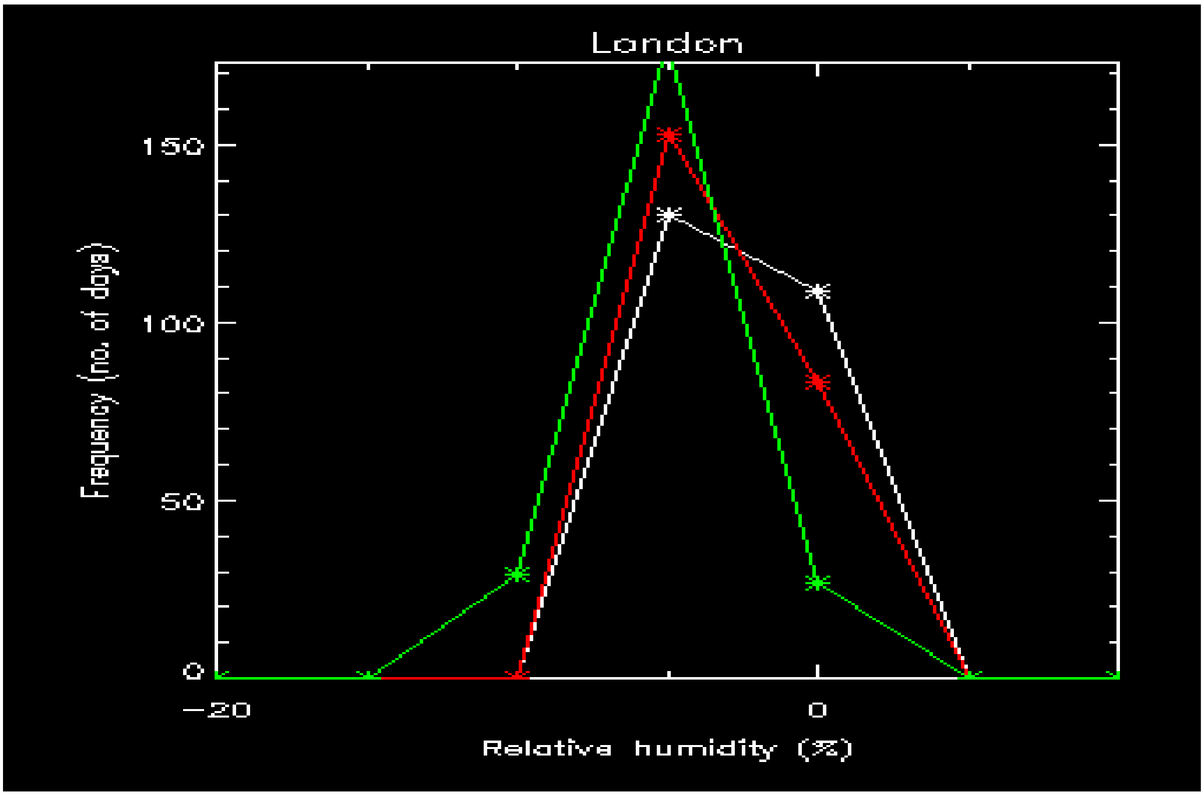


**Figure 7**. Urban relative humidity islands under doubled-$CO_2$, with (i) no anthropogenic heat source (white line), (ii) the present-day heat source (red line) and (iii) the tripled heat source( green line).

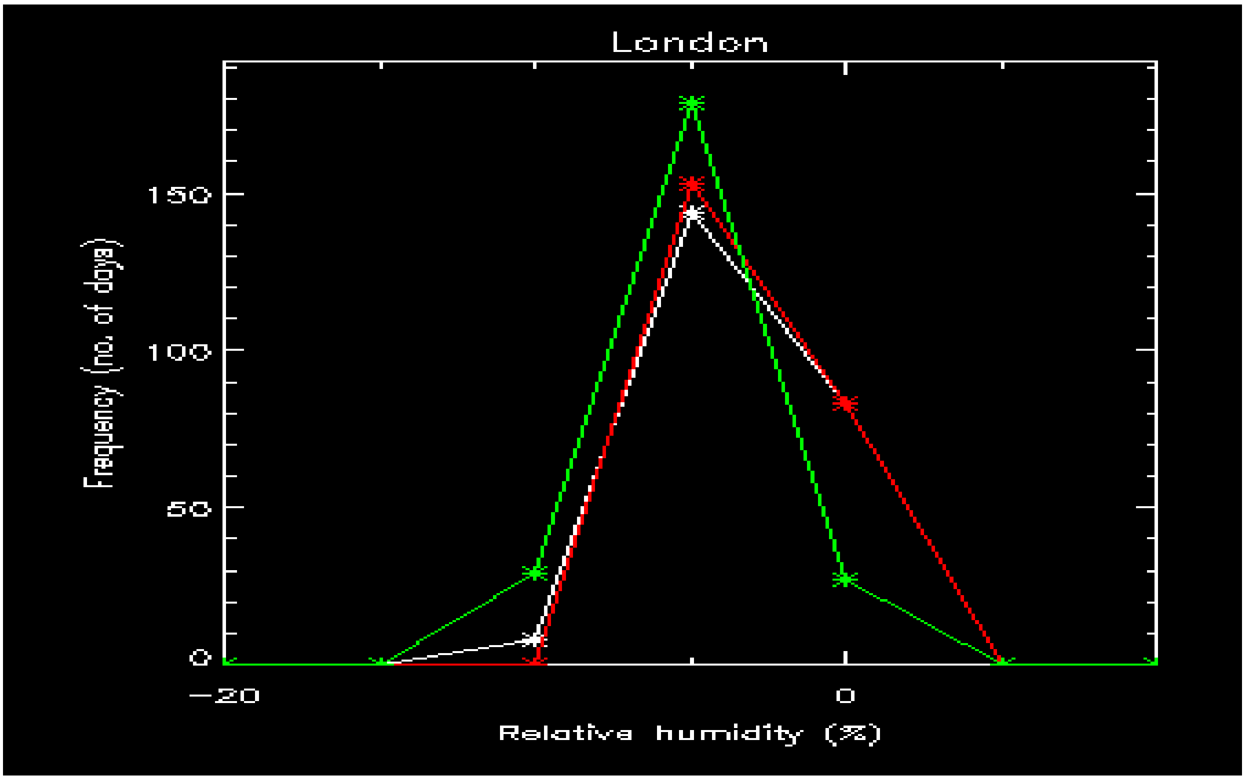


**Figure 8**. Urban relative humidity islands under (i) present-day $CO_2$ with current anthropogenic heat source (white line), (ii) doubled-$CO_2$ with the present-day heat source (red line) and (iii) the tripled heat source( green line).

## 4. Conclusions and implications for the BETWIXT climate change projections

In our simulations, landscape effects cause urban areas to be simulated to be warmer and less humid than surrounding non-urban areas as a result of landscape effects, both at present-day and doubled $CO_2$. Estimated present-day anthropogenic heat sources slightly further increase the strength of the heat island and dry island. Tripling of the heat source causes additional urban warming and drying, with large changes in the variance and skew of the heat island distribution. This suggests that the present-day heat island is not a good indication of a future heat island under modified forcings, so heat islands cannot be properly accounted for by simply adding present-day heat island patterns to gridbox-mean projections of climate warming.

These results suggest that state-of-the-art climate change projections such as those provided by BETWIXT for the BKCC programme may contain systematic biases in estimates of temperature and relative humidity in urban areas, as a result of urban effects being neglected from the climate model simulations. Future climate model simulations intended for use in assessments of potential climate change impacts in the built environment should include changes in urban area and anthropogenic heat sources.

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