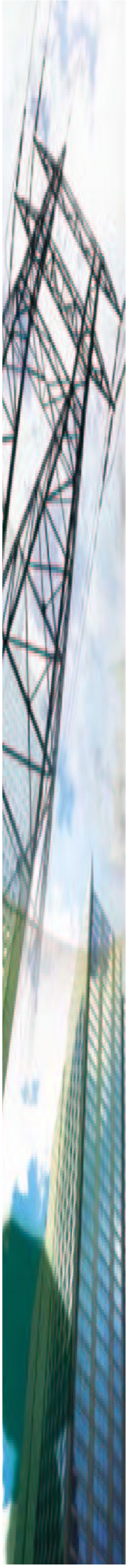

BETWIXT
Built EnvironmenT: Weather scenarios for investigation of Impacts and eXTremes

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SIMULATING CLIMATE CHANGE IN URBAN AREAS: INTERACTIONS BETWEEN RADIATIATIVE FORCING, LANDSCAPE EFFECTS AND HEAT SOURCES

RICHARD BETTS*[†], MARTIN BEST[#]

*Met Office, Hadley Centre for Climate Prediction and Research, Fitzroy Road, Exeter, EX1 3PB.

[#]Met Office, Joint Centre for Hydro-Meteorological Research, Maclean Building, Crowmarsh Gifford, Wallingford, OX10 3BB

[†]Corresponding author: richard.betts@metoffice.com

1. INTRODUCTION

Built-up areas exert significant influences on their local climates, with an "urban heat island" being observed in many cities. 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.

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, such as those undertaken as part of the Building Knowledge for a Changing Climate (BKCC) programme. While this problem may be partially addressed by combining climate change scenarios with representations of present-day urban heat islands, this will not address the interactions between urban landscapes and radiative forcing nor account for increasing anthropogenic heat sources.

Thus, as part of the BETWIXT project, a new land-surface parametrization has been used 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. The treatment of urban areas and the experimental design are described here, together with preliminary results and conclusions.

2. URBAN AREAS IN THE HADLEY CENTRE CLIMATE MODEL

The model used in the BEWTIXT simulations described here is based on the Hadley Centre atmospheric climate model HadAM3 (Pope et al. 2000) with the latest Met Office surface exchange scheme, MOSES 2.2 (Essery et al. 2003). This includes a "tile" representation of the land surface, in which the grid squares of resolution 2.5˚ × 3.75˚ are divided into areas representing different surface types (Figure 1a). Separate energy and water budgets (and hence separate near-surface temperatures and humidities) are simulated for each surface type within each grid box. This contrasts with a number of other climate model land surface schemes, including the earlier version of the Met Office scheme (MOSES1) which was used in the HadCM3 Climate Model to produce the UKCIP2 climate change scenarios. MOSES1 performed a single set of energy and water budget calculations for an entire grid square (Figure 1b), so could not simulate climate changes separately over urban and non-urban land.

a)

b)

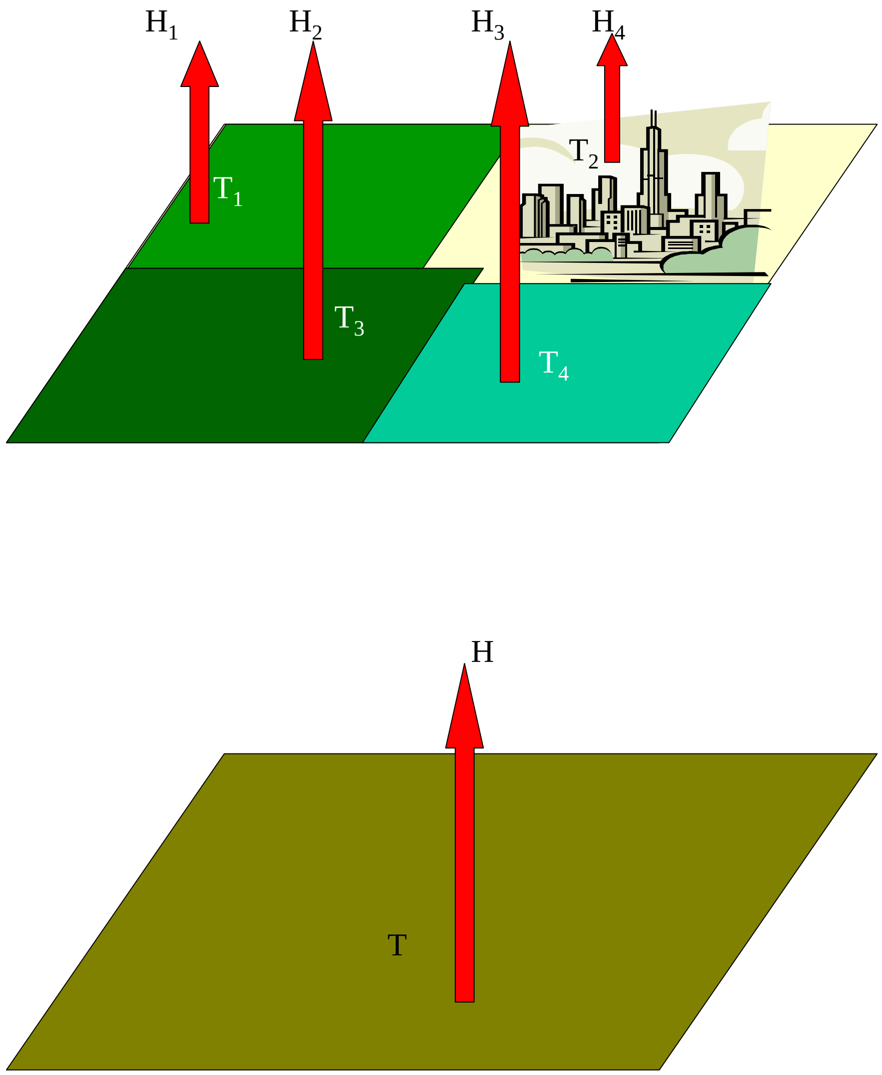

Figure 1. Contrasting treatments of sub-grid heterogeneity in land cover in MOSES2.2 and MOSES1. (a) MOSES2.2 simulates separate sets of fluxes (H1, H2, H3, H4) and separate surface temperatures (T2, T2, T3, T4) and humidities. Up to 9 types per grid box are permitted; broadleaf trees, needleleaf trees, C3 grasses, C4 grasses, shrubs, urban land, water, bare soil, and ice. (b) MOSES1 simulates one set of fluxes (H), one surface temperature (T) and one surface humidity across the gridbox.

One surface type included in MOSES2.2 represents urban areas in terms of physical characteristics such as heat storage in buildings and the frictional drag exerted on the atmosphere. The urban scheme uses a simple canopy representation for cities, whereby the available energy at the surface from the incoming radiation is divided into sensible and latent heat fluxes and heat storage within the canopy (Figure 2). This canopy is then radiatively coupled to the underlying soil. More details of the scheme and its general characteristics are presented in Best (1998) and Best (2000). In this preliminary version of the model used in BETWIXT, all urban land is specified with the same physical characteristics such as heat capacity. The only variation across different locations is the extent of the urban area, which is accounted for in the relative coverage of grid boxes by the urban tile (Figure 3).

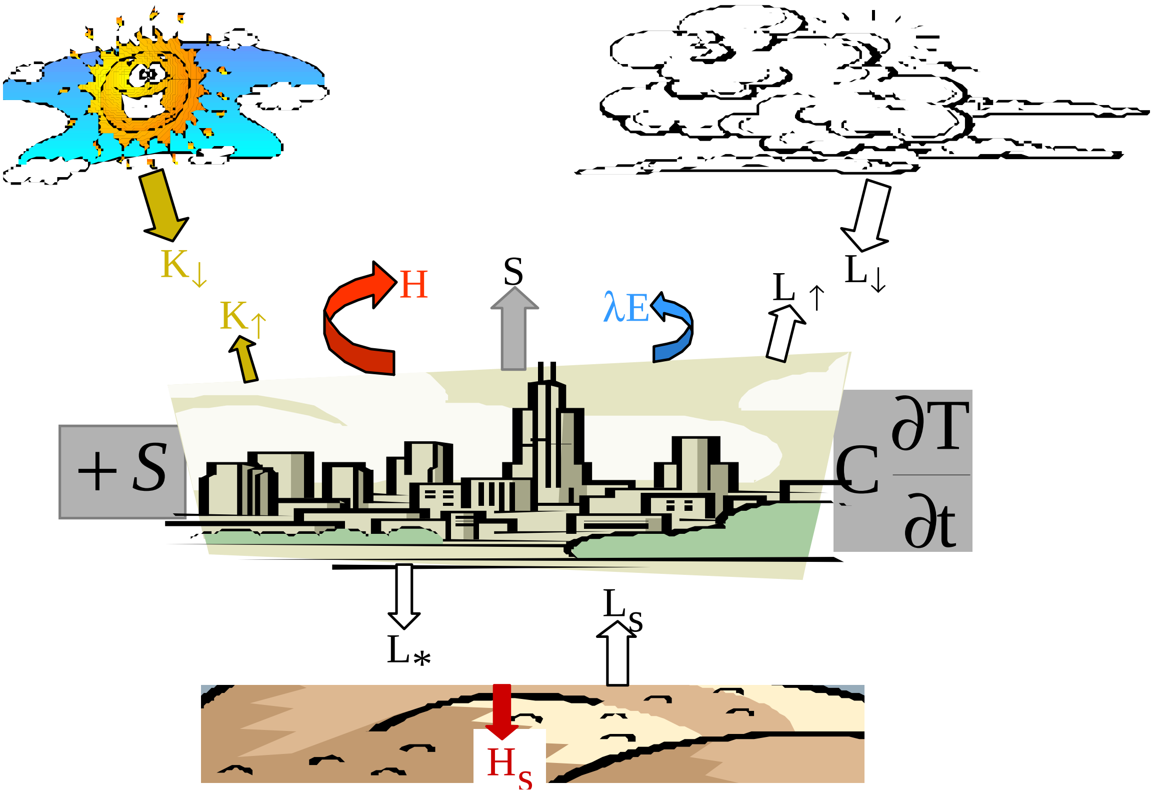

Figure 2. "Canopy" representation for urban surface type. K↓ = downward shortwave radiation flux, K↑ = upward shortwave radiation flux, L↓ = downward longwave radiation flux, L↑ = upward longwave radiation, L* = longwave radiation flux from canopy to ground, L_S = longwave radiation flux from ground to canopy, H = sensible heat flux, Hs = heat flux into ground, λE = latent heat flux, C = specific heat capacity of "canopy", T= temperature, t=time, +S = anthropogenic sensible heat source.

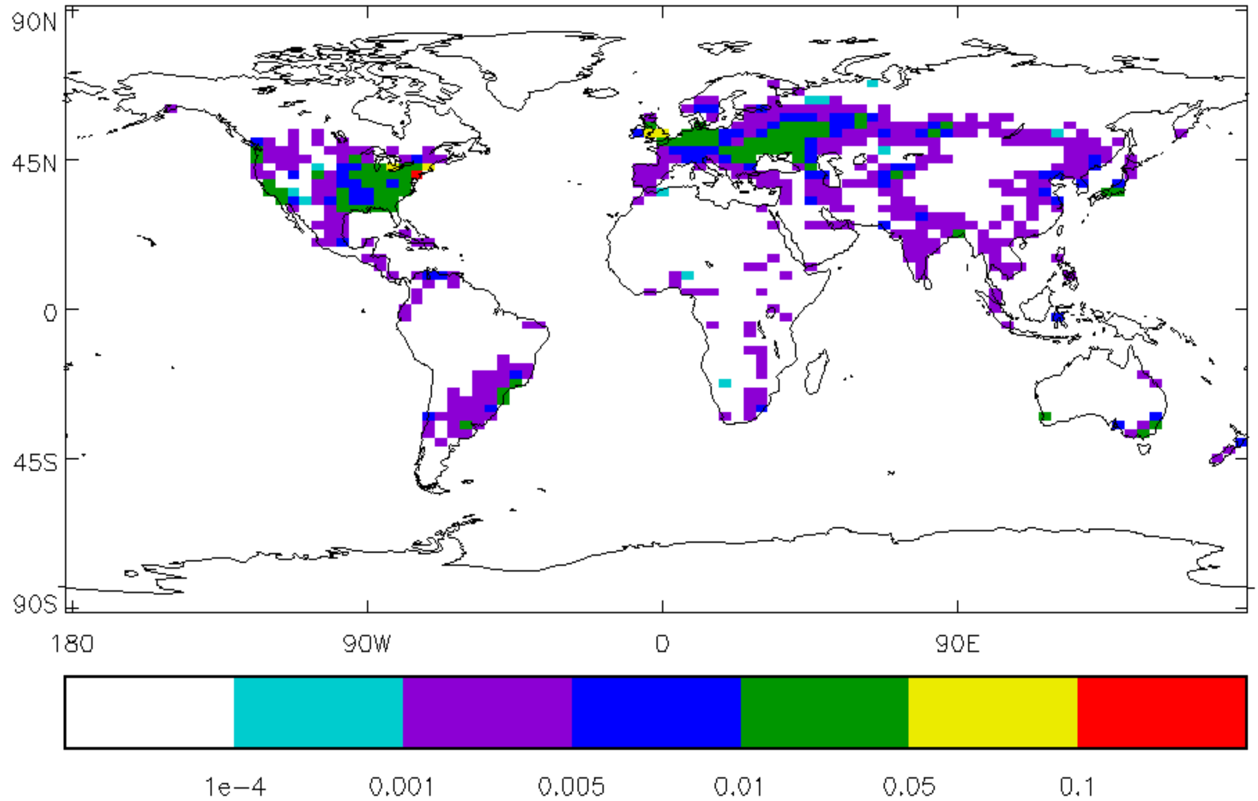

Figure 3. Fraction of GCM grid squares specified as urban land (data from Loveland and Belward, 1997)

An additional heating term can also be input to the urban tiles, to represent direct anthropogenic heat sources. There are essentially two ways in which an anthropogenic heat source can be added to the canopy scheme. It can be included as an additional source to the surface energy balance equation which is then subsequently partitioned between the turbulent fluxes and the heat storage (representing a heat source from, for instance, buildings), or it can be added directly to the sensible heat flux (representing a heat source from, for instance, vehicles). In the BETWIXT simulations, the heat source has been added to the energy balance equation. This has been done to maximise the effect in the results, given that the resolution of a climate model means that any direct heat source into the atmosphere will be a small term given the fraction of urban areas in a gridbox.

3. THE BETWIXT EXPERIMENTAL DESIGN

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. 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.

The size of the current anthropogenic heat source was determined from global energy consumption. During 1996, approximately 8000 million metric tons of oil equivalent was used globally (International Energy Agengy, 1997) which converts to 335 EJ (335 $\times10^{18}$ J) of energy (Appendix 1). If all of this energy was dissipated in urban areas, then it would give a heat source of ~45 Wm^{-2} (Appendix 1). For the BETWIXT study we assumed that about half of this energy is dissipated in urban areas, hence we added an anthropogenic heat source of 20 Wm^{-2}. In addition, to assess the effects of future increases in anthropogenic heat sources, we considered a case in which the fossil fuel energy consumption increases by a factor of three and hence set the anthropogenic heat source to 60 Wm^{-2}.

The following simulations were performed:

a. Current CO_2 with no urban areas
b. Current CO_2 with current urban areas but no anthropogenic heat sources
c. Current CO_2 with current urban areas and current anthropogenic heat sources
d. Doubled CO_2 with no urban areas
e. Doubled CO_2 with current urban areas but no anthropogenic heat sources
f. Doubled CO_2 with current urban areas and current anthropogenic heat sources
g. Doubled CO_2 with current urban areas and tripled anthropogenic heat sources.

In simulations (b), (c), (e), (f) and (g), 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. 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.

Simulations (a) and (d) included a diagnostic model of surface processes on urban land. In this, the same land surface parameterization was used to calculate surface fluxes, temperature and humidity for urban land, but the urban tile was of zero size so feedbacks to the atmosphere were excluded. Comparison of the temperature simulated for this diagnostic urban tile with those for the non-urban tiles shows the extent of the urban heat island without feedbacks between the atmosphere and land surface. Comparison of, for example, simulations (a) and (b) therefore shows the effect of feedbacks on the simulation of urban heat islands.

Comparison of simulations (c) and (b) shows the impact of anthropogenic heat sources on the simulated present-day urban heat islands.

Comparison of simulations (e) and (b) 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.

Further comparisons with simulations (f) and (g) show the effects of anthropogenic heat sources on the character of the urban heat island, and provide simulations of the overall warming in urban areas due to both radiative forcing and anthropogenic heat sources.

4. PRELIMINARY ANALYSIS OF RESULTS: EFFECTS OF FEEDBACKS, CLIMATE CHANGE AND HEAT SOURCES ON URBAN HEAT ISLANDS

Since there are still only small fractions of urban areas in any of the model grid squares, we will concentrate here on the results for the grid square containing New York, as this has the highest fraction of urban area at around 15%. The following results show temperature distributions which have been derived from the daily maximum and minimum temperatures from the last twenty years of 25-year model simulations, i.e. the first five years are discarded to allow for the spin up of the model.

The temperature distribution from a 2xCO_2 run with an interactive urban representation is shown in Figure 4 (labelled as prognostic). Also shown in Figure 4 is the result of taking the temperature distribution from a 1xCO_2 run without an interactive urban area and adding the mean temperature increase from a standard 2xCO_2 run, again without interactive urban areas (labelled as diagnostic). Comparing these two temperature distributions for both maximum and minimum daily temperatures shows that whilst the general shapes of the two curves are similar the details are different, with the interactive urban areas giving a wider distribution for both the maximum and more evidently the minimum temperatures. This shows that it is not possible to use present day urban temperature distributions along with standard climate change results to accurately predict the likely temperature distributions under future climates.

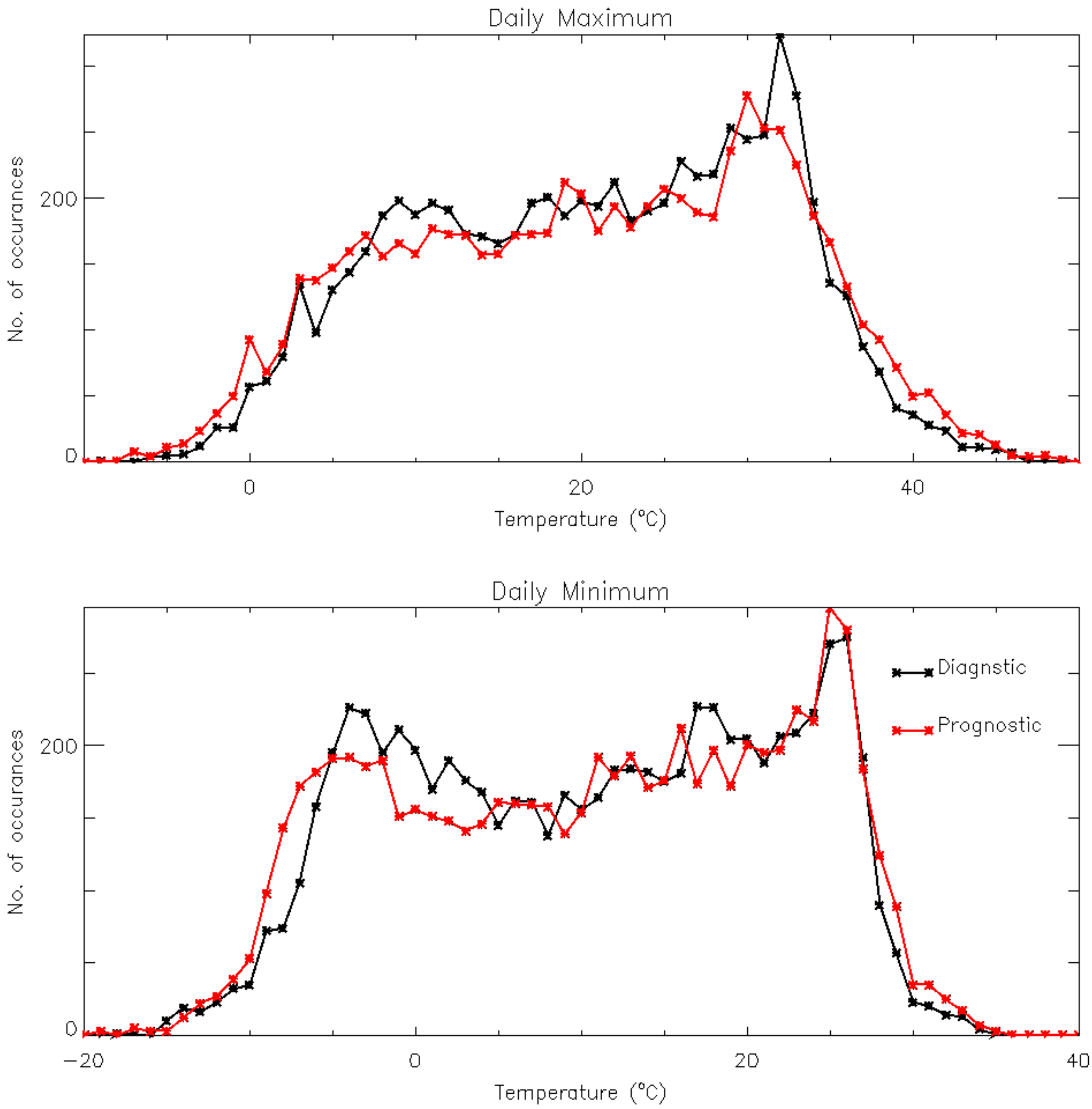

Figure 4: Impact from including urban areas in simulation

To understand how the anthropogenic heat source and climate change impact on the urban heat island, the distribution of the heat island for maximum and minimum temperatures is shown in Figure 5. The results shown are for simulations with $1xCO_2$ and 20 Wm^{-2}, $2xCO_2$ and 20 Wm^{-2} and $2xCO_2$ and 60 Wm^{-2}. The increased atmospheric CO_2 concentration does not have a large impact on the shape of the urban heat island distribution. The maximum distribution has fewer occurrences of daytime heat islands of around 2^oC, but the night-time heat island has an almost identical distribution. This is not the case with the increased anthropogenic heat source. The daytime distribution becomes more peaked with fewer occurrences of heat island between $0\text{-}1^oC$ and more occurrences between $1\text{-}2^oC$, although there are still fewer occurrences of heat islands around 2^oC than under the current climate. The change in the night-time distribution is the most marked however. The shape of this distribution is significantly changed, with a lower peak in the occurrences of small heat islands and more occurrences in the tail of the distribution for higher heat islands.

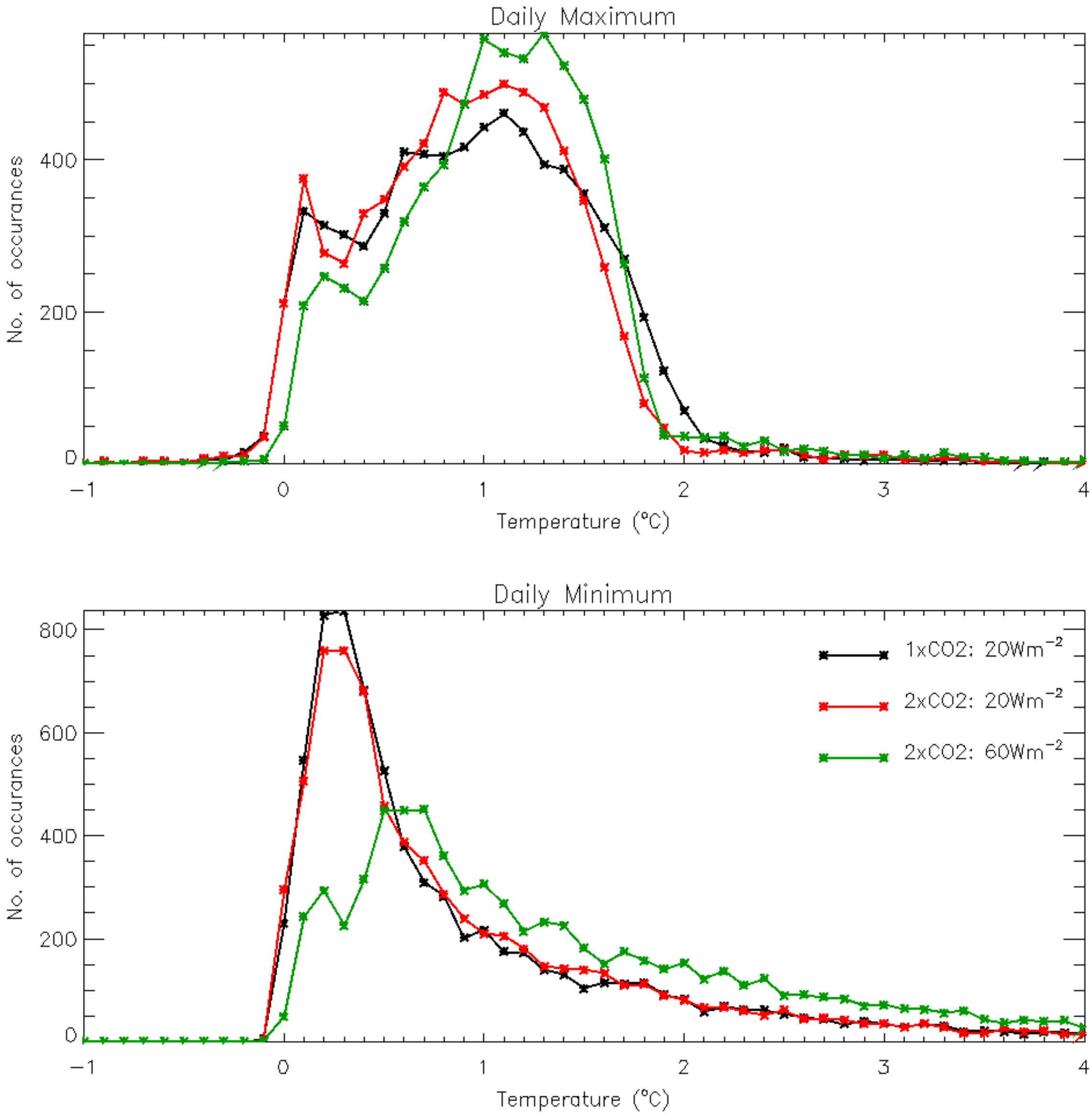

Figure 5: Change in urban heat island due to anthropogenic heat source

5. CONCLUSIONS: IMPLICATIONS FOR BETWIXT

The BETWIXT simulations described here have been performed as part of the first study in which a modelling group has designed and run simulations with the specific purpose of assessing whether the true impact of climate change on our cities requires the direct modelling of urban areas within climate change simulations. The major conclusions from a preliminary analysis of these simulations are:

- Urban areas need to be represented within climate simulations if the aim is to build up a true picture of the impact of climate change within the cities themselves.

- The impact of an increased anthropogenic heat source in the future could significantly change the distribution of the urban heat island. There could be fewer occurrences of a near neutral heat island and a larger number of greater heat islands, especially during the night.

After further analysis, a more detailed BETWIXT report will be produced, describing the analysis of changes to urban and rural temperatures and extremes, and humidity. The significance of the results for the BKCC programme will be explained, and the need for further work reviewed.

Appendix 1

1997 Oil Usage = 8,000 million tonnes

1 Tonne of Oil Equivalent = 41.868 GJ

Distributed Globally = 0.02 Wm^{-2}

Distributed Over Cities = 45.8 Wm^{-2}
(Cities = 0.046% of Globe)

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