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Constructing design weather data for future climates

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We develop a method, here called 'morphing', to produce design weather data for building thermal simulations that accounts for future changes to climate. Morphing combines present-day observed weather data with results from climate models. The procedure yields weather time series that encapsulate the average weather conditions of future climate scenarios, whilst preserving realistic weather sequences. In this sense the method 'downscales' coarse resolution climate model predictions to the fine spatial and temporal resolutions required for building thermal simulations. The morphing procedure is illustrated by application to CIBSE design weather years and climate change scenarios for the UK. Heating degree days calculated from the weather series morphed to future climates show a marked reduction compared to present day, by an amount that agrees well with results calculated directly from the climate model. This agreement gives confidence that the morphing technique faithfully transforms the weather sequences.

Practical application: There is overwhelming consensus amongst the scientific community that the Earth's climate is warming. This warming will have implications for building services in the UK that should be considered now. This article describes a method for producing weather data with best current estimates of future climate that can be used to quantify the risk of building overheating.

1 Introduction

The scientific consensus is that Earth's climate is warming and that a measurable part of the warming seen over the last 150 years is due to anthropogenic emissions of carbon dioxide.[1] This climate change presents challenges to the building designer, first because energy use should be reduced in order to limit the extent of future human-induced (anthropogenic) climate change and second, because buildings designed today need to remain robust under the warming climate.

Thermal simulation of the building coupled to an HVAC system model provides an important tool in analysing the performance of both the building envelope and passive and active systems for heating and cooling. External weather and climate plays a role in this interaction, particularly in setting the solar heat gain, incoming ventilation air temperature, and conductive and convective heat exchanges through the building envelope. To quantify these interactions it is necessary to carry out thermal simulation forced by design weather data, typically at a resolution of an hour or less. It is necessary to consider a range of weather conditions and so simulations are typically run for a whole year's data—a 'weather year'.

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The present paper has three aims. The first, addressed in Section 2, is to review methods for calculating design weather data from simulated future climate scenarios. The second aim, addressed in Section 3, is to develop a practical method to produce design weather data for future climates. In Section 4 the baseline design weather years and climate scenarios for the UK to be considered are described. The third aim, which is addressed in Section 5, is to produce design weather data under different future climates and to examine characteristics of the weather data. In Section 6 the conclusions are given.

2 Constructing design weather data for future climate scenarios

How can design weather data be produced for future, warmer, climates? There are two general methods. The first is so-called 'analogue scenarios', which use present-day weather information from a location distinct from the study site but with a climate similar to the projected climate of the study site. In practice, analogue scenarios for building simulation are difficult to find because of the importance of solar radiation, which depends on latitude, and does not change appreciably under climate change scenarios.

The second method, which is used here, obtains the future climate from global circulation models. Practical constraints on computer power mean that these global circulation models produce data only at a coarse resolution (a typical horizontal resolution is 300 km × 300 km and 24 h in temporal resolution). But assessing the impact of climate change on building performance requires local weather data at higher temporal resolution. The global circulation model output therefore has to be 'downscaled'. There are a number of methods for achieving downscaling.

2.1 Dynamical downscaling

A first method is dynamical downscaling, where detailed regional climate models that resolve small-scale atmospheric processes are run over a limited spatial area and with better representation of, for example, topography and mesoscale processes. This method is however computationally expensive and its use on building design projects is unlikely to be practical.

2.2 Stochastic weather generation

A second approach is to use a 'weather generator', where synthetic weather time series are generated using empirically 'derived statistics'.[2,3] Whilst this method is computationally cheap, it does require large data sets to 'train' the model to give appropriate statistics and fix unknown model coefficients, and the weather series it produces may not always be meteorologically consistent.

2.3 Interpolation

A third method is to interpolate, in space and time, the output from coarse resolution climate models. This method is not generally used for climate change scenario generation.[1] A significant disadvantage of this method is that climate model output is often biased. This means that even the present day climate may be biased, for example warmer than measured. It is generally assumed that any changes to the climate caused by anthropogenic forcing are then biased by the same amount so that the changes in climate are correct. It is for this reason that climate change scenarios generally quote changes rather than absolute values.

2.4 Time series adjustment: morphing

A fourth method of downscaling, and the one that is adopted here, is to adjust present-day design weather data by the changes to climate forecast by global circulation models and regional climate models. We call the method 'morphing'. This method has several practical advantages. First, the 'baseline climate' is reliable, because it is the climate of the present-day weather series. Second, the resulting weather sequence is likely to be meteorologically consistent. Third, spatial downscaling is achieved because the present-day weather series is obtained from observations at a real location. One limitation of the method is that the morphed design weather data for the future climate then has the character and variability of the present-day climate. But the future climate may have a different character. For example, average temperatures during the summer across England are expected to increase. Does this average temperature increase through a constant warming over the whole period, or does the frequency of heatwaves increase during the summer? This is a topic of active research within the climate change community, and there is no firm consensus at present.

We have argued then, that for the purpose of thermal simulation for real building design, the morphing method for producing design weather data under future climates is practical and gives future weather sequences that are both meteorologically self-consistent and a future climate that is consistent with the current best projections.

3 The morphing procedure

In this section the algorithms used to morph the present-day observed weather files to produce future climate weather files are described. The starting point is a set of high-resolution quality-assured weather data for the site. These data are then morphed using predictions from either a global or a regional climate model giving changes to monthly-mean values of the weather variables.

3.1 The baseline climate

The 'baseline climate' is defined as the present-day weather sequence averaged over a number of years. It is important to define a baseline climate in the morphing procedure for the following reason. Some of the changes listed in climate change scenarios are quoted as fractional changes relative to a baseline climate. And the baseline climate may be quite different to the values experienced in particular years. The World Meteorological Organization recommends using an averaging period of 30 years to define a climate baseline, and using the period 1961–1990 to define the 'present climate' baseline. The averaging period for the baseline climate should be the same period as the baseline used for the climate change scenarios. Clearly the availability of data might constrain what is done in practice.

The form of baseline climate depends on the form of the data in the climate change scenarios. Here we will use climate change scenarios that list changes to monthly-mean weather variables. Hence, the baseline climate must be calculated separately for each month, as follows. For each variable, x_0, in the present day weather record (denoted with subscript '0'), and for each month m in the calendar year, the baseline climatological value of x_0 for month m (denoted by $\langle x_0 \rangle_m$) is defined to be variable x_0 averaged over month m for all the averaging years; symbolically:

$$\langle x_0 \rangle_m = \frac{1}{24 \times d_m \times N} \sum_{N \text{ years}} \sum_{\text{month } m} x_0$$

where N is the number of years in the averaging period and d_m is the number of days in month m and the 24 comes from averaging the hourly measurements over the 24 hours of each day. These monthly means provide the baseline climate on which the morphing is based.

3.2 Algorithms for morphing the weather data

The morphing used here involves three generic operations: 1) a shift; 2) a linear stretch (scaling factor); and 3) a shift and a stretch.

1) A shift by Δx_m is applied to the present-day climate variable x_0 by

$$x = x_0 + \Delta x_m \tag{1}$$

for each month m, where Δx_m is the absolute change in the monthly mean value of the variable for the month m. The new monthly mean of the variable is then $\langle x \rangle_m = \langle x_0 \rangle_m + \Delta x_m$, and hence the climate has been shifted from baseline by Δx_m. The monthly variance of the variable is unchanged.

2) A stretch of α_m is applied by

$$x = \alpha_m x_0 \tag{2}$$

where α_m is the fractional change in the monthly-mean value for month m. This method changes the monthly mean to $\langle x \rangle_m = \alpha_m \langle x_0 \rangle_m$, confirming that the desired mapping has been made. The variance is also changed and becomes $\langle \sigma^2 \rangle_m = \alpha_m^2 \langle \sigma_0^2 \rangle_m$.

3) A combination of shift and stretch is obtained by

$$\begin{aligned} x &= x_0 + \Delta x_m + \alpha_m \times (x_0 - \langle x_0 \rangle_m) \\ &= \langle x_0 \rangle_m + \Delta x_m + (1 + \alpha_m)(x_0 - \langle x_0 \rangle_m) \end{aligned} \tag{3}$$

The new monthly mean is then $\langle x \rangle_m = \langle x_0 \rangle_m + \Delta x_m$ and the new monthly variance is $\langle \sigma^2 \rangle_m = \alpha_m^2 \langle \sigma_0^2 \rangle_m$.

A shift is used when the climate change scenario lists an absolute change to the mean. A stretch is used when there is a change to either the mean or variance quoted as a percentage or fractional change rather than an absolute increment or when the variable can be switched off altogether, as in for example, solar irradiance, which is zero at night. A combination of a shift and a stretch is used when both the mean and the variance need to be changed, for example when changing temperature to reflect changes in both the daily mean and the maximum and minimum daily temperatures. The details of the application of the morphing to the CIBSE weather years is reported in the Appendix.

4 Application to the UK

Now that the principles used here to produce the weather data in future climates have been outlined, we describe next the sources of the data.

4.1 CIBSE Guide J weather years

The Charted Institution of Building Services Engineers (CIBSE) Guide J[4] provides the present-day weather data used as the basis of this study. The measurements were taken in London, Manchester and Edinburgh, and were recorded hourly (or synthesized in the case of missing data). Table 1 shows the variables recorded in the CIBSE weather data.

CIBSE Guide J discusses combinations of the present-day weather data that give two types of weather year for building simulation. Test Reference Years (TRYs) are synthesized to give an ‘average year’ of weather. The TRY consists of actual month-long weather sequences for each of the 12 calendar months, but the month-long sequences come from different years. The month-long sequences used in the TRY were selected so that the average dry bulb temperature was closest to the baseline climate mean dry bulb temperature for that month. In this way the TRY has the average January, followed by the average February, etc. TRYs are designed principally for calculating energy use in HVAC systems. The Design Summer Year (DSY) is the year when the mean dry bulb temperature during April to September is closest to a near extreme for the baseline climate, defined as the middle of the upper quartile of the distribution of dry bulb temperatures from April to September. The DSY are intended principally for use in assessing overheating risk in naturally ventilated buildings.

Table 1 Weather variables recorded in the CIBSE weather data

Variable	Guide J: symbol (units)	Notes
1 Global solar irradiation on horizontal	gsr (W/h per m^2)	
2 Diffuse solar irradiation on horizontal	dsr (W/h per m^2)	
3 Sunshine duration: radiation site	sf_r (h)	
4 Sunshine duration: synoptic site	sf_s (h)	
5 Cloud cover	cc (oktas)	
6 Dry-bulb temperature	dbt (°C)	
7 Wet-bulb temperature	wbt (°C)	
8 Atmospheric pressure	atpr (mbar)	
9 Wind speed	ws (m/s)	Converted from speed logged in whole knots
10 Wind direction (degrees clockwise from true north, to nearest 10°)	wd (degrees)	Degrees clockwise from true north, to nearest 10°
11 Rain amount	ra (mm)	mm
12 Rain duration	rd (h)	
13 Present Weather Code	pwc	(0–99) (see Guide J for details)
14 Solar altitude: degrees from horizontal	solalt (degrees from horizontal)	Computed from Yallop's algorithm, at HH −30 min

4.2 UKCIP02 climate change scenarios for the UK

As explained earlier, in the morphing procedure described here the CIBSE Guide J weather data are adjusted to reflect the projected changes to the climate. The climate change projections used to do this were the UK Climate Impacts Programme (2002; hereafter UKCIP02) regional model climate simulations for the UK.[5] These projections provide mean-monthly values of climate variables on a 50 km × 50 km model grid for three time slices for the twenty-first century: 2011–2040 ('2020s'), 2041–2070 ('2050s') and 2071–2100 ('2080s') under four scenarios for anthropogenic emissions of greenhouse gases. The climate variables contained in the projections are given in Table 2. These projections were constructed through a sequence of steps, as follows.

Table 2 Variables in the UKCIP02 climate change projections

Variable	Symbol	Baseline climate 1961–1990 Units for variables	Climate-change scenarios 2020s, 2050s, 2080s Type of change and units:
Maximum temperature	TMAX	°C	absolute, °C
Minimum temperature	TMIN	°C	absolute, °C
Daily mean temperature	TEMP	°C	absolute, °C
Total precipitation rate	PREC	mm/month	percentage, %
Snowfall rate	SNOW	mm/month	percentage, %
10 m wind speed	WIND	M/s	percentage, %
Relative humidity	RHUM	%	absolute, %
Total cloud in longwave radiation	TCLW	%	absolute, %
Net surface longwave flux	NSLW	W/m^2	absolute, W/m^2
Net surface shortwave flux	NSSW	W/m^2	absolute, W/m^2
Total downward surface shortwave flux	DSWF	W/m^2	absolute, W/m^2
Soil moisture content	SMOI	mm	percentage, %
Mean sea level pressure	MSLP	hpa	absolute, hPa
Surface latent heat flux	SLHF	W/m^2	absolute, W/m^2
Specific humidity	SPHU	g/kg	percentage, %

The first step is to make projections of emission of greenhouse gases and the build-up of these gases in the atmosphere. UKCIP02 considers four emissions scenarios taken from the 'Intergovernmental panel on climate change special report on emissions scenarios'[6]: low, medium-low, medium-high and high. These scenarios range from a 'sustainable' future with decreasing greenhouse gas emissions from mid-century onwards (low), to an intensive fossil fuel use future with greenhouse gas emissions at over three times present levels by mid-century onwards (high) (details are given in Section 3.1 of UKCIP02). These emissions scenarios represent a set of possible futures: at present no single scenario can be considered to be any more likely than any other.

The second step is to run a computer simulation to predict how the climate is likely to change under the four greenhouse gas emissions scenarios. The type of model used to do this is similar to that used for weather prediction. The modelling process used in UKCIP02 involved several stages. First, a global circulation model of the atmosphere and oceans, HadCM3, was run for a baseline period from 1961 to 1990 and then as a climate prediction from 1990 to 2100 under the four emissions scenarios. Second, the results of these runs were used to provide boundary conditions for a model of the global atmosphere only, HadAM3, which has higher spatial resolution than HadCM3. These HadAM3 runs then each provide data for 1990–2100 for each of the emissions scenarios. Third, the results from HadAM3 were used to provide boundary conditions on a higher-resolution model of the UK, HadRM3, which has a resolution of 50 km. This regional model is required because global circulation models give poor predictions of local climate as they cannot resolve local weather effects produced by topography, proximity to coastlines, and other factors determining regional climate.

Simulations using the regional model are computationally expensive, and so simulations were only performed for the periods 1961–1990 and 2071–2100, and only under medium-high and medium-low scenarios. The simulation for 1961–1990 provides the baseline climatology for the scenarios. This simulated baseline climate shows some differences from the observed climate over this period. Hence the climate projections are presented as changes between the simulated future climate and the simulated baseline climate. The errors associated with the simulated baseline climate provide a motivation for using the morphing method developed here, rather than using the simulated future climate directly. Projections for the remaining two time slices (2020s and 2050s) and the remaining emissions scenarios were obtained by linearly scaling each variable in the climate changes for medium-high scenario in the 2080s by a factor called the pattern scaling factor, defined to be the ratio of global temperature change in the new scenario to global temperature change in the medium-high scenario 2080s time slice. These factors are shown in UKCIP02.[4]

The projected climates under the different emissions scenarios do not diverge significantly until the 2030–2040s. The reason is that the lifetime of carbon dioxide in the atmosphere is about 100 years, so that atmospheric concentrations up to the 2040s are largely governed by past emissions. There is now an appreciable amount of climate change potential regardless of what is done now to reduce future emissions. By the 2080s the climate sensitivityin the high scenario is around 20% greater than in the medium-high scenario, whereas the climate sensitivity in the low scenario is around 40% less. Even in the most 'sustainable' future scenario an appreciable level of climate change is still projected to occur.

4.3 Application of the morphing procedure

The aim is to derive weather data for future climates that encapsulates the projections of UKCIP02 for monthly-mean climate, and therefore the morphing coefficients were applied to the CIBSE data on a month-by-month basis. A sinusoidal smoothing filter was applied across a 24-h period at the beginning and end of each month to avoid discontinuities in the time series.

The range of years covered by the Guide J data does not correspond exactly with the 1961–1990 baseline used in UKCIP02. The range of data years falls in the latter part of this period and somewhat beyond the end of the baseline period for UKCIP02. Given that there has been a global warming signal over that period, the observed climate baseline is therefore slightly too warm, and the morphed data might overestimate slightly the level of climate change for each future time slice. In order to be consistent with CIBSE Guide J, however, we have chosen to define climate baselines using the complete set of CIBSE data for each location.

The first stage in the procedure is to calculate the climate baseline. The nature of the source data means that the following quantities are required: mean solar irradiance on the horizontal for each month, $\langle gsr_0 \rangle_m$; and mean monthly daily average, minimum and maximum temperatures $\langle dbt_0 \rangle_m$, $\langle dbt_{0\,\min} \rangle_m$, $\langle dbt_{0\,\max} \rangle_m$. Having calculated the baseline climate, the second stage is to morph the sequences of each weather variable given in the CIBSE data using shifts and stretches. Details of the algorithms of the morphing for each variable are listed in the appendix.

Once the algorithms have been set up it is a simple matter to transform any weather year for any time slice or any emissions scenario. This procedure has been applied to each year of data from the CIBSE records for each location (London, Manchester, Edinburgh), for each of the four emissions scenarios, for each of the three time slices (2020s, 2050s, 2080s).

5 Results

5.1 Characteristics of the UKCIP02 climate scenarios at the weather year sites

We focus now on London, Manchester and Edinburgh: the sites of the CIBSE Guide J weather data. The climate change values for London and Manchester were obtained from the UKCIP02 climate change projections by taking averages over the four computational grid cells representing the cities. The cells used were: London: cells 394, 395, 415, 416; Manchester: cells 294, 295, 313, 314. The variation in the climate change projections across the four London grid boxes is relatively small. There are more appreciable variations across the four Manchester grid boxes as these encompass both the northwest maritime climate and the southwestern portion of the Pennines. For Edinburgh the local variation in topography and coastline in the model meant that it did not make sense to take a spatial average and a single cell was used (cell 198).

Of particular interest to the present application are increases in surface air temperature. Figure 1 shows the climate change projections for changes to maximum daily temperature, TMAX, for London, Manchester and Edinburgh, for the 2080s under the medium-high emissions scenario. Maximum changes to TMAX under medium-high emissions occur in August for London at 5.9°C. The increases in summer and autumn temperatures are larger than in winter and spring, and the changes are more pronounced in London than in Edinburgh.

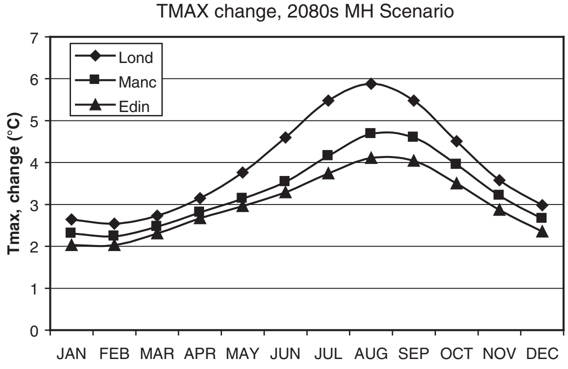

Figure 1 Variation in change to maximum daily temperature, TMAX, with month in the 2080s under the medium-high emissions scenario

Minimum and maximum daily temperatures are projected to change by slightly different amounts, which leads to changes in diurnal temperature range as shown in Table 3. The most appreciable change is in summer, where there is a positive increase in diurnal range by a degree or so. This is due to greater summertime warming during the day than during the night. In winter there is a small decrease in the diurnal range, in this case because there is greater warming during the night than in the day.

The changes in all temperature variables (TMAX, TMIN and TEMP) for Edinburgh and Manchester are quite well correlated, with Edinburgh temperature changes being 90 ± 2% less than those for Manchester. Changes for London are larger and are less well correlated with the other two sites. Temperature changes in Manchester are lower than those in London by around 20% in summer and 10% in winter. The curves for the 2020s and 2050s are linearly proportional to the 2080s because the climate change projections for 2020s and 2050s were obtained by pattern scaling the results from simulations of the 2080s. On applying the pattern scaling factors (derived from Table 3 in UKCIP02 p. 23), the largest change to TMAX in UKCIP02 is 7.0°C, which occurs for London in August in the 2080s under the High emissions scenario.

Examples of temperature variation for January and July for the present day and 2080s under medium high emissions are shown in Figure 2. The main effect of the morphing is to shift the timeseries up by the shift given by the UKCIP02 scenario, but note that the diurnal range has also been slightly altered (this is most noticeable in the July data series; *cf*. Table 3).

Table 3 Changes in diurnal range in °C for London, Manchester and Edinburgh for Winter (DJF), Spring (MAM), Summer (JJA) and Autumn (SON) in the 2080s under medium-high emissions

	London	Manchester	Edinburgh
DJF	−0.1	−0.26	−0.19
MAM	0.36	0.13	0.19
JJA	1.3	0.89	0.77
SON	0.66	0.36	0.17

5.2 Changes to heating degree days

Heating degree days provide simple measures of the heating energy required to maintain the internal environment of buildings at comfortable levels. The heating degree day is calculated to be the total time in the year (measured in days) when the temperature falls below a threshold, weighted by the number of degrees below the threshold. The units are therefore °C days.

Here we use the weather data for the present day morphed to future climate to calculate the changes in the heating degree days in response to climate change. There are two motivations for doing these calculations. First, these measures provide a useful first estimate of the risk posed by climate change to internal environments. Second, the changes to heating degree days are presented in the UKCIP02 report, and so they provide a means of comparing the present morphing method of generating the future weather records with the changes to the degree day computed directly from the regional climate model.

For this study, when hourly data is available the heating degree days are calculated by counting the number of hours that the threshold temperature is exceeded and then dividing by 24 to convert hours to days, symbolically:

$$HDD = \sum_{year} \max(dbt_b - dbt)/24,$$

where dbt is the dry bulb temperature, and dbt_b is the baseline temperature, taken here to be 15.5°C to be consistent with UKCIP02.

Figure 3 shows the heating degree days calculated from a range of years of weather data under present-day climate and under the 2080s climate with medium-high emissions. Notice how even under present-day climate, there is a distinct trend showing a decrease in

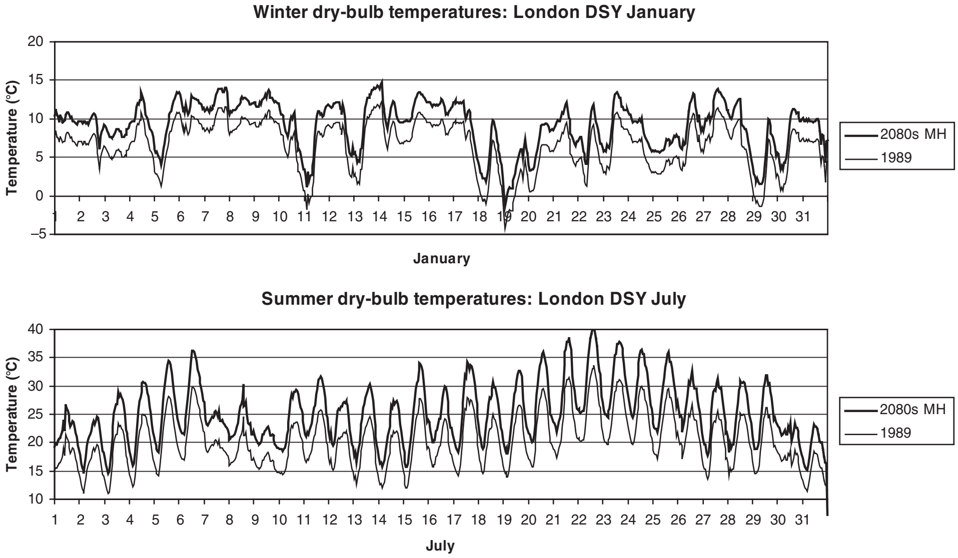

Figure 2 Present-day and 2080s medium-high emissions scenario morphed design summer year dry bulb temperature for (*a*) January and (*b*) July

the number of heating degree days through the period 1979 to the 1990s. On average, the number of heating degree days in both London and Edinburgh dropped by 20–30 degree days per year, which corresponds to a little less than a 10% drop over the 15-year period. This perhaps suggests that the 15 years of the weather data is already showing evidence of warming climate, and hence a reduction in heating degree days. Under the 2080s climate with a medium-high emissions scenario there is a marked reduction in the number of heating degree days. For London there is a decrease of between 35% and 40%, whereas for Edinburgh there is a slightly smaller decrease of about 30%. These reductions compare well with the results presented in the UKCIP02 (Figure 67), which suggest a reduction of 35–40% for London and 25–30% for Edinburgh. The UKCIP02 values are obtained directly from the output from the climate model, whereas the present results have been obtained by morphing the CIBSE data. Hence this agreement in the reduction in heating degree days provides important evidence that the two methods are consistent.

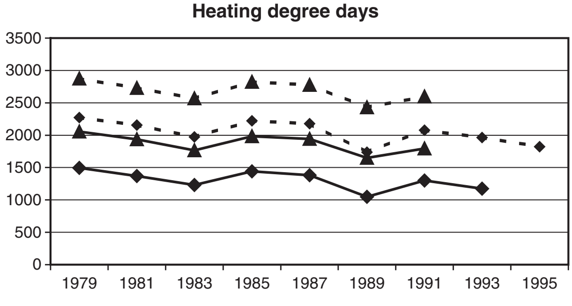

Figure 3 Comparison of the heating degree days from present day and morphed to 2080s under medium-high emissions. Diamonds: London; triangles: Edinburgh; dotted lines: present day; solid lines: 2080s

6 Discussion and conclusions

We have developed a method to generate design weather data that accounts for projected changes in climate for thermal simulation of buildings. The method, which we call morphing, combines observed weather data with projections for how the climate will change under different greenhouse gas emissions scenarios. Morphing involves shifting and stretching the variables in the present-day weather time series to produce new weather time series that encapsulate the average weather of the future climate, whilst preserving the physically realistic weather sequences of the source data. In this sense the method 'downscales' the results from coarse resolution climate models to the fine spatial and temporal resolutions required for building thermal simulations. A potential drawback of the method is that it does not account for changes in the character and variability of weather under climate change, although at this time such changes are not known with confidence. The method is attractive because it is simple and flexible, so that it can be applied across a broad range of climate change scenarios. The method was illustrated here by applying it to CIBSE Guide J weather time series, which are used in UK building simulation, and projections of future UK climate from the recent UKCIP02 regional climate model simulations.

Heating degree days were calculated from the present day and the future weather data in order to give a first estimate of the potential impacts of climate change on the internal environment of buildings. The calculations also allow comparison of the morphing methodology with calculations based on direct output from the climate model. The resulting changes in the heating degree days from the morphed weather data agree well with the results obtained directly from the climate model that are quoted in UKCIP02. This gives us confidence that the morphing technique is an appropriate tool to construct future weather data. A more detailed analysis of heating and cooling degree days under future climates is under way.

The method should prove a useful robust tool enabling designers to produce weather years to 'future proof' designs when using thermal simulation. Ongoing work is assessing the sensitivities of building simulation models to these issues.

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Appendix

The morphing algorithms

Throughout, the notation for variables follows CIBSE Guide J for weather data variables, and UKCIP02 for climate change variables.

1) Solar irradiance on horizontal, *gsr* (Wm-2 h)

The UKCIP02 scenarios give an absolute increment for monthly average solar shortwave flux received at surface (Table 2). Note that the CIBSE solar irradiance is the integrated irradiation over one hour, so that units are Wm-2 h. The UKCIP02 solar shortwave flux is the total increase in monthly mean irradiation. This is the variable corresponding to solar irradiance on the horizontal in the weather files. However, for the morphing procedure we wish to stretch not shift (i.e., use method 2, not uniformly) otherwise the sun would irradiate at night! The appropriate scaling factor can be obtained from the absolute change and the monthly mean from the observed baseline climate:

$$\alpha gsr_m = 1 + (\Delta DSWF_m / \langle gsr_0 \rangle_m) \qquad \text{(M1a)}$$

This scaling factor is then applied to all months m in the time series using Equation [2] i.e.,

$$gsr = \alpha gsr_m \times gsr_0 \qquad \text{(M1b)}$$

This transformation gives the correct absolute increase in monthly means for the transformed timeseries. We note that according to this simple method there is increased solar irradiance on sunny days, but the number of sunny days is unchanged.

2) Diffuse solar irradiation on horizontal, *dsr* (Wm-2h)

The UKCIP02 scenarios do not give information regarding the change to diffuse irradiation, *dsr*, so an indirect method must be used. The simple model assumed here is to suppose that *dsr* changes in proportion to *gsr* i.e.,

$$dsr = \alpha gsr_m \times dsr_0 \qquad \text{(M2)}$$

where αgsr_m is given by Equation [M1a]. More information is required from the providers of the climate change simulations to improve upon this method.

3) Sunshine duration: radiation site *sfr* (h)

Sunshine duration is a variable not given directly by UKCIP02. The related variable that is given is total cloud in longwave, TCLW, which is related to the weather file variable cloud cover, *cc*. The appropriate transformation between these two variables is given below. Sunshine duration, *sfr*, was then obtained from the morphed time series of *cc* using an empirical relationship between *cc* and *sfr* (given in CIBSE Guide[4] Equation [5.17]):

$$sfr = a(0) + a(1) \times cc + a(2) \times cc^2 \qquad \text{(M3)}$$

This operation is carried out after the morphing for *cc* has been done. Note that *cc* was measured at the radiation site. The values of the empirical coefficients determined for two sites by regression analysis are given in Paassen and Luo.[3] The coefficients for Bracknell were used here.

4) Sunshine duration: synoptic site *sfs* (*h*)

This variable is adjusted as *sfr* i.e.,

$$sfr = a(0) + a(1) \times cc + a(2) \times cc^2 \tag{M4}$$

5) Cloud cover, *cc* (oktas)

Cloud cover is generally observed visually using judgement and recorded as the fraction of sky covered on an integer scale of 0–8 in oktas (1 okta = 1/8th sky covered by cloud). In UKCIP02, a surrogate for the visual observation obtainable from the model is the proportion of cloud in the longwave radiation band, TCLW. This variable is recorded as percentage of sky covered, and the increment is given as an absolute amount in percentage sky covered. The first stage in the required mapping is to convert the UKCIP change from percentage to oktas:

$$\Delta cc_m = \mathrm{int}(\Delta TCLW_m \times 8/100) \tag{M5a}$$

where ‘int’ denotes integer value. This increment is then added to the timeseries using method 1 e.g.,

$$cc = cc_0 + \Delta cc_m \tag{M5b}$$

6) Dry-bulb temperature, *dbt* (°C)

UKCIP02 gives changes for daily mean temperature, TEMP, daily maximum temperature, TMAX, and daily minimum temperature, TMIN. Here, we have chosen to use these three parameters to change only two statistical parameters of the timeseries of temperature, namely the mean and the variance. This is achieved by shifting by the UKCIP value for mean temperature and stretching by the diurnal range TMAX–TMIN. The required scaling factor for the stretch is:

$$\alpha dbt_m = \frac{\Delta TMAX_m - \Delta TMIN_m}{\langle dbt_{0\,\max}\rangle_m - \langle dbt_{0\,\min}\rangle_m}$$

The required shift is the UKCIP02 increment, $\Delta TEMP_m$. Hence the required transformation is:

$$dbt = dbt_0 + \Delta TEMP_m + \alpha dbt_m \times (dbt_0 - \langle dbt_0\rangle_m)$$

It can be confirmed that this transformation preserves the UKCIP02 changes to TEMP and TMAX–TMIN (but not TMAX and TMIN independently). Since the changes in TMAX and TMIN are not large this method does not unduly bias the morphed data.

7) Wet-bulb temperature, *wbt* (°C)

To obtain *wbt*, *dbt* is combined either with specific or relative humidity. Note that neither of the latter two quantities is included explicitly in the existing weather files, while increments for both quantities are given in UKCIP02. For ease of calculation the algorithm here uses specific humidity.

First step: calculate historical time series for specific humidity s_0

> Use dbt_0 and wbt_0 from the existing timeseries to derive the historic time series for moisture content g_0 and from this the historic timeseries for specific humidity s (in units of g of water per kg of moist air).[7]

Second step: use a stretch Equation [2] to derive future time series for specific humidity s

> The UKCIP02 changes in specific humidity SPHU are given as a percentage. Therefore the required scaling factor is:
>
> $$\alpha s_m = 1 + SPHU_m/100$$
>
> so:
>
> $$s = \alpha s_m \times s_0$$

Third step: calculate future time series for moisture content g from s

Fourth step: calculate future time series for wet bulb temperature using g and dbt (calculated in 6). The psychometric formulae are given in CIBSE Guide C.[8]

8) Atmospheric pressure, *atpr* (mb)

This variable can be computed directly from the UKCIP02 projections for increment in atmospheric pressure, $MSLP$, using a shift Equation [1] used:

$$atpr = atpr_0 + MSLP_m$$

9) Wind speed, *ws* (m/s)

Wind speed changes in UKCIP02, $WIND$, are given as a percentage. Hence the new wind speed time series is obtained from Method 2 using $WIND$ directly:

$$ws = (1 + WIND_m/100) \times ws_0$$

10) Wind direction, *wd* (degrees)

Since it is assumed that there is no change in the underlying weather, there is no change to wind direction.

11) Rainfall amount, *ra* (mm)

Rainfall changes in UKCIP02 are given as a percentage, so again, a stretch Equation [2] is used:

$$ra = (1 + PREC_m/100) \times ra_0$$

12) Rainfall duration, *rd* (h)

Again, since there is assumed to be no change in underlying weather, rainfall duration is unchanged.

13) Present weather code, *pwc*

No change.

14) Solar altitude, *solalt* (degrees)

No change.