Appendix 1

Design methodology for the assessment of overheating risk in homes

CIBSE

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Foreword

Recent evidence has shown that overheating risk needs to be taken seriously in the residential sector. Many new or refurbished homes have designs that contribute to overheating risk by, for example, having high proportions of glazing (resulting in excessive solar heat gains), inadequate natural ventilation strategies or mechanical ventilation systems that are not delivering intended air change rates.

Overheating risk is also affecting existing homes, especially in buildings that do not have adequate methods for dissipating heat gains and are less resilient to climate change.

The health and wellbeing impacts of overheating can be significant for residents, resulting in stress, anxiety, sleep deprivation and even early deaths in heat waves, especially for vulnerable occupants. The situation is predicted to get worse. The Committee on Climate Change has estimated that mortality rates arising from overheating could rise from 2000 per year in 2015 to 7000 per year by the 2050s.

Assessing overheating risk in homes is a complex issue and not adequately assessed by building regulations. Indeed, it would be wrong to assume that a home that complies with building regulations that were designed to focus on energy conservation also gives sufficient assurance of avoidance of overheating. Hence the recommendation that comfort conditions are separately assessed if it is felt that there could be a risk.

Many factors influence overheating in homes, including the intensity of heat gains, occupancy patterns, orientation, dwelling layout, shading strategy and ventilation method. Dynamic thermal modelling can be used to simulate the internal temperature conditions and will therefore help establish whether threshold conditions of discomfort will be reached. Given the complexity of the factors influencing overheating it is important that a standardised methodology is used to assess risk and hence the need for this technical memorandum. It can be applied to dwellings, care homes and student residences. Early analysis of overheating risk is recommended so that mitigation strategies can be reviewed in design proposals.

In summary, the application of this technical memorandum, by standardising the assessment methodology, should play a key role in limiting overheating risk in new and refurbished homes.

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1 Introduction

Overheating risk has been a growing concern amongst the domestic design, construction and provider community for at least a decade. Domestic overheating has not always been a problem in the UK but climate change, increased urbanisation, construction of highrise apartment blocks and winter energy efficiency measures have all contributed in the amplification of high internal temperatures. Homes that overheat cause significant discomfort and stress to the occupants and can ultimately lead to litigation and costly mitigation measures for the owners/developers.

Yet overheating is subjective — the point at which 'hot' becomes 'too hot' will vary from person to person and depend upon a variety of factors. Whilst this means that not all occupants will be satisfied all the time and that, in a heatwave, it may still be very warm in a naturally ventilated dwelling, there should be a reasonable limit set on how much warmer a dwelling can be inside than outside. There should also be a standard that precludes the worst levels of overheating and enables designers to find cost effective options to limit overheating risk whilst also delivering all the other aspects occupants look for in their homes (e.g. daylight, insulation, view etc). The methodology described here attempts to define that threshold.

An evidence review, *Assessing overheating risk* (Zero Carbon Hub, 2015), concluded that there was no existing guidance that provided this definition, and made a call for a methodology such as this to be produced.

As a result of the Zero Carbon Hub's work on domestic overheating risk, a group of building physicists and engineers worked with CIBSE to develop this domestic overheating risk assessment methodology and test it on live projects.

The methodology needs to be prescriptive so as to be consistently applied. It uses dynamic thermal modelling tools, defined internal gain profiles, and specific weather files with clearly defined thresholds to provide a clear pass/fail result. This does entail some resource, but the process of evaluating overheating risk in this clearly defined way is much more efficient than each assessment needing to define its own methodology, as has previously been the case.

The methodology includes clear reporting requirements to enable all stakeholders to review the outcome and understand its basis and implications for the design. It is vital that the mitigation options selected as a result of the assessment are fully incorporated into the design or the assessment will have no value.

The methodology has been through several rounds of testing on a variety of real and prototype projects. The majority of the testing has focused on developments of apartments, but some houses and extra-care units have also been evaluated. The results of the testing indicate that the methodology works well, but the real proof will come in future years when the units tested are built and occupied. CIBSE is planning further research to provide monitoring and feedback, which may lead to future refinements of the methodology.

1.1 About the methodology

This is a standardised approach to predicting overheating risk for residential building designs (new-build or major refurbishment) using dynamic thermal analysis. The testing of the methodology has focused on flats, as they tend to represent a higher overheating risk than houses. However, the methodology should also be applicable to houses.

The aim is to produce a test that encourages good design that is comfortable within sensible limits, without being so stringent that it over-promotes the use of mechanical cooling. The test needs to be simple to ensure it is used.

This document provides a set of profiles that represent reasonable usage patterns for a home suitable for evaluating overheating risk. Where possible the magnitude of gains is taken from CIBSE guidance. Profiles are developed to test the building design, not to cover all usage modes.

Of necessity, many assumptions have been made to derive the profiles. Further work is warranted, but this methodology was developed due to the importance of defining a consistent approach for use in the interim.

This methodology is intended for use by designers in order to influence building design for the better. It could be used at the planning stage to assess risk, as well as at later stages of design.

1.2 Clarifications

This methodology will:

- allow different designs to be compared with a common approach, based on reasonable assumptions
- support design decisions that improve comfort without cooling
- provide consistency across the industry as all consultants will be using the same methodology for overheating risk prediction.

This methodology will not:

- guarantee that people will always be comfortable in compliant spaces, however they act
- take into account unusual use.

The methodology provides a baseline for all domestic overheating risk assessments. Studies for student accommodation, care homes, prisons or unusual accommodation uses, and heatwave strategy analysis, can employ this methodology as a starting point, provided that such studies state clearly where variations have been made and provide a justification for these changes.

It should be noted that the weather file will have the largest impact on the overheating results. We cannot control the weather or the behaviour of people in their own homes. We can, however, encourage building forms and façade designs that support better comfort in hot weather.

1.3 Basis of design comfort criteria

CIBSE TM52: *Limits of thermal comfort: avoiding overheating in European buildings* (2013) provides the principles of thermal comfort and should be the main reference for any additional detail.

CIBSE Guide A: *Environmental design* (2015a) includes advice regarding sleep quality (that may be compromised at temperatures above 24 °C), and recommends that peak bedroom temperatures should not exceed an absolute threshold of 26 °C.

1.4 Implications of applying the methodology

Balancing the tensions between the energy efficiency requirements (such as the fabric energy efficiency requirements (FEEs) in Building Regulations Part L1A for England (NBS, 2013)), daylighting targets and limiting overheating risk is often a challenge. The intention of this document is to provide pragmatic solutions for resolving these tensions.

Based on the testing undertaken during the development of this methodology, it is anticipated that there will be certain housing developments, particularly those in south east England, with a lightweight construction, large amounts of glazing and single aspect that may not pass the proposed test.

External, moveable shading may be promoted by the methodology for high risk properties. Designers could look to continental northern European examples and publications such as CIBSE TM37: *Design for improved solar shading control* (2006) and BRE 364: *Solar shading of buildings* (Littlefair, 1999) for how to implement this.

Another key area is achieving sufficient ventilation when there are constraints such as noisy or polluted environments, health and safety considerations limiting wide openings, and security concerns (e.g. ground floor or accessible windows). Considering window design that will allow versatile openings or use of acoustically attenuated vents may provide robust solutions within these constraints.

Importance of installation of assumed parameters

This guidance is based on assumptions about installation. The results will only be valid if the parameters used match those of the final building. Design assumptions therefore need to be followed all the way through procurement to installation (e.g. performance and quality of pipework insulation, façade performance, aerodynamic areas of openable windows, blind/external shading performance etc).

All assumptions and mitigations must form part of the construction contract, or the model will need to be re-run to prove compliance of any changes.

2 The methodology

2.1 Identification of risk

This methodology is based on the use of dynamic thermal modelling for the treatment and assessment of overheating risk in residential buildings.

This methodology is proposed for all residences and should especially be considered for:

- large developments
- developments in urban areas, particularly in southern England
- blocks of flats
- dwellings with high levels of insulation and air-tightness
- single aspect flats.

Individual houses and developments with a low risk of overheating may not require the use of dynamic thermal modelling.

Professional judgement must be used when taking the decision to omit dynamic thermal modelling to test overheating. The risk must be considered in the context of the project and the decision should be taken jointly with the client, design team and planners. A list of risk factors for identifying properties at high risk of overheating is provided in *Energy Planning — Greater London Authority guidance on preparing energy assessments* (GLA, 2016) and in BRE's *Home Quality Mark* (BRE, 2015).

2.2 Methodology overview

The assessment should follow the following steps:

(1) A suitable sample of units within a development should be selected, see section 3.1.

(2) Zoning: all sample units should be zoned into the separate rooms including kitchens, living rooms, bedrooms, bathrooms and halls.

(3) Building constructions should be modelled as proposed, accurately reflecting thermal properties such as thermal mass, insulation and solar transmittance for glazing.

(4) Standard profiles should be applied for occupancy, lighting and equipment gains, see section 5.

(5) Guidance on the treatment of communal corridors from section 3.8 should be followed.

(6) Pipework and equipment, e.g. heat interface unit gains from community heating systems, should follow the guidance given in section 3.9.

(7) Operable windows should be included in the model and follow the guidance given in section 3.3.

(8) Any internal or external shading provision should be included in the model and follow the guidance included in section 3.7.

(9) Additional mechanical ventilation including mechanical ventilation with heat recovery (MVHR) or extract systems should be included in the model and follow the guidance given in section 3.5

(10) Air speed assumptions should be based on the guidance given in section 3.6.

(11) The weather file used for the methodology should be the DSY1 (design summer year) file most appropriate for the site location for the 2020s, high emissions, 50% percentile scenario; the guidance given in section 3.2 should be followed.

(12) The assessment should be undertaken using hourly dynamic simulation modelling, which includes all the relevant features of the building.

2.3 Suggested reporting requirements

The methodology recommends a full written report that documents the following details for the assessment:

- dynamic thermal analysis software name and version used for the assessment, which must comply with the requirements of CIBSE AM11: *Building performance modelling* (2015b)
- site location and orientation
- images of the model indicating the sample units selected and the basis for selection
- images showing the internal layouts for the sample units
- information on the construction type with layers of construction (used to determine *U*-values and *g*-values) for all external and internal building elements, plus any additional shading features (including any blinds, and demonstrating that the blinds do not clash with opening windows if blinds are used to contribute to a pass)
- thermal mass, with a written explanation of where the thermal mass is incorporated in the construction
- the ventilation strategy modelled, including details of window opening assumptions, free areas calculated, infiltration rates assumed and any mechanical supply/extract flow rates
- the weather file(s) used for the assessment
- the thermal comfort category assumed based on CIBSE TM52 (2013); this should be Cat. II by default, but Cat. I for vulnerable residents (see section 4.4); Cat. III for existing buildings should not be used for the purposes of this methodology
- the results of the analysis:
    - reports should be clearly reported based on criteria (*a*) and (*b*) in section 4.2
    - a unit is only shown to comply if all occupied spaces meet relevant overheating criteria
    - corridors should be included where there is communal heating pipework
    - the report may include the results for several iterations explored, to demonstrate the route to compliance
    - if blinds were part of the strategy used to gain a pass, then results without blinds must also be included for information
- the report should state clearly whether the project passes or fails the assessment and, where a pass is indicated, it should make clear on what design features this depends (e.g. the inclusion of glazing with *g*-value below *x*, reduced window sizes, etc).

The assessor must discuss with the client any need to assess overheating risk under heatwave or future climate change conditions using more extreme DSYs (i.e. DSY2 or DSY3) or future weather years. The same overheating tests described herein can be used.

3 Guidance

3.1 Sample size

The assessment should try to identify all the dwellings that are at risk of overheating. These are likely to be those (*a*) with large glazing areas, (*b*) on the topmost floor, (*c*) having less shading, (*d*) having large, sun-facing windows, (*e*) having a single aspect, or (*c*) having limited opening windows.

The report should justify the sample of units chosen for the assessment and explain why this is appropriate. The number analysed will depend on the scale of the development, its geographical location and the results of the modelling as they emerge. In addition, lower risk dwellings can be included for illustration of performance to this.

At least one corridor should be included in the assessment if the corridors contain community heating distribution pipework.

3.2 Weather files

Developments should refer to the latest CIBSE design summer year (DSY) weather files and be required to pass using the DSY1 file most appropriate to the site location, for the 2020s, high emissions, 50% percentile scenario.

Other files including the more extreme DSY2 and DSY3 files, as well as future files (i.e. 2050s or 2080s), should be used to further test designs of particular concern, as described below, but a pass is not mandatory for the purposes of the simpler test presented in this document.

Design summer years (DSYs) should always be used for analysis of overheating, and it is good practice to take into account future weather files (see CIBSE TM48: *Use of climate change data in building simulation: the CIBSE Future Weather Years* (2009), TM49: *Design Summer Years for London* (2014a) and CIBSE's *Probabilistic Climate Profiles* (ProCliPs) (2014b) for further advice).

However, a minimum requirement for passing the test is proposed here by using a single DSY (DSY1), with the use of additional weather files recommended to explore performance where there is particular concern (e.g. the presence of vulnerable occupants) and/or where required in the client's brief or for demonstrating mitigation options under more extreme events (e.g. heatwaves). The analysis based on additional weather files can be used to develop a heatwave plan.

3.3 Window and door openings

Windows in each room should be controlled separately and modelled as open when both the internal dry bulb temperature exceeds 22 °C and the room is occupied. If additional security and rain protection details are included in the design then the opening hours during the night could be extended. For example, patio doors should only be modelled as open in unoccupied rooms or at night if they can be locked securely open, and the locked percentage of free area used in the model.

Open areas should be based on the architecturally designed windows including any restrictors that are required. The guidance in CIBSE Guide A (2015a) and CIBSE AM10: *Natural ventilation in non-domestic buildings* (2005) should be followed for calculation of free areas.

Opening areas assumed should take into account any security, acoustic or air quality issues that limit opening area (e.g. on ground floors).

If blinds are to be included in the modelling, they must not interfere with the opening of windows, or the reduction in free area when they are operating should be taken into account in the model.

Internal doors can be included and left open in the model in the daytime, but should be assumed to be closed when the occupants are sleeping.

The compliance report should explain the basis of all assumptions.

3.4 Exposure type

Models should be set up with the appropriate exposure type for the site location and façade orientation, based on the software definitions, and justified in the compliance report.

3.5 Infiltration and mechanical ventilation

The infiltration and the mechanical ventilation rate should be set for every zone based on what is specifically designed for normal, acoustically compliant modes of operation. Refer to CIBSE Guide A (2015a) for more detail on infiltration rates and noise design limits.

Mechanical boost mode (included for occasional use with louder fan noise) should not be assumed in the overheating risk analysis.

3.6 Air speed assumptions

Operative temperature calculations (used within CIBSE TM52 (2013)) require assumptions on air speed. The modelled air speed in a space must be set at 0.1 m/s where the software provides this option unless there is a ceiling fan or other means of reliably generating air movement.

Where fixed ceiling fans are installed as part of the new-build or refurbishment the assumed elevated air speed assumptions must be reported. Typically this should not exceed 0.8 m/s.

3.7 Blinds and shading devices

Blinds and shading devices can be used for the analysis only if specifically included in the design, provided in the base build and explained within associated home user guidance.

Blinds cannot be used properly if they clash with the opening of windows. If blinds are used to pass the overheating test, the report must either demonstrate that there are no clashes with the opening of windows, or the reduction in air flow due to the clashes must also be calculated and included in the model. These calculations must be explained in the compliance report.

The assumed solar transmittance/reflectance properties and usage profiles for blinds will need to be justified and well described in the compliance report.

Where blinds are used to enable a pass, the analysis results without blinds must also be provided for reference.

3.8 Pipework, HIU and heat maintenance tape heat loss

Heat losses from pipework, heat interface units (HIUs) and heat maintenance tape should be included for community heating systems, and/or where heat maintenance tape is used.

When space and water heating is provided by a community heating system, the HIU and the pipework connecting it to the central system is permanently charged with hot water all year around to meet the hot water demand. The distribution pipework for the community heating system often runs through the corridors and common spaces. Since this pipework is constantly emitting heat, even if well-insulated, it can cause an increase in temperature in these spaces.

The assessment should take into account heating pipework distribution gains on the communal side of the HIU (calculated in accordance with guidance in CIBSE Guide C: *Reference data* (2007)), as well as losses from the HIU itself. The modelling should reflect the design of the specific project/property being assessed. However, a default value for pipework (per metre of pipe run) has been provided in case these values are not available at time of analysis; these are based on the simplified method provided by the *Domestic Building Services Compliance Guide* (HMG, 2013).

Table 1 Default heat losses from pipework (HMG, 2013; Table 5)

Outside diameter of pipe (mm)	Maximum heat loss per metre run of pipe (W/m)
8	7.06
10	7.23
12	7.35
15	7.89
22	9.12
28	10.07
35	11.08
42	12.19
54	14.12

Within the home itself, standing gains should be based on primary side (domestic hot water) pipework length up to the HIU in accordance with guidance in CIBSE Guide C (2007). Standing gains from the HIU should be based on manufacturers' recommendations.

Heat maintenance tape to reduce hot water wait times on the secondary side domestic hot water pipework within the apartment, if included, shall be modelled as 8 W/m of pipe, or as calculated according to design.

3.9 Communal corridors

The inclusion of corridors in the overheating analysis is mandatory where community heating pipework runs through them. The overheating test for corridors should be based on the number of annual hours for which an operative temperature of 28 °C is exceeded.

Communal corridor heat gains should be modelled based on calculated losses from pipework (see CIBSE Guide C (2007) and/or the *Domestic Heating Design Guide* (DBSP, 2015)), or based on the simplified method provided in Table 5 of the *Domestic Building Services Compliance Guide* (HMG, 2013). Calculated values based on the design temperatures and specified insulation performance may be lower and can be used if justified.

Corridor ventilation should be included in the analysis as designed.

Whilst there is no mandatory target to meet, if an operative temperature of 28 °C is exceeded for more than 3% of the total annual hours, then this should be identified as a significant risk within the report.

4 Compliance criteria

4.1 Definitions

Homes that are predominantly naturally ventilated, including homes that have mechanical ventilation with heat recovery (MVHR), with good opportunities for natural ventilation in the summer should assess overheating using the adaptive method based on CIBSE TM52 (2013), as described in section 4.2 below.

In order to allow the occupants to 'adapt', each habitable room needs operable windows with a minimum free area that satisfies the purge ventilation criteria set in Part F of the Building Regulations for England (NBS, 2010), and equivalent regulations in other countries, i.e. the window opening area should be at least 1/20th of the floor area of the room (different conditions exist for windows with restricted openings, and the same requirement applies for external doors). Control of overheating may require accessible, secure, quiet ventilation with a significant openable area.

Homes that are predominantly mechanically ventilated because they have either no opportunity or extremely limited opportunities for opening windows (e.g. due to noise levels or air quality) should be assessed for overheating using the fixed temperature method based on CIBSE Guide A (2015a), as described in section 4.3 below.

4.2 Criteria for homes predominantly naturally ventilated

Compliance is based on passing *both* of the following two criteria:

(*a*) *For living rooms, kitchens and bedrooms*: the number of hours during which ΔT is greater than or equal to one degree (K) during the period May to September inclusive shall not be more than 3 per cent of occupied hours. (CIBSE TM52 Criterion 1: *Hours of exceedance*).

(*b*) *For bedrooms only*: to guarantee comfort during the sleeping hours the operative temperature in the bedroom from 10 pm to 7 am shall not exceed 26 °C for more than 1% of annual hours. (*Note*: 1% of the annual hours between 22:00 and 07:00 for bedrooms is 32 hours, so 33 or more hours above 26 °C will be recorded as a fail).

Criteria 2 and 3 of CIBSE TM52 may fail to be met, but both (*a*) and (*b*) above *must* be passed for all relevant rooms.

4.3 Criteria for homes predominantly mechanically ventilated

For homes with restricted window openings, the CIBSE fixed temperature test must be followed, i.e. all occupied rooms should not exceed an operative temperature of 26 °C for more than 3% of the annual occupied annual hours (CIBSE Guide A (2015a)).

4.4 Adjustments for homes with vulnerable occupants

Care homes and accommodation for vulnerable occupants, which are predominantly naturally ventilated (see definition above), should use criteria (*a*) and (*b*) from section 4.2 above but should assume Type I occupancy (see CIBSE TM52 (2013) for description).

If they are predominantly mechanically ventilated (see definition above), the fixed temperature method should be used, see section 4.3.

Where there is particular concern of high risk of overheating in accommodation for vulnerable occupants, a heatwave strategy should also be developed using additional weather files (see section 3.2) to explore performance and for demonstrating mitigation options under extreme events (e.g. heatwaves).

4.5 Corridors: assessment criteria

The overheating test for corridors should be based on the number of annual hours for which an operative temperature of 28 °C is exceeded. Whilst there is no mandatory target, if an operative temperature of 28 °C is exceeded for more than 3% of total annual hours, this should be flagged as a significant risk within the report.

5 Internal gains profiles

The following occupancy and equipment gains and profiles have been developed for the purposes of this methodology. They represent a robust test that ensures the key aspects of overheating are captured, namely the hours when risk is highest (i.e. the middle of the day and early afternoon) and night-time hours when, if rooms do not cool down, sleep can be disrupted.

Whilst all homes will be occupied differently, this test is intended to ensure that the units tested will perform reasonably throughout the day and night.

It is important that these profiles are used for all assessments following this methodology.

5.1 Occupancy and equipment

See Table 2.

Based on CIBSE Guide A (2015a), a maximum sensible heat gain of 75 W/person and a maximum latent heat gain of 55 W/person are assumed in living spaces. An allowance for 30% reduced gain during sleeping is based on Addendum g to ANSI/ASHRAE Standard 55-2010: *Thermal environmental conditions for human occupancy* (ASHRAE, 2013), Table 5.2.1.2 ‘Metabolic rates for typical tasks’.

5.2 Lighting

For the purposes of the assessment, lighting energy is assumed to be proportional to floor area, and lighting loads are measured in W/m^2. From 6 pm to 11 pm, 2 W/m^2 should be assumed as the default for an efficient new-build home. This assumes that good daylight levels are available (also noting that only May to September is assessed within CIBSE TM52).

For existing buildings, or specialist lighting designs, a calculated higher value should be used.

For communal corridors, use 2 W/m^2; this may be assumed as zero if passive infrared (PIR) sensors are present.

5.3 Gain profile tables and charts

Figure 1 (page 8) describes the same data listed in Table 2 in section 5.1 above.

It is assumed that apartments with the same number of occupants and bedrooms are usually provided with the same appliances, therefore the heat loads given by them should be assumed to be independent of floor area for the purpose of overheating risk assessment. Therefore, the equipment loads are defined in watts (not W/m^2).

Figures 2 to 7 (pages 8 and 9) show the occupancy and equipment profile data for each room type. The factors included in the table shown as Figure 1 need to be multiplied by the peak gain for each room to provide the total gains for each hour.

Notes:

(1) Larger or unusual apartments should follow the same principles — assessors should explain the basis of any alternative profile developed for other room types in the compliance report.

(2) Single bedrooms are those that cannot accommodate a double bed.

(3) Bathrooms and halls do not have to pass the criteria, but should be included in the assessment.

6 Supplementary information on profile development

The occupancy and equipment gain profiles listed in section 5 are strongly recommended for the purposes of this methodology. They include the following characteristics:

- Bedrooms are set with a 24-hour occupancy profile, which means that one person is always considered in each bedroom during the daytime, and two people in each double bedroom at night.
- For the 2-bedroom flat, one person is considered during the daytime in both the bedrooms in order to assess robustly. This means that one excess person (a visitor) to the assumed total number of occupants will be considered in the flat during the daily hours.
- Kitchens/living rooms are unoccupied during the sleeping hours and occupied during the rest of the day. This is the worst-case scenario since the room will be modelled as occupied only during the hottest hours of the day.

Table 2 Occupancy and equipment gain descriptions

Unit/ room type	Occupancy	Equipment load
Studio	2 people at 70% gains from 11 pm to 8 am 2 people at 100% gains from 8 am to 11 pm	Peak load of 450 W from 6 pm to 8 pm*. 200 W from 8 pm to 10 pm 110 W from 9 am to 6 pm and 10 pm to 12 pm Base load of 85 W for the rest of the day
1-bedroom apartment: living room/kitchen	1 person from 9 am to 10 pm; room is unoccupied for the rest of the day	Peak load of 450 W from 6 pm to 8 pm 200 W from 8 pm to 10 pm 110 W from 9 am to 6 pm and from 10 pm to 12 pm Base load of 85 W for the rest of the day
1-bedroom apartment: living room	1 person at 75% gains from 9 am to 10 pm; room is unoccupied for the rest of the day	Peak load of 150 W from 6 pm to 10 pm 60 W from 9 am to 6 pm and from 10 pm to 12 pm Base load of 35 W for the rest of the day
1-bedroom apartment: kitchen	1 person at 25% gains from 9 am to 10 pm; room is unoccupied for the rest of the day	Peak load of 300 W from 6 pm to 8 pm Base load of 50 W for the rest of the day
2-bedroom apartment: living room/kitchen	2 people from 9 am to 10 pm; room is unoccupied for the rest of the day	Peak load of 450 W from 6 pm to 8 pm 200 W from 8 pm to 10 pm 110 W from 9 am to 6 pm and from 10 pm to 12 pm Base load of 85 W for the rest of the day
2-bedroom apartment: living room	2 people at 75% gains from 9 am to 10 pm; room is unoccupied for the rest of the day	Peak load of 150 W from 6 pm to 10 pm 60 W from 9 am to 6 pm and from 10 pm to 12 pm Base load of 35 W for the rest of the day
2-bedroom apartment: kitchen	2 people at 25% gains from 9 am to 10 pm; room is unoccupied for the rest of the day	Peak load of 300 W from 6 pm to 8 pm Base load of 50 W for the rest of the day
3-bedroom apartment: living room/kitchen	3 people from 9 am to 10 pm; room is unoccupied for the rest of the day	Peak load of 450 W from 6 pm to 8 pm 200W from 8 pm to 10 pm 110 W from 9 am to 6 pm and from 10 pm to 12 pm Base load of 85 W for the rest of the day
3-bedroom apartment: living room	3 people at 75% gains from 9 am to 10 pm; room is unoccupied for the rest of the day	Peak load of 150 W from 6 pm to 10 pm 60 W from 9 am to 6 pm and from 10 pm to 12 pm Base load of 35 W for the rest of the day
3-bedroom apartment: kitchen	3 people at 25% gains from 9 am to 10 pm; room is unoccupied for the rest of the day	Peak load of 300 W from 6 pm to 8 pm base load of 50 W for the rest of the day
Double bedroom	2 people at 70% gains from 11 pm to 8 am 2 people at full gains from 8 am to 9 am and from 10 pm to 11 pm 1 person at full gains in the bedroom from 9 am to 10 pm	Peak load of 80 W from 8 am to 11 pm Base load of 10 W during the sleeping hours
Single bedroom (too small to accommodate double bed)	1 person at 70% gains from 11 pm to 8 am 1 person at full gains from 8 am to 11 pm	Peak load of 80 W from 8 am to 11 pm Base load of 10 W during sleeping hours
Communal corridors	Assumed to be zero	Pipework heat loss only; see section 3.1 above

* All times in GMT

— No differences between weekdays and weekend are considered. Moreover, the overall apartment will be modelled as occupied for 24 hours.

— Occupied hours should be totalled, as described in CIBSE TM52, as 3672 hours per year for bedrooms (24/7 for the May–September dates covered) and 1989 hours per year for living rooms (13 hours per day for 153 days May–September). This provides a useful check that profiles have been correctly applied. See section 4 for compliance criteria.

The reasons for using this occupancy pattern include:

— The purpose of the assessment is to test the ability of the building design to mitigate overheating risk, and therefore lengthy occupied periods need to be evaluated.

— Having found that the CIBSE TM52 test is very sensitive to occupied hours (as only occupied hours are assessed), spaces with daytime-only occupancy find it more difficult to comply. Night-time-only occupancy only assesses the cooler, no solar gains periods which makes it relatively easy to pass and does not take into account more critical situations (e.g. bedroom used during the daytime by children or people who might use the bedroom as a study/ home office).

— It helps to address the most critical health concerns associated with overheating: vulnerable people (i.e. elderly people, disabled people and babies) who tend to be at home most of the day.

— Most building modelling (e.g. daylighting analysis, SAP assessments) assumes (directly or indirectly)

Figure 1 Heat gain profile

Number of people	Description	Peak load (W) Sensible	Peak load (W) Latent	00–01	01–02	02–03	03–04	04–05	05–06	06–07	07–08	08–09	09–10	10–11	11–12	12–13	13–14	14–15	15–16	16–17	17–18	18–19	19–20	20–21	21–22	22–23	23–24
				1.00	2.00	3.00	4.00	5.00	6.00	7.00	8.00	9.00	10.00	11.00	12.00	13.00	14.00	15.00	16.00	17.00	18.00	19.00	20.00	21.00	22.00	23.00	24.00
1	Single bedroom occupancy	75	55	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0.7
2	Double bedroom cccupancy	150	110	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	1	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	1	0.7
2	Studio occupancy	150	110	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0.7
1	1-bedroom living/kitchen occupancy	75	55	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0
1	1-bedroom living occupancy	75	55	0	0	0	0	0	0	0	0	0	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0	0
1	1-bedroom kitchen occupancy	75	55	0	0	0	0	0	0	0	0	0	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0	0
2	2-bedroom living/kitchen occupancy	150	110	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0
2	2-bedroom living occupancy	150	110	0	0	0	0	0	0	0	0	0	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0	0
2	2-bedroom kitchen occupancy	150	110	0	0	0	0	0	0	0	0	0	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0	0
3	3-bedroom living/kitchen occupancy	225	165	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0
3	3-bedroom living occupancy	225	165	0	0	0	0	0	0	0	0	0	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0	0
3	3-bedroom kitchen occupancy	225	165	0	0	0	0	0	0	0	0	0	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0	0
	Single bedroom equipment	80		0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0.13
	Double bedroom equipment	80		0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0.13
	Studio equipment	450		0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	1	1	0.44	0.44	0.24	0.24
	Living/litchen equipment	450		0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	1	1	0.44	0.44	0.24	0.24
	Living equipment	150		0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	1	1	1	1	0.4	0.4
	Kitchen equipment	300		0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	1	1	0.17	0.17	0.17	0.17
	Lighting profile	2 (W/m2)		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	0

that the dwelling is constantly occupied. Adopting a different approach for overheating is inconsistent and could be confusing.

The profile and the associated loads are based on DECC's Household Electricity Survey (DECC, 2012a) and *Electrical appliances at home: tuning in to energy saving* (DECC 2013).

For reference, the annual electricity usage estimated by UK Power for a 'small house or flat' is 2000 kW·h (UK Power, 2017).

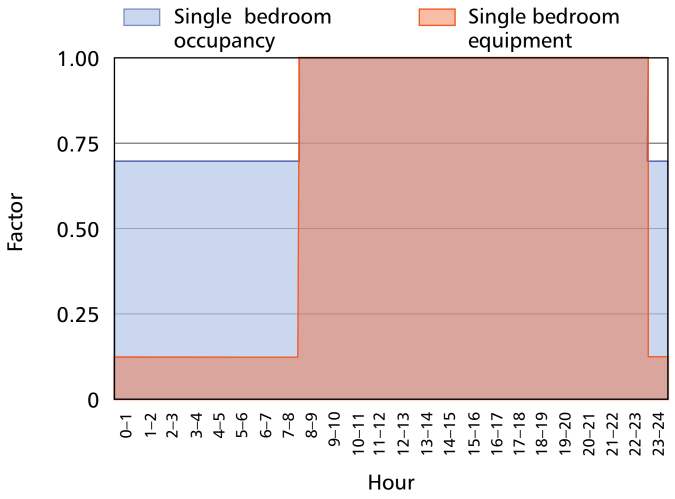

Figure 2 Heat gain profile: single bedroom

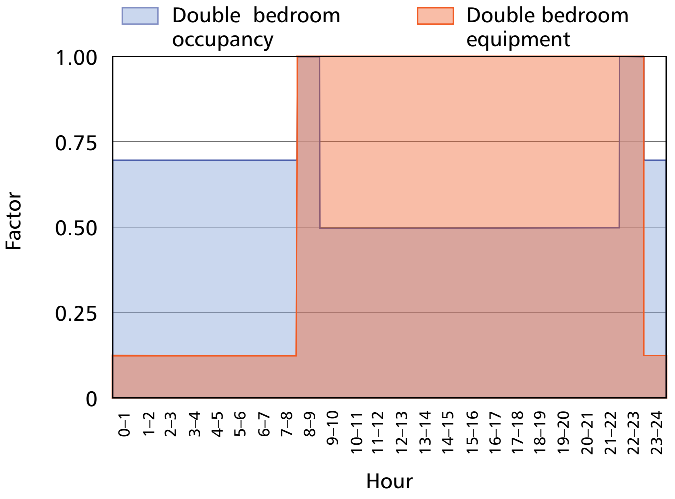

Figure 3 Heat gain profile: double bedroom

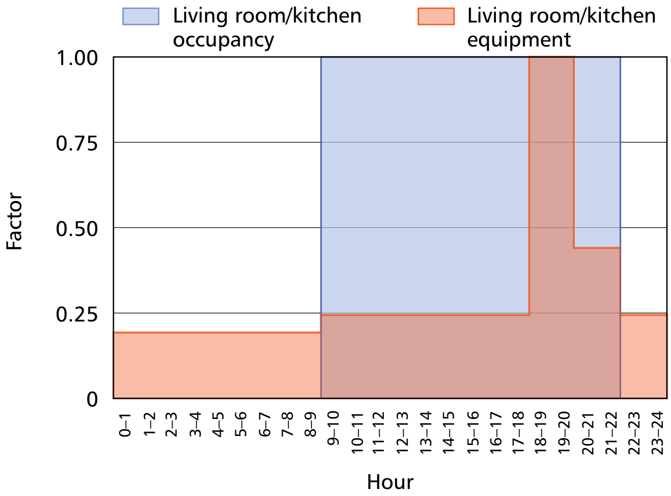

Figure 4 Heat gain profile: combined living room/kitchen

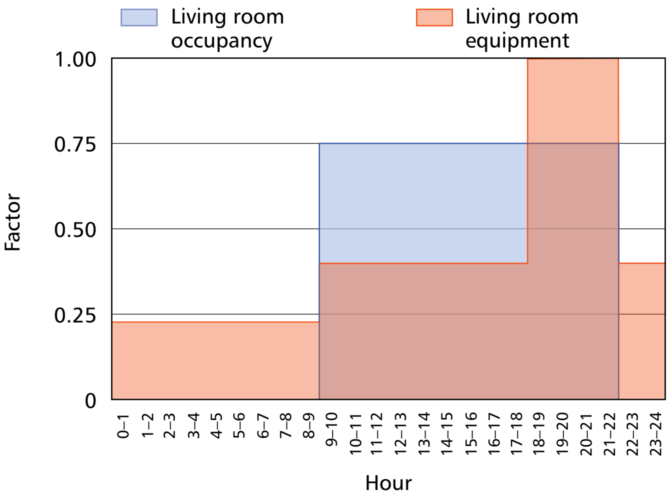

Figure 5 Heat gain profile: living room

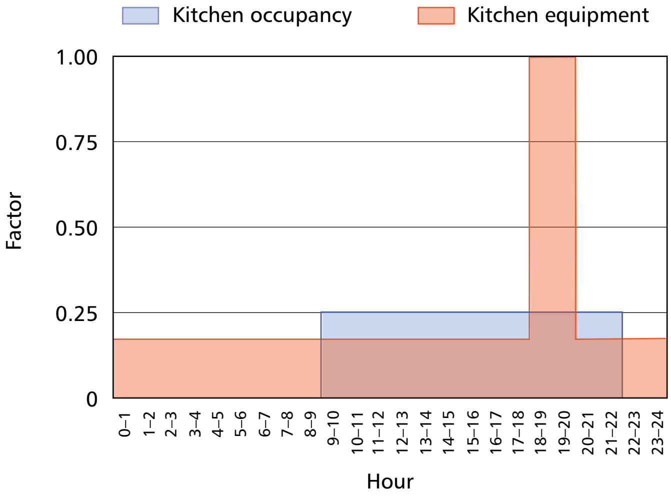

Figure 6 Heat gain profile: kitchen

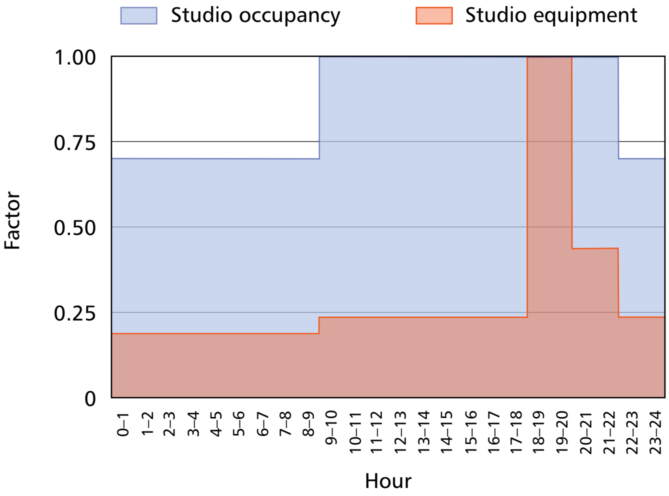

Figure 7 Heat gain profile: studio

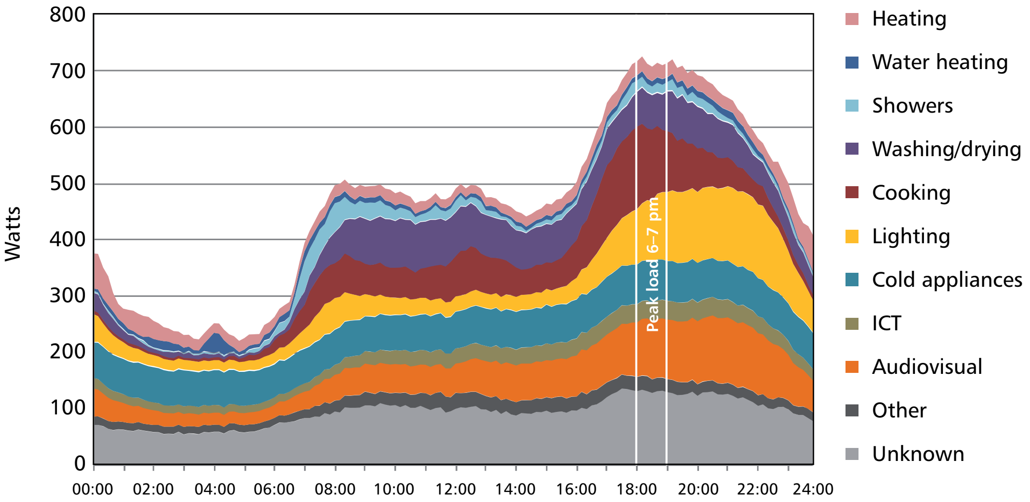

Figure 8 Average 24-hour profile for 250 homes (*source*: DECC, 2013)

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Design methodology for the assessment of overheating risk in homes

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Foreword

Our climate is changing. In the past decade alone, the South East has experienced the hottest summer (2006), the hottest peak temperature (2003), the wettest summer (2012), the coldest December (2010), the driest two winter period (2010–12) and is odds-on for being the wettest winter in a century (2013–14). We clearly cannot and should not be using the past as a guide to the future — not if we want to reduce our carbon emissions and ensure that our buildings are comfortable to live in and affordable to run.

Developing in built-up areas provides a further complication: the ‘urban heat island’ effect that keeps London warmer in winter can also raise local temperatures in summer. This is well evidenced by the fact that on a hot summer’s evening, parts of London can be four degrees Celsius warmer than the surrounding rural areas (and up to 10 degrees Celsius hotter during a heat wave). Where you build at a local level is therefore as important as ‘how’ and ‘what’ you build.

The Greater London Authority commissioned the research that supports this guidance because it is vital that we do not create buildings that add to the ‘retrofit hangover’ of correcting mistakes of the past and require intensive mechanical cooling to remain habitable in the future. This guide therefore aims to provide a risk-based approach to help developers and their advisers simultaneously address the challenges of developing in an urban heat island and managing an uncertain future climate. It provides guidance to help ensure that new development is better designed for the climate it will experience over its design life — more comfortable to live and work in, commanding a higher rental and sale value and be less likely to require expensive additional works.

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The weather data used in this research was supplied by the British Atmospheric Data Centre (BADC) and the UK Met Office.

Editor

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CIBSE Technical Director

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Design Summer Years for London

Executive summary

Overview

This TM addresses the question of whether the current CIBSE Design Summer Year (DSY) for London is the most appropriate year of weather data to assess the summertime cooling needs of buildings in London.

Three questions are addressed:

(1) Is the DSY a sufficiently warm year, or should a warmer year be used?

(2) How will future climate change affect the suitability of the DSY?

(3) What is the effect of the urban heat island (UHI), and should weather data be supplied for other parts of London?

The findings for each of these questions are summarised below:

(1) The current CIBSE DSYs for sites in the UK are selected based on a near-extreme value of April–September average temperature (middle of the upper quartile). A new metric of summer warmth has been used here to select warm years, called 'weighted cooling degree hours' (WCDH), which is more closely related to the likelihood of thermal discomfort. WCDH is defined as the cumulative squared hourly difference between the outdoor dry bulb temperature, T, and the adaptive thermal comfort temperature, T_c, whenever $T > T_c$. This metric, therefore, relates to both the frequency and severity of warm weather and its impact on thermal comfort.

The CIBSE DSY for London is based on weather data from London Heathrow Airport (LHR) and the year used is 1989. In order to determine the degree of summer warmth in this year compared to other recent years, temperature data from LHR was analysed for the period 1950–2006. A return period analysis was made based on the WCDH metric and the 28-year 'baseline' period 1977–2004. The current DSY was found to represent a moderately warm summer with an estimated return period of nine years over this baseline period; that is to say, over the baseline period, there would have been around a 1 in 9 chance of a summer as warm or warmer than the current DSY occurring in each year.

The calculated return period for the current DSY of 9 years is close to the return period normally assigned to the DSY, based on April–September average temperature, of 8 years. Hence the current DSY is concluded to fulfil its purpose of representing a near-extreme warm summer in London, based on historical observations. However a number of points are worth noting:

— There is no general correlation between WCDH (or other metrics representing extremes of summer warmth) and the sixth month average April–September temperature. The fact that the two metrics lead to similar return period estimates for London is coincidental and we do not expect this result to be a general one applicable to other locations in the UK.

— Five years have had warmer summers than 1989 over the period 1950–2006. These years were: 1976, 1990, 1995, 2003 and 2006. The estimated return periods against WCDH for these years with reference to the 1977–2004 baseline period were estimated to be 27 years, 16 years, 19 years, 19 years and 20 years, respectively. Therefore these years are significantly more extreme than the current DSY and so, where the impacts of overheating are important for the operation of a building, warmer summer conditions than the current DSY are worthy of consideration. To accompany this TM, two additional London DSYs have been produced for the years 1976 and 2003. The latter has a two-week extreme heat wave and the former a more persistently warm summer

— The above quoted return periods relate to the historical period 1977–2004. There has been a significant underlying warming trend in London's climate over the last few decades (discussed within this report) and projections for climate change in the UK indicate that a warming trend will continue. Hence, it is more appropriate to use return period estimates based on future climate projections than the historical period. These estimates are discussed with respect to question 2, below.

(2) An assessment of how the return periods of the warm summers may change in the future was made using the latest climate change projections for the UK (the UKCP09 projections). This analysis indicated a substantial increase in the likelihood of warmer summers in the future. For example, for the 2020s time period (2011–2040) under 50th percentile ('best guess') projections and 'medium' greenhouse gas emissions, the estimated return

period for the current DSY (1989) was found to reduce to 3 years, and the return periods of the more extreme summers 1976, 1990, 1995, 2003 and 2006 reduce to 11 years, 6 years, 7 years, 7 years and 8 years, respectively. This analysis indicates that these more extreme years have a likelihood similar to that normally associated with the current DSY over the next three decades — the period over which most buildings built today will be in operation. Hence it is recommended that the warmer years be used in place of the current DSY as suitable 'near extreme' years to use in design.

Further, our analysis based on UKCP09 projections indicated that the more extreme historical summers would become average summers by the middle of the century. Hence, the use of climate change-adjusted weather years is recommended to evaluate overheating risk on these longer timescales.

(3) To enable allowance to be made for the urban heat island of London weather data for other weather stations in and around London have been examined in addition to Heathrow Airport (LHR). Generally, there is a lack of weather observation stations measuring air temperatures within the capital with a particular scarcity of hourly observations. Two additional weather stations with long records of hourly weather observations were identified, however: London Weather Centre (LWC) and Gatwick Airport (GTW). Through comparison with weather data from other observation stations, it was found that LWC and GTW provide representative sites for inner urban and rural climate in the London area, respectively. LHR is representative of intermediate urban and suburban locations. Complete DSYs were produced for these sites for the years 1976, 1989 and 2003.

Recommendations

In summary, the recommendations of this TM are that:

— The current DSY is not considered to be sufficiently extreme to provide a basis for overheating assessments for most buildings in London and warmer weather data should be used. Over the next three decades (the '2020s' period) — the time period over which most buildings built today will need to operate — the return period of the current DSY (1989) was estimated to be only 1 in 3 years.

— New weather data for two warmer years (1976 and 2003) have been provided through this project in addition to the current DSY, with estimated return periods of 11 and 7 years over the next three decades, respectively. Together with the earlier DSY, these years can be used in overheating risk assessments to examine different levels of risk as indicated by the return period estimates above. However, because it is impossible to prejudge the impact of warm weather conditions on a building in a general sense, it is recommended that all three years be used, rather than just one, to investigate the sensitivity of the design to difference weather conditions.

— For buildings with long service lives or where overheating impacts are more critical, more extreme weather data have been generated by adjusting the historical weather years for climate change using the method of 'morphing' using a recent set of comprehensive climate change projections for the UK (the UKCP09 climate change projections) for three greenhouse emissions scenarios, three future periods and differing levels of probability. Which of these possible future climate scenarios is used should be decided upon by the project team, based on an agreed attitude to future climate risk.

— There are significant climate variations across London associated with the urban heat island. To enable the impact of these differences to be investigated, weather years have been provided for three locations: London Weather Centre, Heathrow Airport and Gatwick Airport. The most representative weather station site for the project location should be used. It is recommended that London Weather Centre data be used for development within the Greater London Authority Central Activity Zone (CAZ); London Heathrow airport data be used for development in urban and suburban areas outside the CAZ; and Gatwick Airport data can be used for development in rural and peri-urban areas around the edge of London.

At present, because of the sparsity of high-quality weather data for London, it is not possible to provide more detailed guidance on the issues discussed above, but the new weather data set discussed and presented in this report provides a step forward in the ability to investigate the impact of urban macroclimatic factors and climate change when carrying out overheating risk assessments for buildings in London.

Design Summer Years for London

1 Introduction

Overheating (unacceptably warm thermal conditions for human comfort) is an important issue for buildings in the UK, and has become increasingly important in recent years. In part, this change is due to changes in building design and usage, e.g. improved insulation standards, greater use of glass in façades and increased internal heat gains. The climate data that are used at the design stage to assess overheating are also important, however, as they will determine the extent to which passive and active cooling measures are deemed to be required to avoid overheating. This TM reviews the current summer design climate data provided by the CIBSE for the London area.

Greater London is situated in the warmest climatic region of the UK. It also experiences a strong urban heat island (UHI) and will be particularly vulnerable to the impacts of future climate change. The Mayor of London's climate change adaptation strategy (GLA, 2011a) highlights overheating as one of three key climate change risks facing London and points to the importance of finding low-energy and passive measures to control overheating.

Overheating risk assessment is the procedure used at design stage to determine if a passive cooling strategy will be successful or if mechanical cooling is required and, if so, if lower energy methods will be effective. Currently overheating risk assessments are carried out using dynamic thermal simulation models running under the CIBSE Design Summer Year (DSY) weather data. The DSY is a historical year, selected on the basis of being the year with the third warmest April–September period from a set of 20 years. The current DSY for London is 1989 and the weather data used is from London Heathrow Airport.

Achieving the objective of delivering buildings that are appropriately designed for summer weather conditions in London requires high-quality weather data that is reflective of the geographical location of the building and of current and future climate conditions. Concerns have been raised as to whether the CIBSE DSY for London is adequate to meet these objectives. In response to these concerns, the GLA and CIBSE commissioned research to produce a set of bespoke DSYs that can be used to take a more robust approach to the assessment of overheating risk in buildings in London. This TM describes the results of this research and proposes a new set of DSYs for London. The GLA intends to encourage the use of these DSYs through the London Plan (GLA, 2011b).

The research addressed three key questions:

(1) Is the current CIBSE Design Summer Year for London appropriate for the design of buildings under current climate, or should warmer weather data be used?

(2) What are the implications of future climate change for the likelihood of warm summers?

(3) How representative is Heathrow airport of the climate of the city as a whole, and should other locations be used to reflect the variations in the urban heat island (UHI) across the city?

In order to provide a basis to measure the degree of summer warmth in a given year, a new metric of summer warmth has been developed, termed 'weighted cooling degree hours' (WCDH). The reason for introducing this new metric for summer warmth is that it more closely reflects the duration and severity of conditions likely to cause thermal discomfort than the metric currently used to select DSYs.

It was found that, since 1950, five years have had warmer summer conditions than the current DSY in terms of annual WCDH. These years are 1976, 1990, 1995, 2003 and 2006. For each year an assessment has been made of the level of probability of a summer of similar warmth occurring for historical and projected future climate under the UKCP09 climate change projections (Jenkins et al., 2009). In addition to 1989, two additional years have been selected (1976 and 2003) to provide a set of three DSYs. To distinguish these weather years from the current DSY, they are termed probabilistic DSYs, abbreviated as 'pDSY'.

In order to enable greater allowance to be made for the London UHI, two additional weather sites were identified and pDSYs also produced for these sites. These additional locations are: London Weather Centre (Holborn), representing a central London location, and Gatwick Airport, representing a rural location. These sites were selected as they are the only other weather stations in the London area with long continuous records of hourly weather observations.

The structure of the TM is as follows:

— Section 1 provides a general introduction.

— Section 2 reviews the current DSY and develops a theoretical basis for the pDSYs, including the implications of future climate change.

— Section 3 discusses the UHI and the availability of hourly weather data from other sites.

2 Probabilistic Design Summer Years

2.1 The CIBSE Design Summer Year

The Design Summer Year was introduced in 2002 (CIBSE, 2002) in recognition of the need to have a sequence of warm weather data for use with dynamic thermal simulation programs for the assessment of overheating risk in naturally ventilated and passively cooled ('free running') buildings. The DSY represents a 'near extreme' warm summer. CIBSE also provides another year of weather data, called the Test Reference Year (TRY), which represents a typical climatological year and is intended to be used for average annual energy prediction. Currently CIBSE provides DSY and TRY weather years for 14 locations in the UK (CIBSE, 2006).

The measure of summer warmth used to select the DSY is the average temperature over the six-month period from April to September. Although in meteorological terms summer is normally defined as the three-month period June, July and August, the longer April–September period was used as overheating problems are also sometimes experienced in spring and early autumn.

To select the DSY, a reference climate period is first selected, typically of around 20 years. The current selection period for the London DSY is 1983–2004. The April–September average dry bulb temperature is evaluated for each of the years which are then ranked according to this metric. The DSY is selected as the year that falls in the upper-middle quartile of this distribution (i.e. the 3rd warmest year in a set of 20 years). Assuming a uniform probability distribution and climate with no underlying trends (a 'stationary' climate) the DSY is, in terms of an annual exceedance probability, a '1 in 8' year. That is to say, on average, in any one year, there is a 1 in 8 chance that the April–September period will be as warm or warmer than that in the DSY. Another way of expressing this likelihood is in terms of a return period, e.g. the return period would be 8 years in the above example. *Note*: this should not be taken, however, to imply that summers such as this will occur with a regular spacing of 8 years, even in a statistically averaged sense. For example, years with warmer summers often cluster together because of natural cycles in the climate system.

A problem with the DSY definition is that overheating in free-running buildings is not typically associated with average conditions over the six-month April to September period, but with shorter periods of extreme weather, e.g. heat waves. It is possible that the procedure described above can lead to the selection of a DSY that is on average warm, but has no particularly warm spells and therefore no critical periods for overheating. It is possible that another year, that has a cooler six-month average period, could have warmer conditions over a shorter period of time that are more likely to produce overheating. The DSY, in its present form, does not then provide a basis for overheating risk assessment since there is not necessarily a correlation between the likelihood of the DSY occurring and the likelihood of overheating occurring in the building.

In this TM, an alternative definition of the DSY is investigated, which is based on three components:

— a conceptual reference 'free running' building

— a metric of summer warmth that is more directly related to likelihood of thermal discomfort than the April–September six-month average temperature

— a return period analysis to calculate return periods for each year against the summer warmth metric.

2.2 Reference conceptual building

In order to develop a definition for the pDSYs, some assumption needs to be made about how the properties of the external climate relate to the occurrence of overheating in a building. This is difficult to do in any general sense, as different buildings respond in different ways to climate conditions, depending on their form, fabric, usage patterns and mechanical services. In order to make progress, however, we will define a conceptual free running building. This building is one in which the internal operative temperature is equal to the outside dry bulb temperature at all times. This conceptual building corresponds physically to a building in which there is always a very high ventilation rate, so that heat gains are quickly removed and the internal temperature is close to the outside temperature.

Many naturally ventilated buildings work most effectively in this mode to control overheating, resulting in a close coupling between internal and external temperatures in summer, e.g. as demonstrated by Coley et al. (2010). Arguably, this simple model is less appropriate for high thermal mass night-cooled buildings with longer time constants for thermal response. However, even in such buildings when heat gains are high and high ventilation rates are required the above conceptual model will be appropriate, e.g. as demonstrated by Huggett (2012) through computer simulation of a night-cooled office building in London.

Other conceptual reference buildings might be more appropriate in other contexts. For example, temperatures in a high thermal mass building with moderate heat gains and night cooling might be more closely related to average night-time temperatures over a period of days. A highly glazed mechanically ventilated building may have temperatures more closely related to instantaneous solar gain. The simple model also does not take into account the effect of mean radiant (surface) temperatures or air movement in lowering the operative temperature associated with thermal comfort. However, it is not possible to produce any one definition of reference building that covers all building types and further research is required to identify alternative definitions. For the purpose of this study, the conceptual model described above is considered to be the most widely applicable choice for free-running naturally ventilated buildings. Furthermore the model is convenient in its simplicity as external temperatures can be taken as a proxy for internal temperatures and an initial assessment of overheating risk can be made on the basis of the weather data alone.

Having established this definition, it is then possible to select a metric for the selection of a pDSY that relates to the likelihood of thermal discomfort being experienced in the reference building. We consider possible metrics in the following section.

2.3 Metrics of summer warmth

Saying that a building has 'overheated' is generally accepted to mean that an unacceptable level of thermal discomfort has occurred in the building, either on a particular day or over some period of time. Although there is no universally accepted definition of overheating, CIBSE has issued guidance on this subject (CIBSE, 2013).

For the research carried out in this study, a review was carried out of the different measures to calculate overheating described in BS EN 15251 (BSI, 2007). Three different approaches are suggested:

(A) *Percentage outside range*: this is the number of occupied hours for which the operative temperature in the building is above a specified threshold discomfort temperature.

(B) *Degree hours criteria*: this is the cumulative number of occupied hours the operative temperature is above the threshold discomfort temperature weighted by the magnitude of the exceedance.

(C) PPD-weighted criteria: this is similar to the degree hours criterion, but the weighting used is based on the percentage of persons dissatisfied (PPD) according to a thermal comfort model, rather than the simple magnitude of temperature exceedance.

The current overheating criterion for free-running buildings in CIBSE guidance falls under Criterion A: specifically, the amount of time the operative temperature is above 28 °C* should not exceed 1% of occupied hours (CIBSE, 2006). A problem with this type of criterion is that it quantifies the frequency of overheating, but not the severity. Criterion B quantifies both frequency of occurrence and severity, but assumes a linear relationship between temperature exceedance and discomfort, whereas in practice this relationship is more complex. Criterion C is more difficult to implement, but is the most closely aligned to thermal discomfort.

To implement Criterion C a thermal comfort model is required. BS EN 15251 suggests use of the Fanger thermal comfort model (CIBSE, 2006) with percentage persons dissatisfied (PPD) as the basis of the weighting. However, the standard also indicates that an adaptive thermal comfort model is the appropriate comfort model to use to assess comfort in free running buildings, provided sufficient 'adaptive opportunity' is available

In the adaptive model given in BS EN 15251 the operative temperature (CIBSE, 2006) for neutral comfort (neither too cool or too warm), i.e. the comfort temperature, is related to the running mean of the outside dry-bulb temperature, according to the following relationship:

$$T_{\text{conf}} = 0.33\, T_{\text{rm}} + 18.8 \qquad (1)$$

where T_{conf} is the predicted comfort temperature on a given day (°C), and T_{rm} is the running mean daily average temperature given by:

$$T_{\text{rm}} = \alpha\, T_{\text{rm}-1} + (1 - \alpha)\, T_{\text{mean}-1} \qquad (2)$$

where α is a constant (0.8), $T_{\text{rm}-1}$ is the running mean temperature for the proceeding day (°C) and $T_{\text{mean}-1}$ is the average temperature for the proceeding day (°C).

BS EN 15251 (BSI 2007) does not provide a formula to calculate PPD for the adaptive thermal comfort model. However, Nicol et al. (2009) have developed a criterion C-type overheating metric using adaptive thermal comfort concepts, which they termed the 'potential daily discomfort' (PDD), defined by:

$$\text{PDD} = \frac{1}{24} \sum_{\substack{\text{all hours}\\ \Delta T>0}} F\,(\Delta T) \qquad (3)$$

where F is the predicted fraction of people uncomfortable (voting either 'warm' or 'hot'), given by:

$$F = \frac{1}{1 + e^{(2.61 - 0.473\,\Delta T)}} \qquad (4)$$

and,

$$\Delta T = T_{\text{op}} - T_{\text{conf}} \qquad (5)$$

where ΔT is the difference between the operative temperature, T_{op} (°C) (CIBSE, 2006), and the comfort temperature T_{conf} (°C) predicted by equation 1.

In the research described in this publication, a simpler form of this metric was used, called 'weighted cooling degree hours' (WCDH), in which the function F is approximated by a quadratic relationship:

$$\text{WCDH} = \sum_{\substack{\text{all hours}\\ \Delta T>0}} \Delta T^{2} \qquad (6)$$

For smaller values of ΔT, the quadratic relationship approximates the form of the function F, but places greater emphasis on larger values of ΔT, i.e. more extreme departures from the comfort temperature (Figure 1).

Nicol et al. (2009) also proposed the concept of the 'potential discomfort index' (PDI), in which the external dry bulb temperature is used as a proxy for the internal operative temperature. On the basis of the conceptual naturally ventilated building defined above, any metric of summer warmth based on dry bulb temperature could be used as the basis for a PDI.

WCDH is adopted here as the basis for a PDI on the grounds that it is both related to the likelihood of thermal discomfort and gives particular emphasis to more extreme temperatures, where more serious effects of heat are likely to occur.

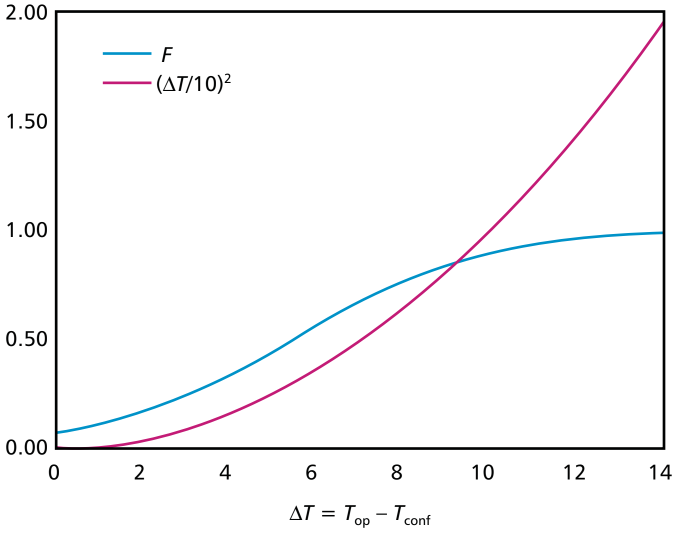

Figure 1 Relationship between the departure from the comfort temperature and (a) the function F in equation 4, giving the proportion of people uncomfortable in the adaptive thermal comfort model, and (b) a quadratic relationship

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* For bedrooms in dwellings the temperature threshold is 26 °C.

The following section examines how different metrics of summer warmth vary between years in the London Heathrow weather data.

2.4 Analysis of London Heathrow temperature data

In order to examine the context of the current DSY in terms of the summer warmth metrics discussed above, in this section hourly dry bulb temperatures at London Heathrow are examined. These data are available from 1949 and here we have considered the period 1950–2006.

The following metrics of summer warmth were investigated:

- April–September average temperature (current basis for the DSY selection)
- June–August average temperature (meteorological summer average temperature)
- annual maximum temperature
- hours above 28 °C
- cooling degree hours (CDH), with base temperature equal to the adaptive comfort temperature, T_c
- weighted cooling degree hours (WCDH) as defined in equation 6.

Figure 2 shows the trend in each of these metrics for the time period 1950–2006. There were some warm summers in the 1950s and 1960s, but there is little evidence of a warming trend until the late 1970s. The summer of 1976 stands out as a particularly warm and anomalous summer in comparison to neighbouring years against all the metrics, with the exception of peak summer temperature. Since 1976 there has been an appreciable warming trend, albeit accompanied by a considerable amount of inter-annual (year-to-year) variability. The linear trends in each metric for the time periods 1950–2006 and 1977–2006 are given in Table 1. The latter period represents the 30-year period to 2006 and so may be taken to be more reflective of the current situation. However, there have been a number of cooler summers since 2006 and the omission of 1976 also affects the magnitude of this trend.

The current DSY for London, 1989, is highlighted in Figure 2. Although 1989 is the third warmest summer in terms of April to September average temperature over the period 1983–2004, over the complete period of data shown in Figure 2, there have been four summers that have been warmer with respect to all the metrics, notably 1976, 1995, 2003 and 2006. In addition, 1983 was warmer against two metrics (June–August average temperature and hours above 28 °C) and 1990 was warmer against the metrics relating to extremes of summer warmth (annual maximum temperature, hours above 28 °C, CDH and WCDH).

Figure 3 shows the correlation between the April to September average temperature and the other metrics. Although all the metrics are correlated to some extent, the correlation is weaker for the metrics relating to extremes of summer warmth and particularly for the warmest years. The relative ranking of the warmest years also differs between the metrics.

In order to better understand the differences between the warmest years, time-series showing the daily temperature range over the April to September period for the six warmest years are presented in Figure 4. Also shown is the daily adaptive comfort temperature, T_c, which forms the base temperature for CDH and WCDH. The cumulative annual values of these metrics come from a number of 'warm spells' where temperatures are above T_c. Each warm spell has differing characteristics in terms of duration and intensity. The warm spell of June–July 1976 was characterised by a prolonged period of sustained warmth; 1989 had one major warm spell in July and then a number of more minor warm spells; 1990 had one particularly intense short lived warm spell; 1995 was characterised by a succession of relatively intense warm spells for a two month period from late June to late August; 2003 had a particularly intense and relatively prolonged warm spell in August, which is the most intense heat wave on record in London (Burt, 2004; Burt et al., 2004); 2006 had a long double-peaked warm spell in July, and two additional warm spells earlier in the year.

The characteristics of the 20 warmest warm spells ranked by cumulative WCDH are given in Table 2. Half of these warm spells occurred in the six warm years identified above, but a number of other years also feature, notably 1975 and 1983, in the top ten ranked warm spells. All of these warm spells occurred in June, July or August, with the majority beginning in July.

The variation in the number, timing, intensity and duration of warm spells between years highlights the difficulty in using a single year to assess the response of buildings to warm weather under all circumstances. In the future it may become possible to carry out multi-year dynamic thermal simulations to predict the statistics of building thermal response over a longer period of time. However, at the present time it is likely designers will continue to use a single, or small number, of weather years to assess designs. To facilitate the selection of particular years we look in more detail in the next section at the question of how to assign a probability of occurrence to each of the years.

Table 1 Changes per decade at Heathrow Airport in the six metrics of summer warmth; all the trends are significant (positive) to within at least 98% confidence

Period	April–Sept. temp. (T_{mean}) (°C)	June–Aug. temp. (T_{mean}) (°C)	Annual max. temp. (T_{max}) (°C)	Annual amounts		
				Hours at >28 °C (hour)	Cooling degree hours (K·hour)	Weighted cooling degree hours (K^2·hour)
1950–2006	0.27	0.32	0.47	10	42	166
1977–2006	0.68	0.73	1.58	28	117	514

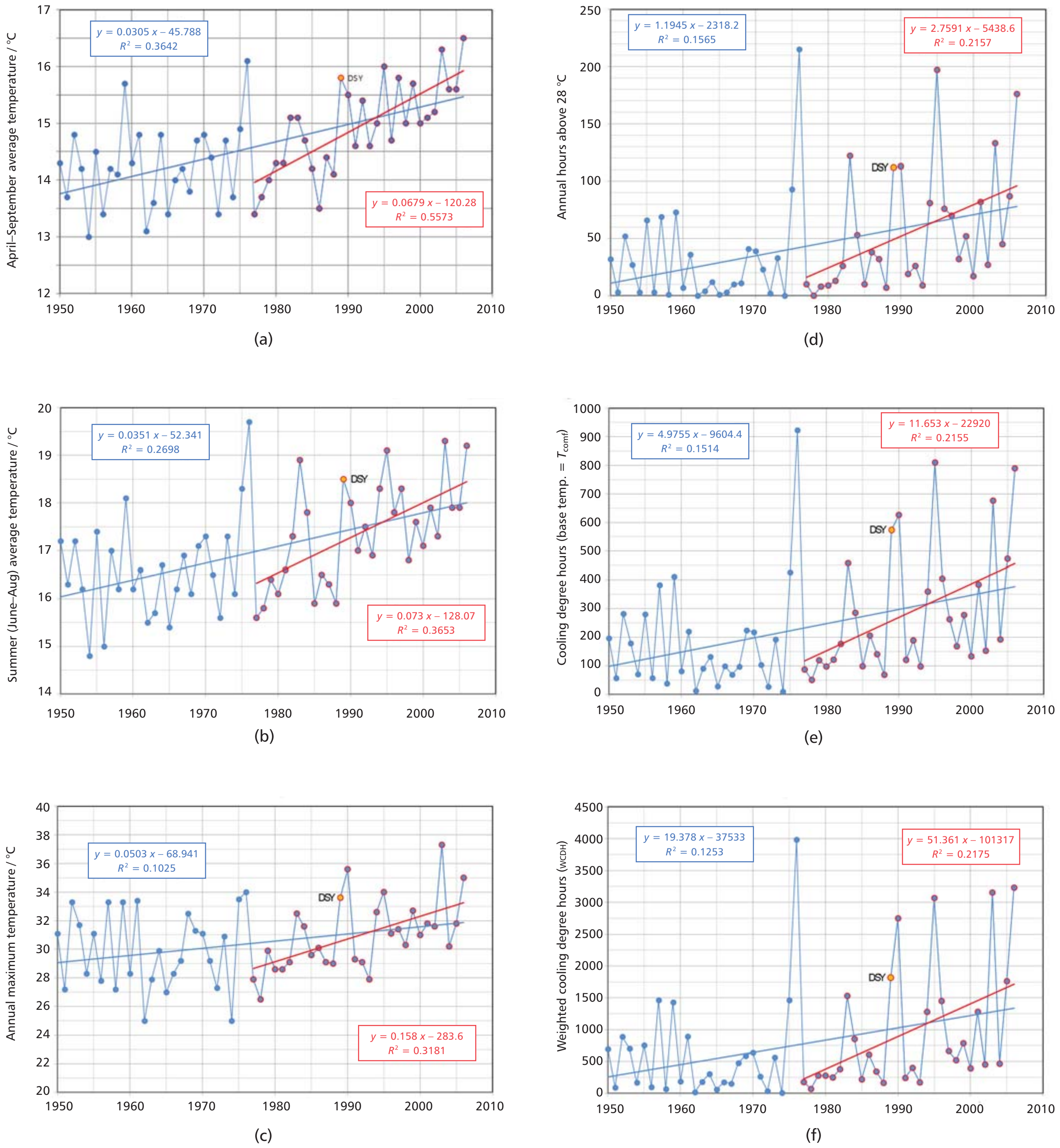


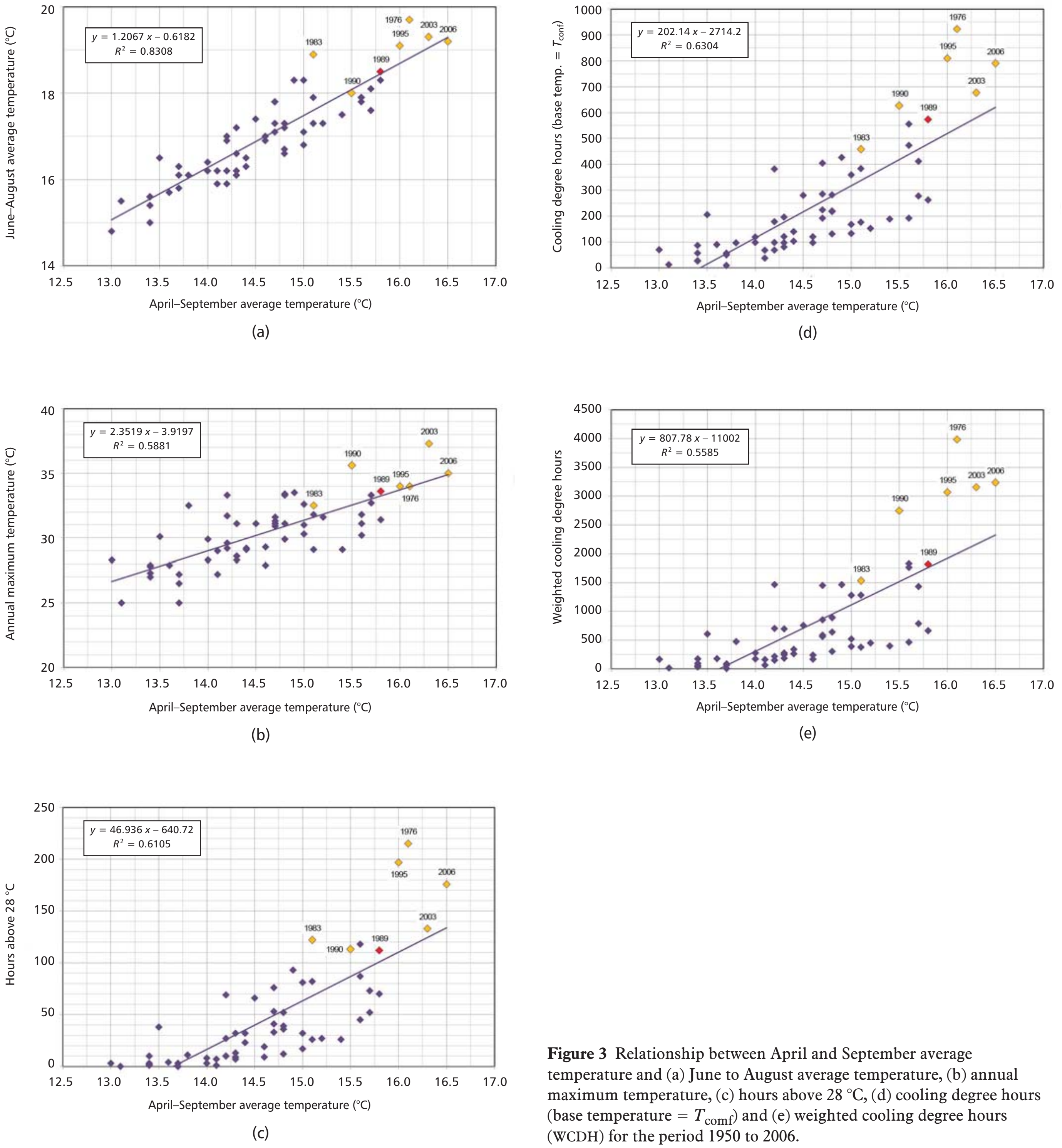
Figure 2 Trends in different metrics of summer warmth from 1950 to 2006; (a) April–September average temperature, (b) June–August average temperature, (c) annual maximum temperature, (d) hours above 28 °C, (e) cooling degree hours (base temperature = T_c) and (f) weighted cooling degree hours (WCDH).

2.5 Estimate of return periods for warm summers

It is possible to make a simple assessment of return periods against the empirical distribution of the warm years, e.g. as was done earlier to assign the current DSY with a '1 in 8 year' probability of occurrence (section 2.1). However, this simple approach neglects the fact that the finite nature of the sample leads to an imperfect description of the underlying probability distribution.

In order to provide a better estimate, we fitted a particular class of theoretical probability distribution to the empirical frequency distributions called the Generalised extreme value (GEV) distribution (Coles, 2001). The GEV distribution is typically used as a model of the distribution of extremes taken from designated 'blocks' of data (typically a time period say of one year). Here we apply this technique to the WCHD data.

The results of the return period analysis for two periods, 1977–2004 and 1950–2004, are shown in Figures 5 and 6 respectively, and in Table 3. The period 1977–2004 was



(a)

(b)

(c)

(d)

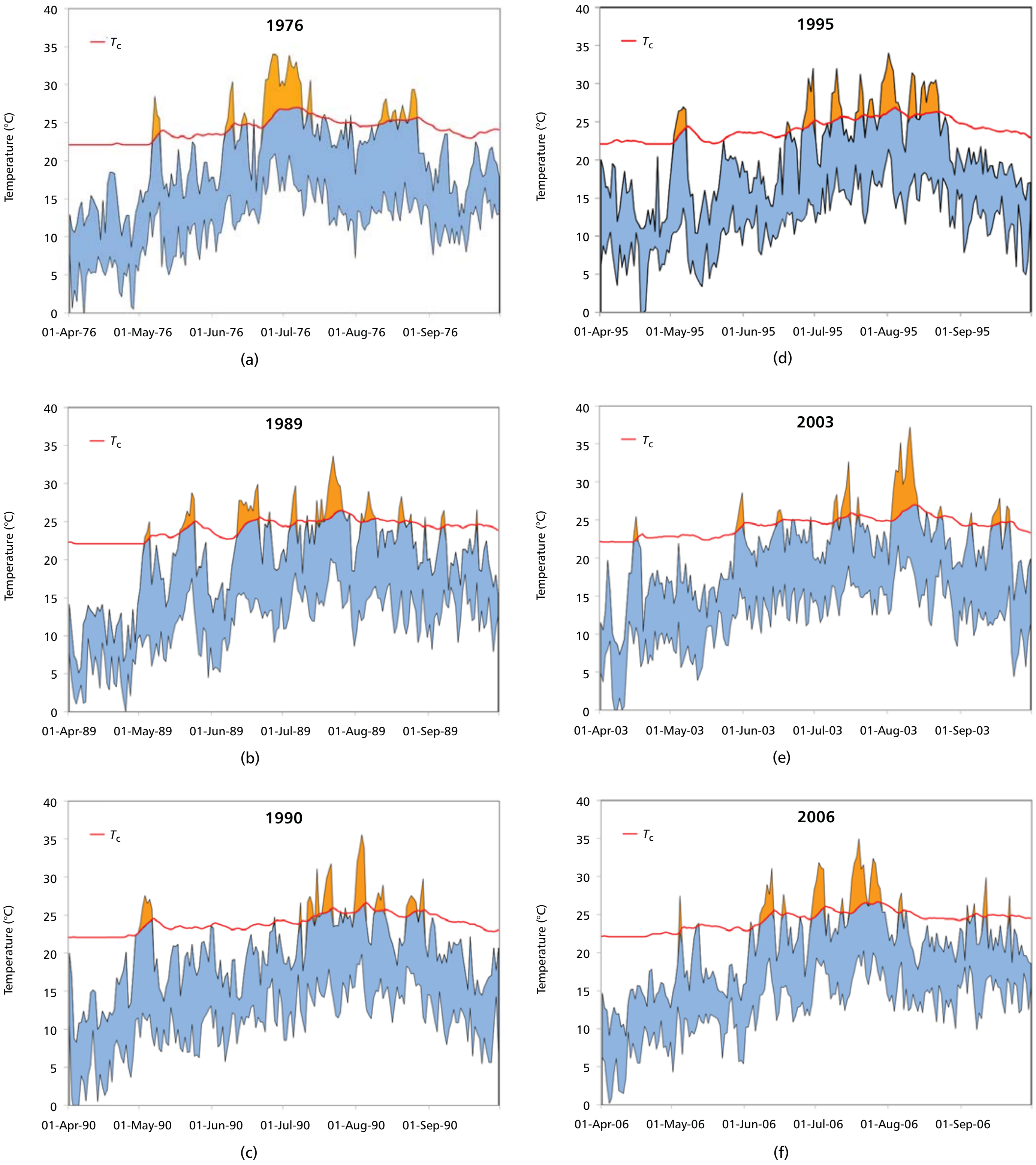
(e)

Figure 3 Relationship between April and September average temperature and (a) June to August average temperature, (b) annual maximum temperature, (c) hours above 28 °C, (d) cooling degree hours (base temperature = T_{comf}) and (e) weighted cooling degree hours (WCDH) for the period 1950 to 2006.

chosen as this was the period for which data were available to carry out the climate change assessment reported in section 2.7. The return periods estimated for the two periods are similar, but somewhat larger for the longer time series, as is expected due to the underlying trend.

For the more recent time period, the analysis indicates a return period for the current DSY of 9 years against the WCHD metric. This value is similar to the return period of 8 years normally assigned to the current DSY based on April–September mean temperatures (section 2.1). The three years 1995, 2003 and 2006, which have similar values of WCHD, are estimated to have similar return periods, of between 19 and 20 years. For the other two warm years, 1990 is estimated to have a return period of 16 years and 1976 a return period of 27 years.

Formally, the type of return period analysis presented above only applies to a ‘stationary time series’, i.e. one that has no underlying trends. The return periods above should be interpreted, therefore, as only applying to the particular period in question, and would only be repeated in the future should a similar sequence of years occur. This is unlikely, given the presence of the underlying trend. Because of this, the return periods are ‘retrospective’.



(a) (d)

(b) (e)

(c) (f)

Figure 4 Characteristics of the six warmest years at LHR over the period 1950–2006: daily max–min temperature range (solid filled area) and adaptive comfort temperature T_c (red line); periods where temperatures are above T_c are filled in orange and areas where temperatures are below T_c are filled in blue; (a) 1976, (b) 1989, (c) 1990, (d) 1995, (e) 2003, (f) 2006

One way to remove the influence of the underlying trend is to 'de-trend' the data based on a regression analysis (cf. Figure 2). However, this simple approach can lead to unreliable or misleading results and was not felt to be appropriate for the analysis of the WCDH data. In section 2.7 we will look at how the return periods may be expected to change in the future using climate change projections from models rather than the observed trends.

An additional problem in the analysis of extremes is that, by definition, extreme events occur infrequently, and hence the assessment of return periods for the most extreme events are inherently inaccurate. One approach that can be used to refine the assessment of the underlying distributions is to make use of a statistical weather generator to generate a larger number of years. This approach was tried using a weather generator that has been produced for the UK

Table 2 Characteristics of the twenty warmest warm spells ranked against WCDH for the period 1975–2006. A warm spell is classified as any continuous period when there is at least one hour of each day with temperature above the adaptive comfort temperature T_c; warm spells separated by less than 3 days have been counted as a single warm spell

Rank	Year	Start date	End date	Duration (days)	Warmth metrics		Mean values (°C)				Max values (°C)	
					WCDH	$h > 28$	T_c	T_{mean}	T_{min}	T_{max}	T_{min}	T_{max}
1	1976	22/06/1976	08/07/1976	17	3168	136	26.3	24.8	17.9	31.6	20.9	34.0
2	2003	02/08/2003	13/08/2003	12	2471	79	26.0	24.4	18.2	31.3	21.7	37.3
3	2006	15/07/2006	28/07/2006	14	1846	82	26.1	23.7	17.8	30.2	20.3	35.0
4	1990	31/07/1990	04/08/1990	5	1656	42	25.8	25.4	17.6	32.4	19.9	35.6
5	1975	26/07/1975	08/08/1975	14	1260	60	25.5	22.7	16.9	29.1	22.0	33.5
6	1983	02/07/1983	18/07/1983	17	1106	50	25.5	22.5	16.9	28.5	19.4	32.5
7	1995	29/07/1995	06/08/1995	9	1055	48	26.3	23.6	17.4	30.2	21.4	34.0
8	1989	15/07/1989	26/07/1989	12	961	44	25.6	22.5	16.6	28.7	20.2	33.6
9	2006	29/06/2006	04/07/2006	6	740	34	25.1	23.1	17.5	29.6	19.3	31.9
10	2005	17/06/2005	23/06/2005	7	694	25	24.9	23.0	17.3	28.4	20.0	31.8
11	1995	26/06/1995	30/06/1995	5	575	16	24.4	20.4	13.6	28.7	14.9	32.0
12	1996	05/06/1996	07/06/1996	3	550	14	24.0	22.9	16.3	29.6	19.4	31.1
13	1997	06/08/1997	20/08/1997	15	544	35	25.9	22.9	18.1	28.2	21.7	31.4
14	1999	29/07/1999	06/08/1999	9	538	28	25.6	22.0	16.9	28.1	18.9	32.7
15	1994	10/07/1994	14/07/1994	5	496	16	25.1	21.7	15.8	27.5	17.7	32.6
16	1994	19/07/1994	30/07/1994	12	465	26	25.7	21.6	16.9	27.1	20.4	31.6
17	2001	23/07/2001	31/07/2001	9	454	23	25.1	21.9	16.3	27.3	19.4	31.4
18	1990	18/07/1990	21/07/1990	4	437	20	25.5	22.9	15.8	30.0	17.9	31.8
19	2005	10/07/2005	18/07/2005	9	435	20	25.2	21.7	15.7	27.8	18.5	30.7
20	2003	09/07/2003	15/07/2003	7	425	17	25.2	22.0	15.7	28.0	19.0	32.7

climate for the UKCP09 Climate Change Projections (Jenkins, et al., 2009). It was found, however, that the weather generator did not produce years that were as warm in terms of WCDH as in the observed data. This is thought to be due to two reasons. First, although the weather generator reproduced the means of the observed temperature distribution well, the variance and extremes were not well replicated*. Secondly, the weather generator also does not contain a model for inter-annual variability (each year has no memory of the proceeding year), and so the extremes of the temperature distribution are not clustered together into particular warm years to the same extent as they are in the observed data. Hence, it was concluded that this approach did not constitute a reliable method. Further development of weather generator models may make this approach more viable in the future.

2.6 Selection of the probabilistic Design Summer Years

On the basis of the analysis above, the following three years were selected to form the set of probabilistic design summer years:

— pDSY-1: 1989

— pDSY-2: 2003

— pDSY-3: 1976

The first of these years, 1989, is the current DSY and represents a moderately warm summer, as is interpreted in current CIBSE guidance. The years 1976 and 2003 were chosen as more extreme years with different types of summer: the former is a year with a long period of persistent warmth, whereas the latter has a more intense single warm spell.

Hourly weather data files containing the full set of weather variables required for building dynamic thermal simulation were produced for these years. The task of doing this involved checking the data and interpolating missing data values. The procedure used to do this is described Appendix A1.

2.7 Climate change projections for London and implications for the pDSYs

In order to estimate how the likelihood of the pDSYs will change in the future, the return period analysis above has been repeated using the UKCP09 Climate Change Projections (Jenkins, et al., 2009). The method used was to adjust the sequence of historical years, 1977–2004, under the climate change projections using the method of 'morphing' (Belcher et al., 2005; Hacker et al., 2009). This method involves 'shifting' and 'stretching' the observed weather data so that it has the mean monthly statistics given in the climate change projections but retains the observed hourly and day-to-day weather variability.

Morphing has been used previously to adjust simulation weather years under the UKCIP02 climate change projections. The essential difference between the UKCIP02 and UCKP09 projections is that the former scenarios were 'deterministic', in that a single set of changes was given for a given time period and greenhouse gas emissions scenario, whereas the UKCP09 scenarios are 'probabilistic', in that a range of changes are given according to different likelihoods of change. In UKCP09, likelihood is expressed in terms of percentile change; e.g. a 10% percentile change gives the change encompassing the lowest 10% of the projected changes; a 50% percentile change encompasses 50% of the projected changes (i.e. represents the middle of the range, or the 'best guess'), and so on. To use the morphing method with the UKCP09 projections, a set of monthly change factors was generated in which the percentile probability

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* A newer version of the weather generator has been produced to rectify this problem; this version of the weather generator was not used in the work described here.

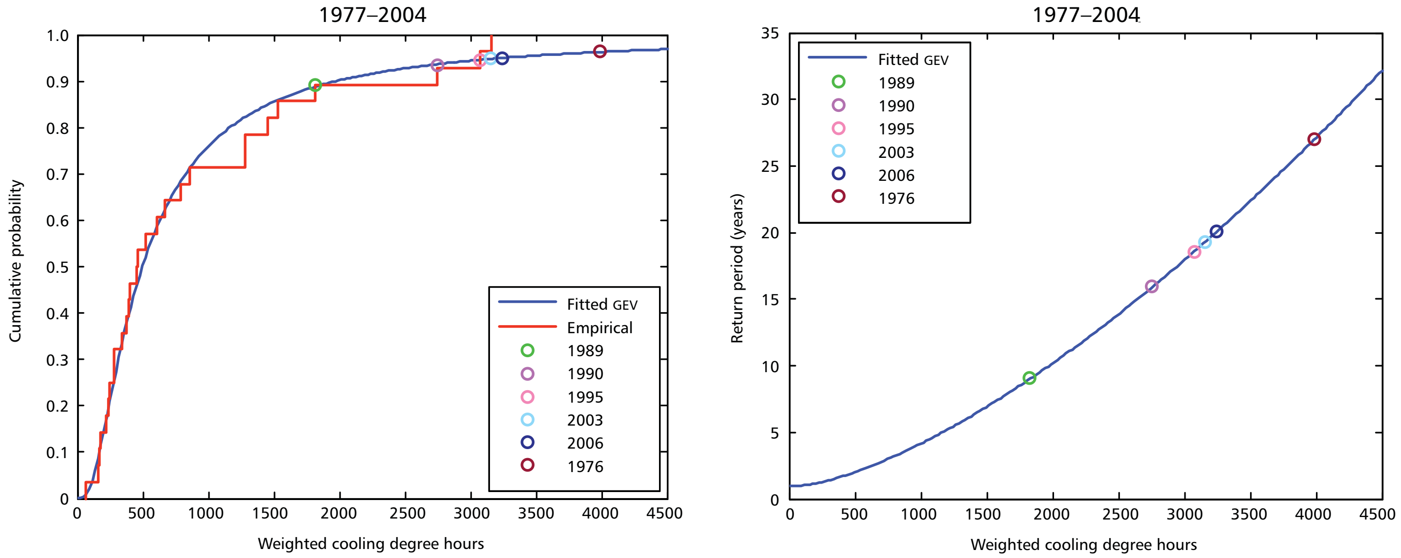

Figure 5 Return period analysis against WCDH for London Heathrow weather data for 1977–2004 using the generalised extreme value (GEV) distribution. The location of historical warm summers on the GEV distributions obtained is also shown (coloured circles).

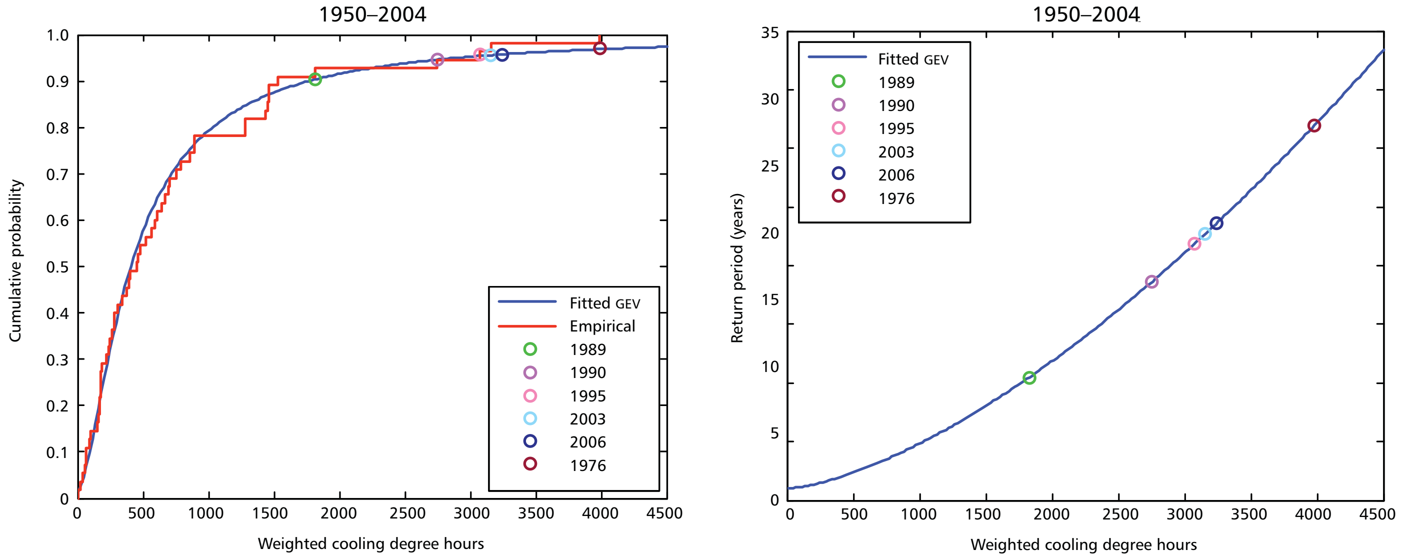

Figure 6 Return period analysis against WCDH for London Heathrow weather data for 1950–2004 using the generalised extreme value (GEV) distribution. The location of historical warm summers on the GEV distributions obtained is also shown (coloured circles).

Table 3 Return period analysis against WCDH for the six warmest years

Year	Period	
	1977–2004	1950–2004
1989	9.0	10.4
1990	15.8	18.6
1995	18.5	21.8
2003	19.3	22.7
2006	19.9	23.4
1976	27.0	32.1

relates to the change in mean monthly dry bulb temperature and the other variables are correlated to the dry bulb temperature change. This procedure is described further in (Hacker and Shilston, —)

To calculate the return periods under the UCKP09 projections the set of years 1977–2004 was morphed 'en block' for a number of greenhouse gas emission scenarios, time periods and percentile changes. This method ensures consistency with the calculation of the historical return periods. The greenhouse gas emissions scenarios considered were the Medium and High scenarios; the time periods were the 2020s, 2050s and 2080s (each a 30-year period centred on the stated decade); and the percentile changes considered were the 10%, 50% and 90% percentiles.

Once the GEV distributions for each climate change scenario had been calculated, it was possible to assess where the historical warm years sit within these distributions to give a revised estimate of return periods. These future return periods are given for the Medium and High emission scenarios in Table 4. The projected return periods of the historical years decrease markedly under the 50% and 90% percentile changes, and to a lesser extent for the 10% percentile changes.

The 2020s period is of particular interest as this relates to the period 2011–2040, which is the period we have now entered. For the 50% percentile changes, which may be viewed as the 'best guess' level of change, the estimated return periods for 1976, 1989 and 2003 drop to 11 years, 3 years and 7 years, respectively. Given the underlying

Table 4 Return periods against WCDH for the historical years for the climate change scenarios under (a) 'Medium' emissions and (b) 'High' emissions

Historical year	Baseline	Time period and percentile change								
		2020s			2050s			2080s		
		10%	50%	90%	10%	50%	90%	10%	50%	90%
(*a*) Medium emissions										
1976	27.0	25.3	10.6	3.3	17.0	5.0	1.2	13.0	2.3	1.0
1989	9.0	9.1	3.3	1.3	5.9	1.6	1.0	4.5	1.1	1.0
2003	19.3	18.5	7.3	2.3	12.3	3.4	1.0	9.4	1.7	1.0
(*b*) High emissions										
1976	27.0	23.7	11.1	3.8	16.5	3.8	1.0	10.1	1.3	1
1989	9.0	8.2	3.4	1.4	6.0	1.4	1.0	3.5	1.0	1
2003	19.3	17.2	7.7	2.6	12.2	2.7	1.0	7.3	1.1	1

warming trend seen in the observed data, it is felt that these return periods provide a more appropriate measure of the likelihood of similar summers to those in the historical pDSYs occurring over the next 30 years.

For the 2080s period, under the 50% and 90% percentile changes, the return periods of the pDSYs have reduced towards around 2 years or less, i.e. every other summer or nearly all summers will be as warm or warmer. For longer range climate change assessments, 'extreme' years are needed for these time periods also. For these time periods, the morphed counterparts of the pDSYs can be used. Within the context of the block of baseline data, each year has a similar return period to that for the historical block (because a uniform set of changes are applied across the complete block) and so the extreme years can be selected in a similar way as done for the historical period.

3 London's urban heat island: additional weather sites

The urban heat island (UHI) effect is the propensity of the city to stay warmer on average than the surrounding rural areas. In most cities, the UHI primarily manifests at night, and the 'urban heat island intensity' is typically taken to be the difference in the night minimum temperature between the city and a rural reference location. The UHI is primarily associated with the different rate at which solar heat is stored in and released from the land surfaces, due to the differing land surface characteristics of rural and urban areas. The direct input of heat from buildings and transport also contributes to the UHI to some extent, but is thought to be less important in London than the climatological drivers.

The UHI of London was first studied by Luke Howard (Howard, 1833) in the 19th century and further by Chandler in the 1960s (Chandler, 1965). More recent information has been obtained from monitoring carried out in the late 1990s (Watkins et al., 2002; Graves, et al., 2001), from research commissioned by the Greater London Authority (GLA, 2006) and through the LUCID research project (Bohnenstengel et al., 2011; Kolokotroni et al., 2008; Giridharan et al., 2009). These studies have indicated the spatial pattern of London's modern UHI and investigated causative factors. Research has also been carried out to examine longer term trends in the London UHI from Met Office observation stations within and around London (Jones et al., 2009; Wilby et al., 2011). The urban heat island tends to be most intense under conditions of light winds and clear skies and is on average centred on the centre of the city being somewhat elongated to the east over the City of London and Docklands according to the pattern of land use and the prevailing wind direction. Local reductions of the UHI are associated with major parks. There have been some trends detected in the strength of the UHI but recent research has suggested that these are more likely due to decadal climate variability rather than climate change or changes in land use (Wilby et al., 2011). It is thought, therefore, that the UHI of central London probably has not changed significantly over the last few decades, despite the changing nature of energy usage in the city and the changes in land use.

In the research reported here, weather records from a number of Met Office weather stations were examined in order to identify data sources that could be used to provide counterparts to the London Heathrow pDSYs for other locations in London. Ten weather station sites within and surrounding London were examined. Each is a recognised weather station for which quality assured data is disseminated by the British Atmospheric Data Centre (BADC). Figure 7 shows the locations of the ten sites. The details of the sites and the station name abbreviations used in this report are given in Table 5. The sites were classified as either rural (outside the M25 and away from major conurbations), peri-urban (on the suburban fringes of London) or urban (within central London). Aerial views of the immediate surroundings of the sites are shown in Figure 8 (overleaf).

These sites were identified as the complete set of BADC weather stations for London for which temperature data was available[★]. It is noticeable that there are few stations within the city itself, and none to the east and south east. Generally there is a lack of a network of weather stations recording temperature and other synoptic weather variables within London.

All of the stations have daily observations (e.g. maximum and minimum temperatures) but only some have hourly observations. Of these, only three have sufficient scope and

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[★] Subsequently it has been noted that there are some other BADC weather stations in London for which daily observations are available, notably Camden Square in central London and Greenwich Observatory in south-east London. Private and amateur data sets also have not been consulted.

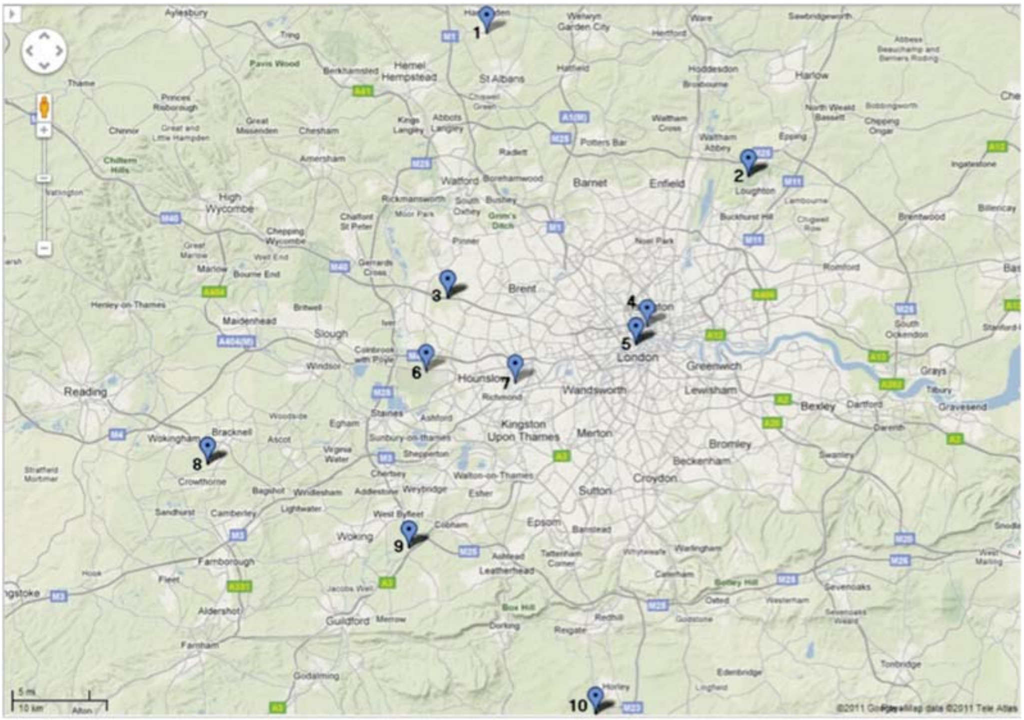


Figure 7 British Atmospheric Data Centre (BADC) sites; (1) Rothamstead, (2) High Beach Essex, (3) Northolt, (4) London Weather Centre, (5) London, St James' Park, (6) London Heathrow, (7) Kew Gardens, (8) Beaufort Park, (9) Wisley, (10) Gatwick Airport (©2011 Google; ©2011 Tele Atlas)

Table 5 Station details for each of the BADC sites

Site	Abbreviation	Geography type	Station identifier		Lat. (°N)	Long. (°E)	Elev. (m)
			WMO	DCNN			
1 Rothamstead	RTH	Rural	—	3537	51.807	–0.360	128
2 High Beach Essex	HBE	Rural	—	3604	51.664	0.041	110
3 Northolt	NTH	Peri-urban	3672	5127	51.549	–0.417	40
4 London Weather Centre	LWC	Urban	3778	5047	51.522	–0.112	43
5 St. James' Park	SJP	Urban	3770	5034	51.505	–0.131	5
6 Heathrow	LHR	Peri-urban	3772	5113	51.479	–0.451	25
7 Kew	KEW	Peri-urban	3775	5259	51.468	–0.316	5
8 Beaufort Park	BBP	Rural	3764	5592	51.390	–0.786	74
9 Wisley	WSY	Rural	—	5237	51.311	–0.476	38
10 Gatwick	GTW	Rural	3776	5271	51.152	–0.193	59

length of data to make hourly simulation files for peri-urban, urban and rural locations. These are LHR, LWC and GTW, respectively. The availability of data for these stations is reviewed in more detail in Appendix A2.2.

In the following section we examine how the daily average temperature data from LWC, LHR and GTW compare with the other sites in order to gauge their suitability to represent the three geographical areas.

3.1 Daily minimum and maximum temperatures

The average summer night minimum (T_{min}) and daytime maximum temperatures (T_{max}) at the weather sites are plotted in Figures 9 and 10 and tabulated in Table 6. The temperature statistics of the weather stations differ because of UHI effects, but also because of other factors such as the elevation of the site, latitude, distance from the coast and so on. However, the data are presented here in their 'raw' form, and no corrections have been made for station elevation.

Broadly speaking, night-time temperatures increase moving into the centre of the city, indicating the presence of the UHI. However, the data also indicates variations that are not associated with distance from the centre of the city. LWC is relatively warm compared to its nearest neighbour, SJP. This may be due to the fact that the SJP weather station is situated in the park itself. LHR is relatively warm compared to its nearest neighbours, which may be a consequence of the airport being an area of extensive hard-standing and intensive energy consumption. Although cooler at night than the central urban sites, LHR should perhaps be considered then to not be a true peri-urban site, but an 'intermediate UHI' urban site. Although GTW is also an airport site, T_{min} values are similar to those at the nearest rural site, WSY. This suggests that the presence of the airport may not be unduly affecting temperatures and this station can still be considered to be a true rural site.

The T_{max} temperatures differ to a much smaller extent, with the largest difference between the urban and peri-urban sites being around 0.5 °C. The T_{max} values also show no systematic geographical variation, which is consistent with the UHI being primarily a night-time effect. LWC has

(1) Rothamstead (2) High Beach Essex (3) Northolt

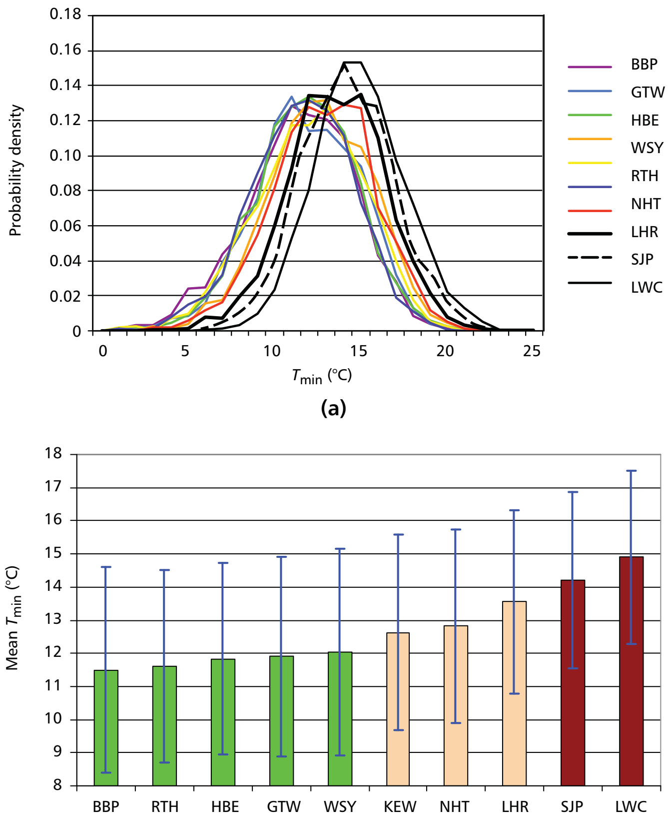
(4) London Weather Centre (5) London, St James' Park (6) London Heathrow

(7) Kew Gardens (8) Beaufort Park (9) Wisley

(10) Gatwick Airport

Figure 8 Aerial views of the ten BADC weather stations (©2011 Google)

a lower daytime average temperatures than SJP and the peri-urban sites. A feature of the LWC weather station is that it is a rooftop site. However, the fact that the night-time temperatures are still consistently higher than the other stations suggests this may not be the reason for the lower day-time temperatures and that these are due to the 'urban cool island' effect which is sometimes observed in cities during the day.



(a)

(b)

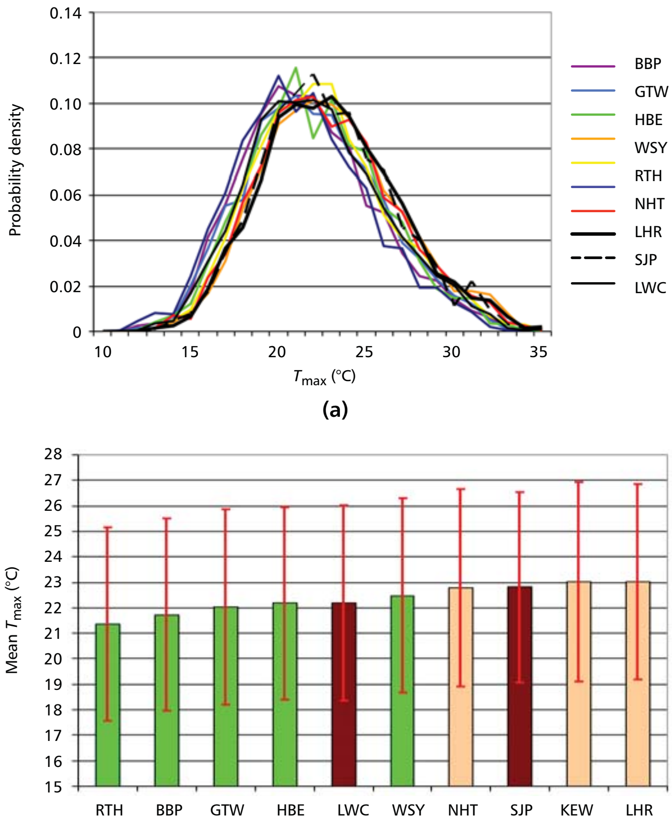
Figure 9 London (BADC) sites T_{min} data: (*a*) probability distribution functions and (*b*) mean and variances (bars are coloured according to geographical classification)

Table 6 Mean and variance values of the (daily) T_{min} and T_{max} probability distribution functions; data are listed in order of increasing T_{min} mean

Site	T_{min} (°C)		T_{max} °C	
	Mean	Variance	Mean	Variance
BBP	11.5	9.6	21.7	14.3
RTH	11.6	8.4	21.4	14.4
HBE	11.8	8.4	22.2	14.3
GTW	11.9	9.0	22.0	14.8
WSY	12.0	9.8	22.5	14.5
KEW	12.6	8.7	23.0	15.2
NHT	12.8	8.5	22.8	15.0
LHR	13.6	7.6	23.0	14.7
SJP	14.2	7.1	22.8	14.0
LWC	14.9	6.8	22.2	14.7

3.2 Selection of rural and urban sites

On the basis of the above analysis it was concluded that GTW and LWC provided usable data to represent rural and urban sites and pDSYs were produced for these sites for the three years identified for LHR*. Separate return periods have not been assigned to the additional sites, and those for LHR can be taken to be indicative.



(a)

(b)

Figure 10 London (BADC) sites T_{max} data: (*a*) probability distribution functions and (*b*) mean and variances (bars are coloured according to geographical classification)

3.3 Relationship between UHI intensity and warm weather

As discussed above, the UHI intensity tends to be largest at night under conditions of low wind speed and clear skies. With respect to thermal comfort and overheating risk, however, a key question is whether larger UHI intensities occur under conditions of warm weather.

Figure 11 shows a scatter plot of daily values of UHI intensity at LWC against both T_{min} and T_{max} temperature. There is very little correlation (although there is some indication of a weak correlation with T_{max}) indicating that neither warm night or warm daytime temperatures are necessary for the formation of strong urban heat islands. High values of UHI intensity can occur at any time of the year, and likewise low and even negative values of UHI intensity can occur at any time during the year. However, the conditions for strong UHI development — light winds and clear skies — often occur during heat waves, and so it is to be expected that strong heat islands may often occur during heat wave periods. This question is returned to in the next section

3.4 Differences in hourly data values between rural, peri-urban and urban sites

In order to demonstrate the differences in the pDSY files for the different locations, Figure 12 shows hourly time series of temperatures at the three locations for the 10 warmest spells ranked against WCDH at LHR. Also shown

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* For 2003, a different meteorological station (Charlwood), close to GTW, was used as data from GTW are not available for that year.

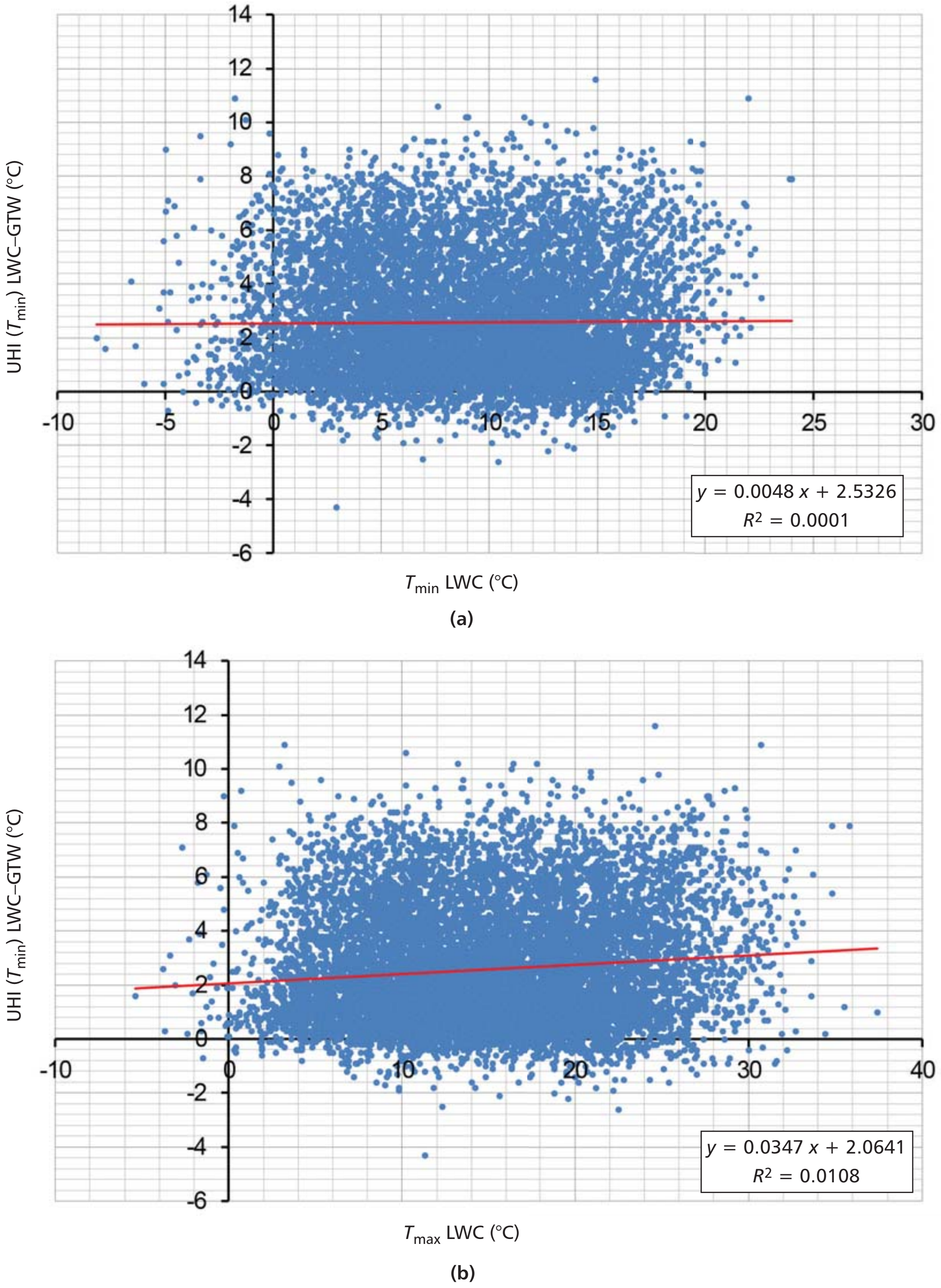


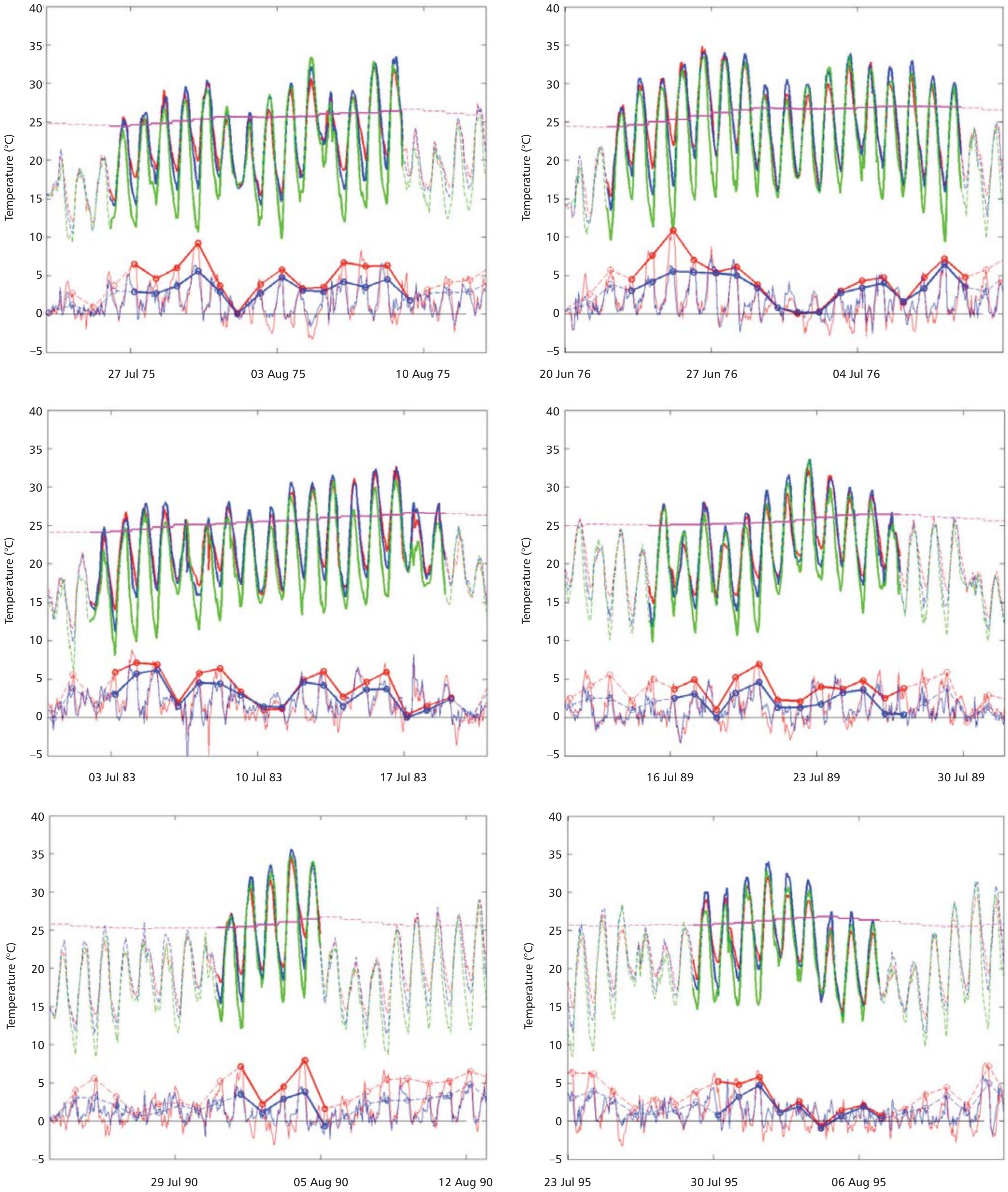
Figure 11 Correlation between daily values of UHI intensity at LWC relative to GTW with T_{min} and T_{max} at LWC; data from 1975–2006 (all seasons)

is the temporal variation of the UHI at LHR and LWC relative to GTW.

A number of features of the UHI can be seen in Figure 12. First, peak temperatures are very similar at all three sites. Secondly, the night-time UHI is consistent and coherent across these sites: on a given night GTW is nearly always the coolest site, LWC the warmest, and LHR somewhere in between.

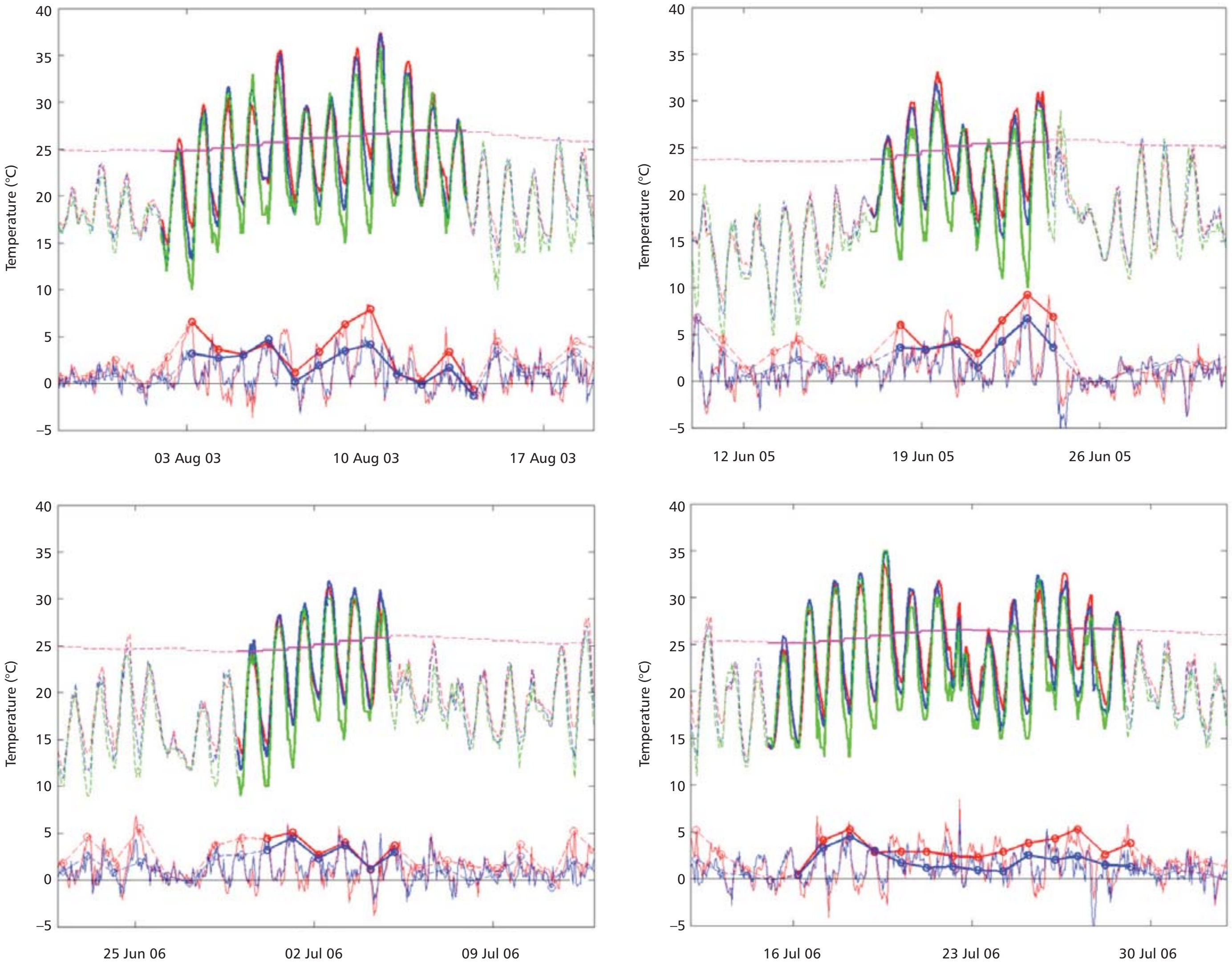
Figure 12 also provides some insight into the development of strong UHI events. A feature of many of the warm spells is that during periods when daily maximum temperatures are increasing, night minimum temperatures in the city increase at a similar rate but at the rural site increase at slower rate and in some cases are actually decreasing. This behaviour leads to a strong UHI intensity, and several of the warm spells have nights with particularly strong heat islands (e.g. >10 °C). These observations suggest that strong UHIs often occur during warm spells. Figure 13 shows that there is a suggestion in the data that high peak UHI intensities during warm spells are correlated to some extent with the warmth of the warm spell as expressed by WCDH. There does not appear, however, to be a similar correlation between average UHI intensity during the warm spells and WCDH, although the average UHI intensity during warm spells is around 1 °C higher than the seasonal mean.

These observations point to some fascinating aspects of temporal development of the UHI of London that are worthy of further research.



Legend: temperatures (upper graph): LWC (red), LHR (blue), GTW (green) (solid lines indicate period defined as the heatwave); UHI (lower graph): LWC (red), LHR (blue); fine line is hourly difference between site and GTW; circles and bold line gives daily T_{min} difference (plotted at hour of GTW T_{min})

Figure 12 Temperature time series for the 10 warmest heatwaves (ranked against WCDH) (*figure continues overleaf*)



Legend: temperatures (upper graph): LWC (red), LHR (blue), GTW (green) (solid lines indicate period defined as the heatwave); UHI (lower graph): LWC (red), LHR (blue); fine line is hourly difference between site and GTW; circles and bold line gives daily T_{min} difference (plotted at hour of GTW T_{min})

Figure 12 Temperature time series for the 10 warmest heatwaves (ranked against WCDH) (*continued*)

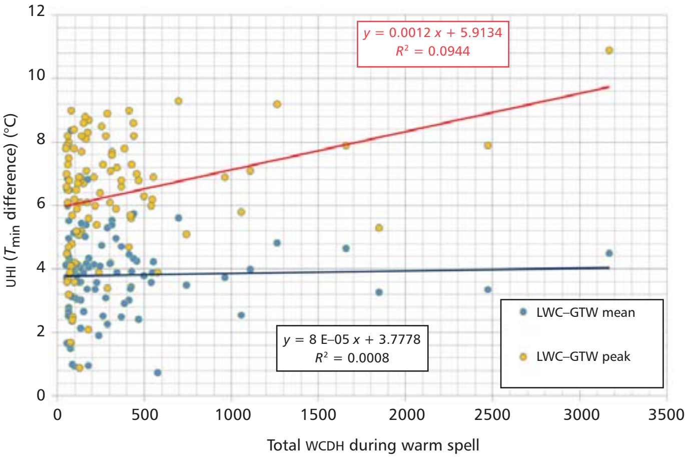


Figure 13 Correlation between UHI intensity at LWC relative to GTW and WCDH in the 100 warmest ranked heatwaves

4 Conclusions

This TM has presented and discussed new weather data sets created for the London area to be used with building simulation models to inform summertime design decisions.

It has been shown that there are significant variations in the characteristics of warm summers in London, both from year to year and between different locations due to microclimatic variations across the city.

It has been shown that while the current CIBSE Design Summer Year for London represents a 'near extreme' warm summer, as originally intended, several summers in the past few decades have been warmer, and there is a significant probability that summers as warm or warmer will occur in the future. Furthermore, the implications of climate change are that the likelihood of such warm summers will increase markedly in the next few decades.

It is recommended, therefore, that for building design projects where the implications of the building overheating are critical for the usability of the building, and where critical design or investment decisions will be based on the results of a simulation-based overheating analysis, that the warmer summers presented here should be used to inform those decisions. The weather data should be selected based on an appropriate level of risk and probability for the building which can be established through informed discussion between the design team, the client and the other stakeholders involved in the project.

A conceptual model was suggested through which a level of risk can be established for the weather data prior to building simulation modelling being carried out. However, it was noted that this conceptual model is a simple one and that different types of building will respond in different ways to climatic conditions. It is therefore recommended that several years of weather data be used in the overheating risk assessment. The set of three warm years accompanying this TM will enable designers to explore a broader range of climate variability that would be possible by considering only a single DSY.

An examination of weather data from different weather observation stations across London has shown that at any one time there can be significant variations in temperatures in different parts of the city. Whereas peak daytime temperatures are similar everywhere (and can even be lower in the city centre), temperatures during other parts of the day, and particularly at night, are significantly lower in rural areas and less densely developed urban areas because of the urban heat island effect. These climate differences will affect the results of overheating risk assessment modelling and weather data from the most appropriate meteorological station for the site of the building under examination should be used.

Weather data for three locations in and around London have been provided to accompany this TM: London Weather Centre (LWC), London Heathrow airport (LHR) and Gatwick airport (GTW). LWC provides the best currently available weather station to represent central London, e.g. as defined by the Mayor's Central Activity Zone (CAZ); LHR can be considered representative of urban areas outside the CAZ; GTW can be considered representative of rural areas around London. The relative sparsity of temperature observations stations in the London area makes precise definitions of these boundaries difficult and where there is any doubt conservative choices should be made, i.e. to use the next warmest more central weather station. There also remain uncertainties regarding the weather data provided, because of microclimatic factors at LWC (a rooftop observation location) and at the two airport locations. However, the weather data currently available suggests that these microclimatic factors are of secondary importance to the macroclimatic factors associated with the London urban heat island and that these macroclimatic variations are captured by the weather data provided.

At present it is not possible to provide more detailed guidance on these issues but it is hoped that the weather data sets discussed here provide a substantial step forward with respect to the level of detail in which macroclimatic and climate change factors can be taken into account for the summertime design of buildings in London.

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Appendix A1: Methodology of weather file generation

This appendix describes how the weather data used for the generation of the weather years was sourced, checked and treated for missing data.

A1.1 Data format

All of the original raw data used in the weather files was supplied by the UK Meteorological Office (UKMO). It was checked for spurious values and quality assured by UKMO.

The meteorological variables contained in the weather year files are:

— present weather code
— cloud cover
— dry bulb temperature
— wet bulb temperature
— atmospheric pressure
— wind speed and direction
— global horizontal solar irradiation
— diffuse horizontal solar irradiation

As described in the main body of this TM, data were required for three sites: London Weather Centre (LWC), London Heathrow Airport (LHR) and Gatwick Airport (GTW) for three years: 1976, 1989 and 2003.

A1.1.1 Synoptic data

For LWC and LHR, synoptic data (all variables excepting solar irradiation) were provided for all three years. For GTW, synoptic data were provided for 1976 and 1989 but were not available for 2003; for this year, data from the nearby weather station at Charlwood (CHW) were used to represent GTW.

Note that the data for the LHR 1989 weather year are equivalent to the synoptic data in the former (2005 issue) London DSY. This is not true of the solar data, which are discussed below.

A1.2.2 Solar data

In the 2005 issue of the CIBSE DSY for London, solar irradiation values were calculated from cloud cover observations using empirical correlations. This was done in order to ensure consistency with the weather year data provided by CIBSE for 14 sites, which in the main had no solar observation sites nearby. However, in the 2002 issue of the CIBSE DSY (see also CIBSE Guide J (CIBSE, 2002)) direct observations of global and diffuse irradiation were used. It has been found that the empirical correlations have limited accuracy in reproducing the observations and, in particular, peak values are lower in the calculated versus the observed data. Hence, for the TM49 weather years, a decision was made to use observed solar irradiation values as far as possible.

Global and diffuse solar irradiation is only measured at a few sites in the UK but, until 2002, measurements of both global and diffuse irradiation were made at the UKMO weather station at Beaufort Park in Bracknell, approximately 50 km to the west of London. This data set is the most comprehensive solar observation data set available for London and was used for the 2002 issue of the London DSY and is described in CIBSE Guide J (CIBSE, 2002). Although not coincident with the location of the synoptic observations, this data set was used for the weather years for all three sites for 1976 and 1989, due to lack of alternative observations. The reason for doing this rather than using data synthesised from the synoptic observations was that it was felt that the error produced by the geographical separation of the synoptic and solar observation sites was likely to be smaller than the error produced in using empirical correlation models (Muneer, 2004).

For 2003, measurements of global irradiation were available for LWC and for Charlwood (CHW) from April onwards. The observations from LWC were used for the weather years for LWC and LHR, and for GTW until April. For GTW, the observations from CHW were used from April onwards. No measurements of diffuse irradiation were available for the London area for 2003. Instead, values of diffuse irradiation were calculated by Professor Tariq

Table 7 Missing data amounts in hours (zero unless otherwise specified)

Site	Year	Present weather code	Dry bulb temperature	Wet bulb temperature	Cloud cover	Pressure	Wind direction	Wind speed
LWC	1976	—	—	5	—	3-hourly	129	—
	1989	—	—	—	—	—	6	2
	2003	—	—	11	3	—	2	3
LHR	1976	—	—	84	—	3-hourly	0	—
	1989	—	—	—	—	—	2	—
	2003	—	—	—	—	—	199	197
GTW	1976	—	—	285	—	—	401	—
	1989	—	—	—	—	—	181	—
CHW*	2003	206	77	77	313	—	341	359

* Charlwood data. Excludes points prior to 24th March; all data missing up to that point.

Table 8 Dates of long runs of missing data (more than 12 contiguous hours)

Site	Year	Nature, numbers of hours and dates of long gaps
LWC	1976	None
	1989	None
	2003	None
LHR	1976	None
	1989	None
	2003	Wind speed and direction: — 137 hours, starting 01-Jan-2003, ending 06-Jan-2003 16:00:00 — 52 hours, starting 07-Jan-2003 08:00:00, ending 09-Jan-2003 11:00:00
GTW	1976	Wind direction: 15 hours, starting 05-Dec-1976 21:00:00, ending 06-Dec-1976 11:00:00
	1989	Wind direction: 13 hours, starting 19-Jan-1989 22:00:00, ending 20-Jan-1989 10:00:00
CHW	2003	All variables 1980 hours, starting 01-Jan-2003, ending 24-Mar-2003 11:00:00 Present weather code: — 23 hours, starting 4-Mar-2003 12:00:00, ending 25-Mar-2003 10:00:00 — 18 hours, starting 10-Jul-2003 07:00:00, ending 11-Jul-2003 — 37 hours, starting 11-Jul-2003 12:00:00, ending 13-Jul-2003 — 18 hours, starting 13-Jul-2003 07:00:00, ending 14-Jul-2003 — 20 hours, starting 14-Jul-2003 07:00:00, ending 15-Jul-2003 02:00:00 — 23 hours, starting 15-Jul-2003 05:00:00, ending 16-Jul-2003 03:00:00 — 16 hours, starting 30-Sep-2003 18:00:00, ending 01-Oct-2003 09:00:00 — 29 hours, starting 07-Oct-2003 07:00:00, ending 08-Oct-2003 11:00:00 Wet and dry bulb temperature and pressure: — 179 hours, starting 10-Jul-2003, ending 17-Jul-2003 10:00:00 — 16 hours, starting 30-Sep-2003 18:00:00, ending 01-Oct-2003 09:00:00 — 28 hours, starting 07-Oct-2003 07:00:00, ending 08-Oct-2003 10:00:00 Cloud cover: — 1980 hours, starting 01-Jan-2003, ending 24-Mar-2003 11:00:00 — 179 hours, starting 10-Jul-2003, ending 17-Jul-2003 10:00:00 — 16 hours, starting 30-Sep-2003 18:00:00, ending 01-Oct-2003 09:00:00 — 28 hours, starting 07-Oct-2003 07:00:00, ending 08-Oct-2003 10:00:00 Wind speed and direction: — 240 hours, starting 01-Aug-2003, ending 10-Aug-2003 23:00:00 — 18 hours, starting 30-Sep-2003 18:00:00, ending 01-Oct-2003 11:00:00 — 51 hours, starting 07-Oct-2003 07:00:00, ending 09-Oct-2003 09:00:00

Muneer and co-workers at Napier University, using a method based on sky clearness index (Muneer, 1987).

A1.1.3 A note on leap years

1976 was a leap year. In order to provide consistent 8760 entry files, for this year the data for 31 December was omitted and date entries kept as for a non-leap year (e.g. 29 February becomes 1 March, etc.).

A1.2 Treatment of missing data

The source data set provided by UKMO contained some missing data points (Table 7). Some missing data is typical in meteorological data sets due to instrument malfunction, station closures, or data failing to meet quality assurance criteria.

For runs of missing data of up to 12 contiguous hours in length, missing data points were filled with values interpolated from measurements at either end of the run of missing data. For dry bulb temperature, wet bulb temperature and atmospheric pressure, a cubic spline interpolation method was used. For cloud cover, wind speed and wind direction linear interpolation was used. For wind direction, the convention used was to interpolate in the direction of smallest wind angle difference; e.g. a missing data point with wind direction values either side of 350° and 30° would be interpolated as 10° rather than 190°. Wind direction at hours with wind speed measured zero was also interpolated using neighbouring data. Although it is not normally possible to measure wind direction reliably at zero or very low wind speeds, this interpolation was done in order to provide a continuous time series of wind directions.

For runs of missing data longer than 12 hours (Table 8), data were not interpolated but substituted from one of the other sites:

- LWC: there were no long runs of missing data.
- LHR: data were substituted from LWC.
- GTW: data were substituted from LHR, if available, otherwise from LWC.

For each method for filling missing data points, a 'data code' was noted in the final data file to indicate where there were missing data and the filling method used.

A1.3 Climate change data

Climate change-adjusted versions of the weather years for each site were produced using a form of 'morphing' (Hacker et al., —) for three time periods: the 2020s, the 2050s and 2080s (2071–2090) using the UKCP09 Climate Change Projections for the United Kingdom (Jenkins et al., 2009).

As noted in the main body of this TM, the UKCP09 projections provide climate changes for three different emissions scenarios (Low, Medium and High) and different levels of probability.

For each site and historical weather year, morphed years were provided for 10th, 50th and 90th percentile probabilities and the following emissions scenarios and time periods:

- 2020s (2011–2040): High emissions
- 2050s (2041–2060): Medium and High emissions
- 2080s (2071–2090): Low, Medium and High emissions

The reason for not considering all emission scenarios in each time period was to reduce the number of analysis files to manageable numbers. The rationale for the choice was that: in the 2020s there is little difference between the projections for each emissions scenario; for the 2050s, the Medium and High emissions scenarios are currently viewed to be more likely; for the 2080s all three emissions scenarios were included for completeness.

Appendix A2: London weather data sites — data availability

In section 3, an analysis of data from a number of weather stations within and outside London was presented. The sites differ in the scope of data available and the time periods for which observations were made, see Figure 14. All the sites have some records for daily maximum and minimum temperatures. Some have hourly observations of temperature and observations of other climate variables as well. The analysis in this report considered available data to the end of 2006.

All of the sites have reasonably long periods of daily observations, although only four have records spanning the whole period (LHR, RTH, SJP and WSY) and three stop short of 2006 (BBP, GTW, KEW) due to station closures.

Several of the sites have periods of hourly weather data, but only three have records of the length of the order of two decades or more (GTW, LHR and LWC). The lack of commonality in the time periods of weather records at Met Office weather stations in and around London combined with station moves and closures makes interpretation of climate trends and UHI effects in the capital problematic.

To create weather years requires hourly data for a number of variables, but most critically dry bulb temperature, wet bulb temperature, and cloud cover or sunshine hours. In addition, it is necessary that there are not large amounts or runs of missing data. It has been determined that only four of the sites meet these criteria: GTW, NTH, LHR and LWC, making these the only candidate sites for the pDSYs (Figure 15).

LHR has available data from 1949 until the present day. LWC has hourly data available from 1975 until 2005, although it was found there is a noticeable dip in quality at the end of period and sunshine hours data are no longer available. GTW has a period of data from 1971–1997, but not thereafter. This was due to the closure of the Met Office station at that time and replacement with an automatic weather station which does not report a full set of variables. However hourly temperature data recorded to integer resolution is available from 1997. NTH does have reasonable hourly data since 1998 and so provides a potential substitute for GTW but as noted above represent a different climatological classification, being peri-urban versus rural, as well as being on the opposite side of London.

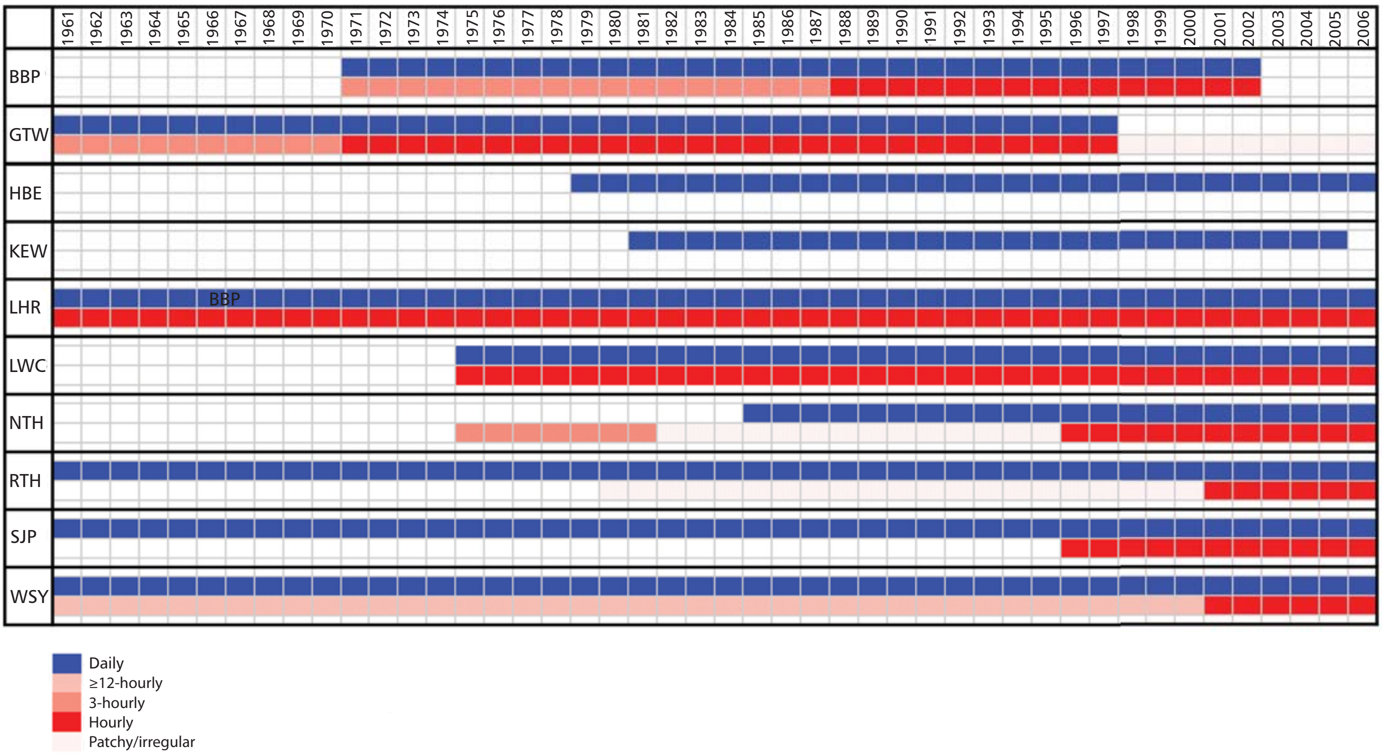

Figure 14 London (BADC) sites: data availability

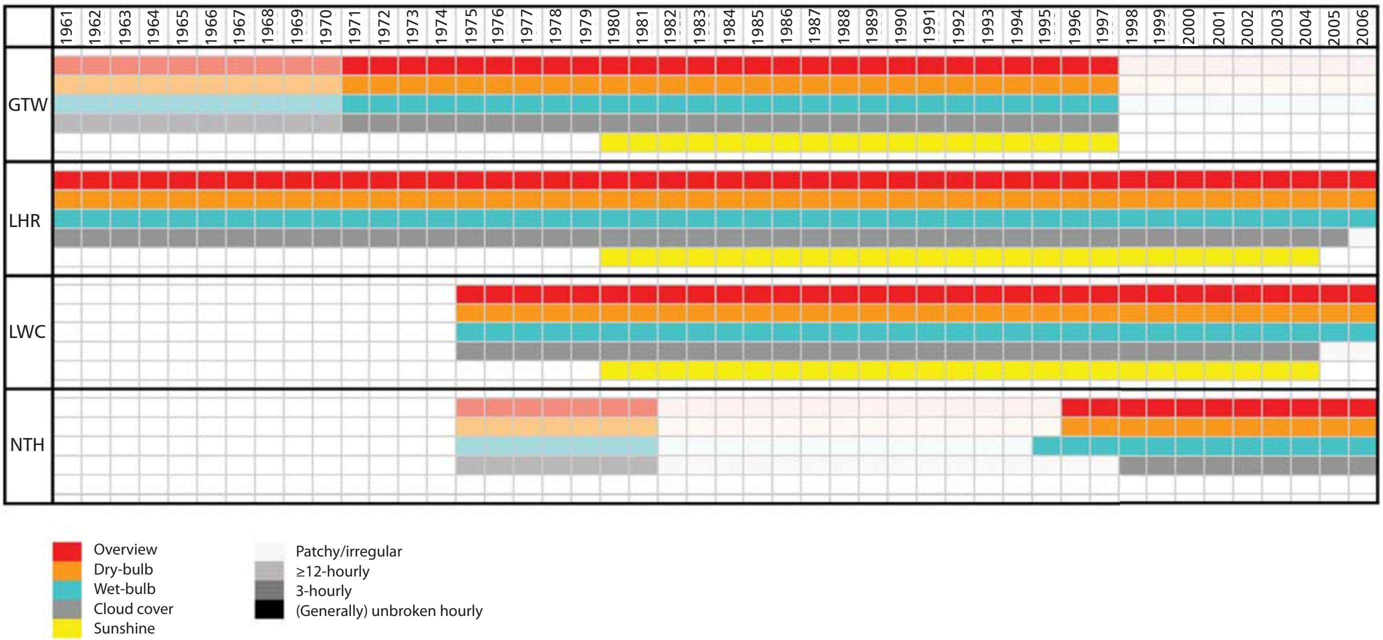

Figure 15 Sites deemed suitable for the generation of hourly weather years and the corresponding data availability of the critical variables