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The appropriate spatial resolution of future weather files for building simulation

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Building thermal modelling packages require weather data in order to predict representative internal conditions. Typically, around the world, reference weather years of various forms are used which are created from observations at a particular location. However, it is unlikely that this location is identical to that of the building. This can lead to weather files for coastal locations being applied to inland and upland sites or visa versa. In the UK, the UKCP09 weather generator has the ability to produce weather at a 5 km resolution. Currently it is unclear how useful this extra spatial resolution will be and it is this question that is addressed here. It is found that for both future and present climate the spatial variability of the weather is the dominating factor. While there are geographies where a low spatial resolution can be used, there are regions where a much higher resolution is necessary.

Keywords: Weather files, Climate change, Spatial resolution, Built environment, Thermal models

1. Introduction

Building simulation is a common practice in the design process of new buildings and even for the refurbishment of existing buildings. When using building thermal modelling packages there is the need to provide the model with a time series of weather data for the location where the building is to be located. For many countries it is common to use a file of example weather created from an analysis of many years of observations from a weather station. However, it is unlikely that the building being simulated and the weather station are co-located, so the geographically nearest station is usually selected. When testing a building for compliance in the UK the Chartered Institution of Building Services Engineers (CIBSE) [1] Test Reference Years (TRYs) are used. These reference years are only available for 14 locations and are based upon historic observations of weather typically from the period 1983 – 2004. The limitation of only 14 locations to cover the whole of the UK can cause substantial differences in the simulation results if the typical weather of the building location is significantly different to that at the weather station. For instance one might expect the weather in coastal locations to be significantly different to that experienced on upland areas. Such errors have the potential to lead to incorrect and expensive design decisions being made in order to ensure compliance with building regulations or guidance e.g. number of occupied hours over some limit.

Future weather files currently available from CIBSE use estimates of future climate from the UK Climate Impacts Programme 2002 (UKCIP02) [2] projections. These estimates are available at a 50 km resolution and can be used to mathematically transform (morph)[3] the reference weather files to produce a time series representative of a future time period such as the 2080s (defined as the period 2070 to 2099). Hence, such future weather files are also limited to the same 14 locations.

With the release of the 2009 UK climate projections (UKCP09) [4] and the associated weather generator, data is available at a much finer resolution. In UKCP09, climate change projections are available at a spatial resolution of 25 km, while the weather generator can produce daily or hourly time series of weather at a 5 km resolution for a base climate (1961-1990 or the 1970s) and for future climates. This suggests that it would be possible to produce example weather files at a much higher spatial resolution. This would significantly increase the amount of data required to be made accessible to modellers. However, this would only seem to be justifiable if it can be shown it makes a difference to the results of building simulations to a degree that could lead to different solutions being posed by engineers. In this paper, the spatial variation in the natural variability of the weather and the projected levels of climate change will be investigated. This will be done using the outputs of UKCP09 and gridded historical observations to inform what spatial resolution of example weather years across the UK is required. Both the natural variability and the projected climate change information will be investigated for the whole of the UK and then in detail for two localised regions, the Southwest (Devon) and the East (Norfolk). Devon was chosen since it contains a variety of landscapes including coastline and upland areas while Norfolk is much less topographically varied in terms of elevation.

The spatial and temporal resolution of a weather generator is determined by the underlying observations which are used to calibrate it. In this case, the UKCP09 weather generator uses data from the period 1961 to 1990. All weather statistics and inter-variable relationships have been interpolated from 115 weather stations on to a 5 × 5 km grid across the UK using the topographical variables of elevation, aspect, eastings, northings, urbanisation and distance from the coast [5]. This procedure allows the weather generator to produce a time series of weather for each 5 km grid square across the UK (there are 11,368 grid squares in total available within the weather generator). For comparison the climate change factors are available on a 25 km grid and have a total of 440 grid squares covering the UK [6]. The weather generator uses a stochastic rainfall model that simulates rainfall sequences calibrated by observed rainfall sequences from the 5 km grid. Change factors for the corresponding 25 km grid square are then used to refit the rainfall statistics. Other variables are then generated using inter-variable relationships as observed historically, and additionally perturbed by the corresponding change factors. The weather generator outputs both future weather data (with a choice of future period and emissions scenario) and the base period weather typical of the 1970s climate. With this much finer resolution weather data now available one can envisage using weather files for the closest 5 km grid square for building simulation instead of the closest of the 14 current locations. However, this would result in many thousands of weather files having to be created and distributed to buildings engineers with a large burden on memory for the storage of such files (16 Gb for the whole of the UK per emissions scenario per decade per sample of possible future climate change). While modern computers and thermal simulation software are capable of sorting these files and providing the user with a list of the available files in order of geographical distance from a given location in a matter of seconds, there is currently no information on how much benefit this extra spatial resolution would provide over the current method, or whether files should be provided at 5 km centres (as the weather generator is capable of providing), or 14 locations (as present), or some other spatial resolution. However, with so many weather files there is likely to be some redundancy with many predicting very similar resultant internal environments, therefore there is the need to assess the required spatial resolution required to balance accuracy against logistical ease.

In this paper only the UK is studied, but the approach would equally apply to any other location. However, the results may be different, as natural variability across a landscape is a function of the landscape itself. Areas of uniformity, such as deserts are likely to show less variability than areas which include mountains and hence substantial changes in elevation, or different terrains.

The three questions that need to be addressed are:

1. What is the level of natural variability across the landscape in the UK?
2. How does this compare with the changes predicted due to climate change?
3. When passed through the filter of a building thermal model, how much of the variability is preserved? i.e. even if there is substantial variability in the weather data between adjacent grid squares, does this lead to any material difference in output from a thermal model in, for example, mean internal temperature or heating energy requirement?

These are addressed in turn in the following sections. This is done by (a) reviewing the natural variability of mean air temperatures between adjacent grid squares, (b) looking at the predicted changes due to climate change and (c) using a thermal model of a building sited at various collections of adjacent grid squares.

2. The Spatial Variability of the Observed Climate

In order to assess the required spatial resolution of future weather files needed for building simulation, first knowledge of how the natural variability of the weather changes spatially is required. In the UK, gridded data sets have been created for a range of climatic variables based on surface observations. Perry and Hollis [5] used regression and interpolation to generate the values on a regular 5 × 5 km grid. The 5 × 5 km grid consists of 10,359 squares in total. This is less than the number available from the UKCP09 weather generator and is because the gridded observations do not include grid squares which are mainly sea and remains true to the Northern Ireland border. This data was then re-sampled to the same rotated 25 × 25 km grid used by the regional climate model within UKCP09 and contains 440 squares. Using the Perry and Hollis data sets and geographical information system software, 5 km resolution maps of the UK for the different weather variables can be created. This will identify any apparent spatial trends in the current climate and give an indication of how many weather files would be needed to fully capture the spatial variability in the base climate. The external temperature is the biggest driver of building internal environment and the energy usage so will be the focus of this study.

Figure 1 shows the mean annual temperature at a 5 km resolution (left). Also shown is the difference in mean annual temperature between adjacent grid squares (right). The difference in annual mean temperature data is calculated by taking each grid square in turn and comparing the value with the adjoining squares which are south and east. The largest difference is then recorded for that square. This difference between adjacent grid squares allows the relative rate of change of spatial variability to be examined; regions with a high rate of change (a large difference value) are likely to require a greater number of weather files than areas where the rate of change is slower. There is much less variability in the difference data than the mean annual temperature. The range in mean annual temperatures is found to be 9.9 °C across the UK and the lowest annual mean temperature is found in the highlands of Scotland at 1.7 °C. The difference maps show there are large areas of the UK with little variation in the temperature between grid squares with 58 % of the grid squares have a difference to the adjacent grid square of less than 0.5 °C demonstrating that the difference between grid squares is generally small. The largest differences are found in mountainous areas such as the Highlands of Scotland. However it must be noted that this region has the highest error in the data set due to the complex terrain and sparse station coverage [5]. The smallest differences are found in the Midlands and South East of England.

These maps provide an indication of the extent of the variability in the present climate across the UK. It must be noted that that the spatial variability of other weather variables such as solar radiation have been checked and have been found to vary much less spatially than the temperature.

3. The Spatial Variability of Future Climate

In order to examine the variability of future climate, the latest projections of climate change for the UK (UKCP09) have been used. The data shown in Figure 2 and Figure 3 shows projections of future climate for the 2080's under the A1FI [7] (high) emissions scenario. Using the 2080s period and the A1FI scenario one can assume that the predicted variability across the UK represents an upper bound to what would be shown in the nearer future or indicated by the A1B (medium) or B1 (low) emissions scenarios. The UKCP09 climate data is probabilistic in nature and all future climate data shown here represents the 50th percentile or central estimate (median) for the given scenario and time period. Figure 2 shows maps of the variation in the projected change of mean annual temperature across the UK and the difference data between adjacent grid squares calculated in the same manner as described above. The UK shows an increase in mean annual temperature of between 2.5 °C and 4.5 °C with the larger increases in the South and smaller increases in the North. In this case there is very little variation between adjacent grid squares with over 95 % having a difference of less than 0.2 °C. The largest differences are found in Scotland but the differences are still small at around 0.5 °C. This implies that the projected variation in climate change is less dependant on the topography than the weather.

Figure 3 shows maps of the predicted change to the mean annual diurnal temperature swing ($\Delta T_{max} - \Delta T_{min}$) across the UK and the difference between adjacent grid cells as projected by UKCP09. The mean change to the annual diurnal temperature swing is calculated as the difference between the change in the mean maximum daily temperature (ΔT_{max}) and the change in the mean minimum daily temperature (ΔT_{min}). A reduced diurnal cycle can have an impact on a building's ability to lose heat; this in turn can have impacts on overheating levels, human health and productivity. The change in mean diurnal temperature swing is small and less than 1 °C for the whole of the UK where the smallest changes are found mainly in the North. However, for the majority of the UK (59 %) the absolute change in the mean diurnal temperature swing is predicted to be less than 0.4 °C. The difference between adjoining squares is found to be very small, and is below 0.2 °C for more than 95 % of the UK, with the largest differences found once again in Scotland. Once again the spatial variability of other weather variables have been checked and has been found to be very small.

The spatial variation in changes to mean temperature as a result of climate change shown in Figure 2 and Figure 3 is far smaller than the spatial variability of the current climate shown in Figure 1. The question however remains, how well does the distribution of the current set of weather files (14 locations) match the current climate and will the same be true in the future? Figure 4 shows the areas of influence for the current set of 14 weather files and the difference between mean annual temperature for the 1970s climate in the Perry and Hollis data set and that at the grid square containing the geographically closest weather station in the set used for compliance modelling. In the UK the chosen weather file, in most cases, is taken as the location which is closest in distance to the proposed building. While it is possible to use a file from a different location, the weather of the file must be representative of the location. From figure 4 it is clear that a building in Penzance would be modelled as located in Plymouth while majority of Scotland is served by two files; Edinburgh and Glasgow. The error introduced by using such a coarse spatial representation of climate across the UK is generally small with 42 % of the country having an absolute difference to the nearest weather station smaller than 0.5 °C. It also shows that for the majority, 81 % of the UK, the weather stations used for compliance modelling are an overestimate of the temperature. The largest errors are generally in the more mountainous and upland areas of the UK. What is surprising is that comparing the magnitude of these errors with the data shown in Figure 2 under the A1FI scenario by 2080 (50th percentile), the difference is similar in magnitude to the effects of the projected climate change with regards to the annual mean temperature change. This suggests that, overall, if climate change is to be included accurately in thermal modelling work, the spatial variability of the underlying weather is extremely important and must be given equal consideration. It is worth noting that, for any set level of accuracy, the degree of spatial resolution required depends on the location.

Carrying out the same analysis for the future climate by combining the 25 km Perry and Hollis data set with the relevant climate change projections, the distribution of the errors is very similar to the base climate as shown in Figure 5. In this case 45 % of the UK has an absolute error less than 0.5 °C and once again for the majority of the country, 78%, the nearest weather file is an overestimate. The clearest difference between the two climates is the change in the Southwest, from being generally an overestimate for the base climate to being an underestimate for the future climate.

4. Sensitivity of Building Simulation to the Spatial Resolution of Weather Data

To investigate the resolution of the available UKCP09 data further and to demonstrate its impact on the internal environment, two transects across different geographic regions are considered in more detail. The first area is in the Southwest across Devon, where there is a range of topography including coastlines and upland areas. The second is in the Eastern region across Norfolk, where the topography is much more uniform in terms of relief and the variability of the base climate is small. The two transects selected are shown in Figure 6 with the grid squares arbitrarily numbered for clarity. Both the historic base period and a single future period are used in this analysis where the future weather files for each location were created using the methodology proposed by Eames et al [8]. For simplicity, only the central estimate or 50th percentile is used for the future period of the 2080s under the high emissions scenario (A1FI).

The impact on internal conditions from using weather data from different locations was compared using an industry standard dynamic thermal building simulation package [9] to measure the sensitivity of building models to the different weather. Two test buildings are used within this analysis with different occupancy profiles. The first is a new build house conforming to 2002 UK regulations, occupied during the evening. The second test building is a school with high occupancy during the day and unoccupied at night and is used in the analysis of overheating.

The house consists of brick and block external walls, studwork internal walls and timber joist ceilings. The building is assumed to be occupied by a working couple. The window openings and heating requirements are handled dynamically according to an occupancy schedule.

Using the thermal model of the test house it is possible to explore to what extent the variability in the weather files affects the internal environment. To demonstrate the effect of the base climate on the internal environment, the mean internal temperature, mean external temperature, the annual heating energy consumption and the heating degree days (with a set point of 18 °C) are shown for the Devon (table 1) and Norfolk (table 2) transects.

Unsurprisingly there is less variation in the predicted mean internal temperature than in the external for both the Norfolk and the Devon transects, however, there are clear differences between the two regions. The range in the internal temperature across the Devon region is 1.29 °C while the range in the external temperature is 3.76 °C. Across the Norfolk region the range is much smaller with a difference in internal temperatures of 0.26 °C compared to 0.74 °C for the external temperatures.

The predicted heating energy requirement of the building for the 1970s climate shows a similar trend. The heating is set to control the internal temperature to 18 °C during occupied hours. There is considerable variation in the amount of energy required across the Devon transect with a difference of 2.77 MWh between cells compared to 0.66 MWh for Norfolk. This trend is also reflected by the number of heating degree days with a range of 285 across Norfolk compared to 1288 across Devon. This is not that surprising since there is a large variation in elevation in Devon. These tables also demonstrate that a file in Devon with a similar mean external temperature is not a proxy for a file in Norfolk. While grid square 12 (Devon) has a mean external temperature of 9.77 °C its heating energy consumption is 2.06 MWh. In comparison, grid square 21 (Norfolk) has a mean external temperature of 9.76 °C but a heating energy consumption of 2.52 MWh. This is not the only example. It is found that there is a clear difference between the two transects. In locations where the mean external temperatures are almost identical, the annual heating energy consumption is approximately 25 % larger in Norfolk. These tables also imply that the use of the Cardiff and Plymouth TRY files, both of which are relatively low lying coastal cities, would underestimate the energy usage of many inland locations, in Devon (the Cardiff weather files are typically used for locations in North Devon as the geographically closest weather file location).

To demonstrate the location-dependent effect of the future climate as predicted by UKCP09 on the internal environment, the internal mean temperature, external mean temperature, the annual heating energy consumption and the heating degree days (with a set point of 18 °C) are shown for Devon and Norfolk in table 3 and table 4 respectively.

For all grid squares the future mean external temperature and the mean internal temperatures are found to be greater on the order of 4 °C and 1.5 °C respectively, whereas the heating energy is reduced by a factor of 20-40% when compared to the data shown in tables 1 and 2. This clearly shows that for both regions overall temperatures are predicted to be warmer, with winter temperatures also increasing, thereby reducing the requirement for heating. This is also reflected by the reduction in the number of heating degree days by up to 41%.

While there are general increases across the two regions, the spatial variability remains. While the range of the mean external temperature for the Devon transect is again at 3.8 °C, for the Norfolk transect the range is again much smaller at 0.7 °C. The variability of the mean internal temperature of the building is found to be larger, at 1.6 °C and 0.3 °C for the Devon and Norfolk transect respectively. The variability of the heating energy is reduced for both transects but is still much larger for the Devon transect at 1.4 MWh compared to 0.4 MWh for the Norfolk transect.

While the heating energy usage and mean internal temperature are useful for examining likely internal conditions, they are not used in the UK for the compliance with building regulations. The number of occupied hours over a set temperature is often used as a measure of building performance, particularly for offices and education buildings. For schools one such measure currently takes the form of no more than 120 occupied hours >28 °C from the 1st of May to 30th September inclusive [10]. For this test, the school is modelled using a TRY file typically from the geographically closest of the 14 locations. As shown above, the reference year locations are generally an over estimate of likely external and internal temperatures, which could lead to costly, unnecessary design alterations. To investigate the likelihood of a building failing at the different grid locations, the weather files for both the Norfolk and Devon transects have been used within a thermal model of a typical new build primary school (again with constructions conforming to 2002 UK building regulations details can be found in the appendix, with typical occupancy and ventilation strategies for a primary school.) The number of hours over 28 °C for the Devon and Norfolk transect is shown in tables 5 and 6 respectively for both the current and a future climate. Across the Plymouth transect there is a large range in the degree of overheating. While the School fails this particular criterion using the Plymouth weather file there are areas across the Devon transect where it passes in the current climate. Using the Plymouth file could result in an expensive design solution to be employed to reduce overheating in areas where it is not necessary. For the future climate each grid square fails the criterion but there is a large range in the absolute number. Over the centre of Dartmoor there are approximately half as many hours over 28 °C compared with grid squares on the edge of the transect. Once again this would suggest a different design solution would be required for the different locations. However, the school has a very similar number of hours over 28 °C for each square of the Norfolk transect for both the current and future climate. Although the school fails on this specific overheating criterion on every grid square, for both climates, the level of overheating is similar and thus any design solution might be similar to reduce this overheating.

Although in this study only two buildings have been chosen, a different building model with different internal loads, occupancy schedule or construction might show slightly different results, it is clear that moving a building a short distance can have a significant effect on both the energy use and the level of overheating.

In order to check that the variation observed between different grid squares is not just random variation within the weather generator, 7 different random seeds were chosen for two adjacent grid squares (grid squares 4 and 5 in Figure 6). The random seed primes the weather generator and represents a different randomly chosen sampling of the climate change probability density functions and weather statistics. Hence, each different seed will lead to a different discrete set of 3000 years being created from which reference years representing the future and current climate can be created. Table 7 shows that while there are clear differences in the weather, given by changes to the minimum and maximum temperatures, the differences in the yearly statistics such as mean temperature, heating degree days and cooling degree days, are very small. This shows the difference between the different random seeds is small compared to the difference between grid squares. Very similar average climates are being produced in each case so it is reasonable to assume that the variation between grid squares, as shown in tables 5 and 6, is a true representation of variability between cells rather than just fluctuations in the output of the weather generator.

5. Discussion and Conclusion

It is clear from the colour maps of the UK that the current spatial variation in the climate as shown by figure 1 is greater than the predicted future climate change as shown by figures 2 and 3 and varies at a finer resolution. This implies that when deciding how many weather files are required to realistically model the impact of future climates on buildings one should first be aware of the natural variability within the current climate. The distribution of mean annual external air temperatures shown in Figure 1 indicates that there is ~10 °C of variability across the UK. The distributions of climate change data as shown in Figure 2 and Figure 3 will only serve to exaggerate the difference in temperatures between the North and South of the UK. It must be noted that while only the climatic effects of air temperature have been considered here for two time periods the methodology is applicable to other variables such as precipitation and solar radiation as well as other time periods and emissions scenarios.

The data in tables 1 to 4 show that there is a link between the mean external temperature and the mean internal temperature where an increase in the mean external temperature across the transect generally leads to an increase in the mean internal temperature. The variability across the Norfolk region is generally very small; such that the Norwich weather files currently used for compliance modelling are most likely to be a good representation for the region. However, the same is not true for locations such as Devon where the variability is very much greater: with the difference in mean temperature between the coolest and warmest being of the order of the predicted change in mean temperature under the A1FI emissions scenario by the 2080s (central estimate). The choice of such files is much more critical for thermal modelling both for the current climate and for any future climate as it can lead to a large discrepancy in the results generated.

It is clear from the spatial climate information presented in this paper that there is significant variation in the climate across the UK and that it will be difficult for this to be captured within the weather files for the 14 TRY/DSY locations around the UK as shown within Figure 4. It is also clear that not all grid squares represented within the weather generator are required to accurately represent the UK. However it seems prudent to model buildings with the most location specific data available. While this presents a logistical problem to buildings engineers and thermal modelling software companies, in this age of high-speed computers and networks this can be overcome by downloading higher resolution weather files as and when they are needed from a remote server. Since the weather data produced by the UKCP09 weather generator does not carry the same copyright as the historically observed data used for the current TRY and DSY files, the production of many weather files will not discriminate against smaller building engineering practices. The authors hope that the adoption of more localised weather files will allow better design of buildings dependent on location and lead to lower energy usage and reduced risk of building failure both now and in the future.

Although only the 50th percentile has been shown within this work, it has been found that other percentiles from the distribution are found to not influence the conclusions. Even at the extremes of the distribution the natural weather variability still dominates any climate change signal on a 5km scale.

In summary, care is needed when estimating the impact of future climates on specific buildings and drawing up design solutions to combat climate change when there can be such large variations in environmental variables between the current 14 weather file locations and the building location. Although this is not the case for all regions; for example around Norfolk, the variability is much smaller. Care must be taken in areas of greater topography not to prescribe design solutions aimed at achieving specific objectives, such as the number of occupied hours over a set target, unless more localised weather files can be used.

6. References

1. Chartered Institute of Buildings Services Engineers, http://www.cibse.org.
2. UKCIP02. Climate change scenarios for the United Kingdom. Available from: UKCIP http://www.ukcip.org.uk/index.php?option1⁄4com_content&task1⁄4view&id⁄4161&Itemid1⁄4291; 2002.
3. Belcher SE, Hacker JN, Powell DS. Constructing design weather data for future climates. Building Serv. Eng. Res. And Technol. 2005; **26**: 49-61.
4. UK Climate Projections 2009, http://ukclimateprojections.defra.gov.uk/ Scientific reports available from: http://ukclimateprojections.defra.gov.uk/content/view/1370/686/
5. Perry M, Hollis D, The generation of monthly gridded datasets for a range of climatic variables over the United Kingdom, International Journal of Climatology, **25** (2005), 1,041-1,054
6. Murphy, J. M., Sexton, D. M. H., Jenkins, G. J., Booth, B. B. B., Brown, C. C., Clark, R. T., Collins, M., Harris, G. R., Kendon, E. J., Betts, R. A., Brown, S. J., Humphrey, K. A., McCarthy, M. P., McDonald, R. E., Stephens, A., Wallace, C., Warren, R., Wilby, R., Wood, R. A. (2009), UK Climate Projections Science Report: Climate change projections. Met Office Hadley Centre, Exeter.
7. IPCC. (2000). Special Report on Emissions Scenarios (SRES). Available from: http://www.grida.no/publications/other/ipcc%5Fsr/?src=/climate/ipcc/emission/
8. Eames M, Kershaw T, Coley D. On the creation of future probabilistic design weather years from UKCP09. Building Serv. Eng. Res. And Technol. 2011; **32:** 127-142.
9. Integrated environmental solutions, http://www.iesve.com/content/.
10. Building Bulletin 101: Ventilation of School Buildings – Version 1.4, Department of Education and Skills (DfES), London, 2006.

Appendix: Building constructions

Ground floor: soil (0.75 m), brickwork (outer leaf), cast concrete (0.1 m), EPS slab (0.0635 m), chipboard (0.025 m), carpet (0.01 m), U-Value = 0.2499W/m^{2}K.
Ceiling/floor: carpet (0.01 m), chipboard (0.025 m), cavity (0.25 m), plasterboard (0.013 m), U Value = 1.2585W/m^{2}K.
Internal walls: plasterboard (0.013 m), cavity (0.1 m), plasterboard (0.013 m), U-Value = 1.6598W/m^{2}K.
External walls: brickwork (0.1 m), EPS slab (0.0585 m), concrete block (0.1 m), plaster (0.015 m), U-Value = 0.3495W/m^{2}K.
Flat roof: U-Value=0.2497W/m^{2}K. Glazing: 6mm glass, 12mm cavity, 6mm glass, U-Value (including frame) = 1.9773W/m^{2}K.

New Build House
Floor area = 135.29m^2, Ext wall area = 178.56m^2, Glazed area = 11.98m^2.

School
Floor area = 287.66m^2, Ext wall area = 216.08m^2, Glazed area = 30.04m^2.

Devon	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Mean external temperature °C	9.72	9.79	9.11	8.80	8.21	6.86	7.39	7.75	8.19	8.31	10.45	9.77	9.13	10.62
Mean internal temperature °C	20.87	20.92	20.67	20.60	20.36	19.94	20.10	20.22	20.39	20.44	21.12	20.89	20.74	21.23
Annual heating energy usage (MWh)	2.01	2.01	2.47	2.65	3.12	4.26	3.85	3.45	3.22	3.01	1.76	2.06	2.40	1.49
Heating degree days (18 °C)	3108	3042	3264	3386	3588	4075	3878	3751	3576	3546	2873	3048	3274	2787

Table 1. Environmental data for the Devon transect for the 1970s base climate

Norfolk	15	16	17	18	19	20	21	22	23	24	25	26	27	28
Mean external temperature °C	9.37	9.21	9.34	9.39	9.50	9.65	9.76	9.81	9.86	9.82	9.65	9.67	9.87	9.95
Mean internal temperature °C	20.81	20.74	20.80	20.82	20.85	20.87	20.92	20.94	20.93	20.95	20.92	20.88	20.97	21.00
Annual heating energy usage (MWh)	2.73	2.87	2.77	2.73	2.63	2.46	2.52	2.43	2.34	2.40	2.59	2.51	2.31	2.21
Heating degree days (18 °C)	3238	3287	3253	3230	3184	3144	3096	3087	3060	3079	3131	3124	3044	3002

Table 2. Environmental data for the Norfolk transect for the 1970s base climate

Devon	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Mean external temperature °C	13.79	13.86	13.31	12.96	12.39	11.10	11.60	12.03	12.54	12.58	14.67	13.95	13.39	14.78
Mean internal temperature °C	22.39	22.44	22.20	22.08	21.84	21.31	21.56	21.74	21.96	21.91	22.77	22.45	22.20	22.89
Annual heating energy usage (MWh)	0.43	0.42	0.55	0.68	0.94	1.72	1.49	1.27	1.05	0.96	0.32	0.53	0.66	0.19
Heating degree days (18 °C)	1909	1853	2018	2138	2295	2687	2529	2398	2282	2241	1699	1876	1989	1636

Table 3. Environmental data for the Devon transect for the 2080s climate under the A1FI emissions scenario at the 50th percentile.

Norfolk	15	16	17	18	19	20	21	22	23	24	25	26	27	28
Mean external temperature °C	13.41	13.21	13.36	13.51	13.57	13.57	13.70	13.71	13.78	13.80	13.54	13.64	13.78	13.89
Mean internal temperature °C	22.23	22.12	22.19	22.31	22.27	22.37	22.41	22.37	22.40	22.33	22.22	22.33	22.35	22.45
Annual heating energy usage (MWh)	0.82	0.98	0.92	0.82	0.80	0.81	0.83	0.76	0.71	0.71	0.74	0.72	0.65	0.54
Heating degree days (18 °C)	2051	2123	2092	2046	2021	2021	1984	1941	1940	1928	1995	1956	1922	1845

Table 4. Environmental data for the Norfolk transect for the 2080s climate under the A1FI emissions scenario at the 50th percentile.

Devon	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Base Climate	145	152	139	83	64	36	49	62	81	64	207	176	121	194
Future climate	558	559	500	485	433	329	359	411	433	490	629	588	479	645

Table 5. The number of Occupied hours over 28 °C. The future climate uses the 2080s, A1FI emissions scenario at the 50th Percentile. The Plymouth TRY produces 128 hours of overheating.

Norfolk	15	16	17	18	19	20	21	22	23	24	25	26	27	28
Base Climate	180	193	179	182	166	211	193	246	205	221	193	215	214	183
Future climate	547	526	570	555	572	596	603	594	571	581	564	578	602	534

Table 6. The number of occupied hours over 28 °C. The future climate uses the 2080s, A1FI emissions scenario at the 50th Percentile. The Norwich TRY produces 184 hours of overheating.

Grid square 4, percentiles are for 2080 high emissions.

Seed	10	11	12	13	14	15	16	Range
1970s	-9.9	-6.4	-7.2	-8.4	-7.8	-6.1	-6.1	3.8
	25.5	24.8	26.2	27.0	27.1	25.6	26.5	2.3
	8.80	8.88	8.83	8.80	8.83	8.82	8.81	0.08
	3386	3358	3388	3391	3382	3382	3389	33
	40	42	52	46	47	42	47	12
2080s 50%	-2.6	-2.8	-2.3	-3.4	-4.4	-3.2	-6.8	4.5
	32.0	32.1	32.9	31.7	30.4	30.2	35.6	3.6
	12.96	13.07	13.19	13.04	13.00	13.01	13.10	0.23
	2138	2082	2053	2117	2097	2072	2090	85
	312	294	307	314	281	260	312	54

Grid square 5, percentiles are for 2080 high emissions.

Seed	10	11	12	13	14	15	16	Range
1970s	-7.3	-8.6	-7.9	-8.6	-7.8	-8.7	-11.7	4.4
	24.7	28.0	26.2	25.2	24.5	27.0	27.6	3.5
	8.21	8.21	8.21	8.17	8.15	8.23	8.24	0.09
	3588	3591	3592	3605	3609	3584	3580	29
	28	32	34	33	31	35	33	7
2080s 50%	-2.8	-2.6	-6.0	-3.8	-2.0	-3.6	-3.7	4.0
	31.8	30.0	29.8	32.1	32.7	30.5	31.4	2.9
	12.39	12.45	12.58	12.45	12.42	12.44	12.49	0.19
	2295	2265	2214	2270	2274	2269	2274	80
	261	252	252	259	250	252	276	26

Table 7. Minimum, maximum and mean external air temperature, heating degree days and cooling degree days (both for a set point temperature of 18 °C) for grid squares 4 and 5 for different random seeds and two different time periods.

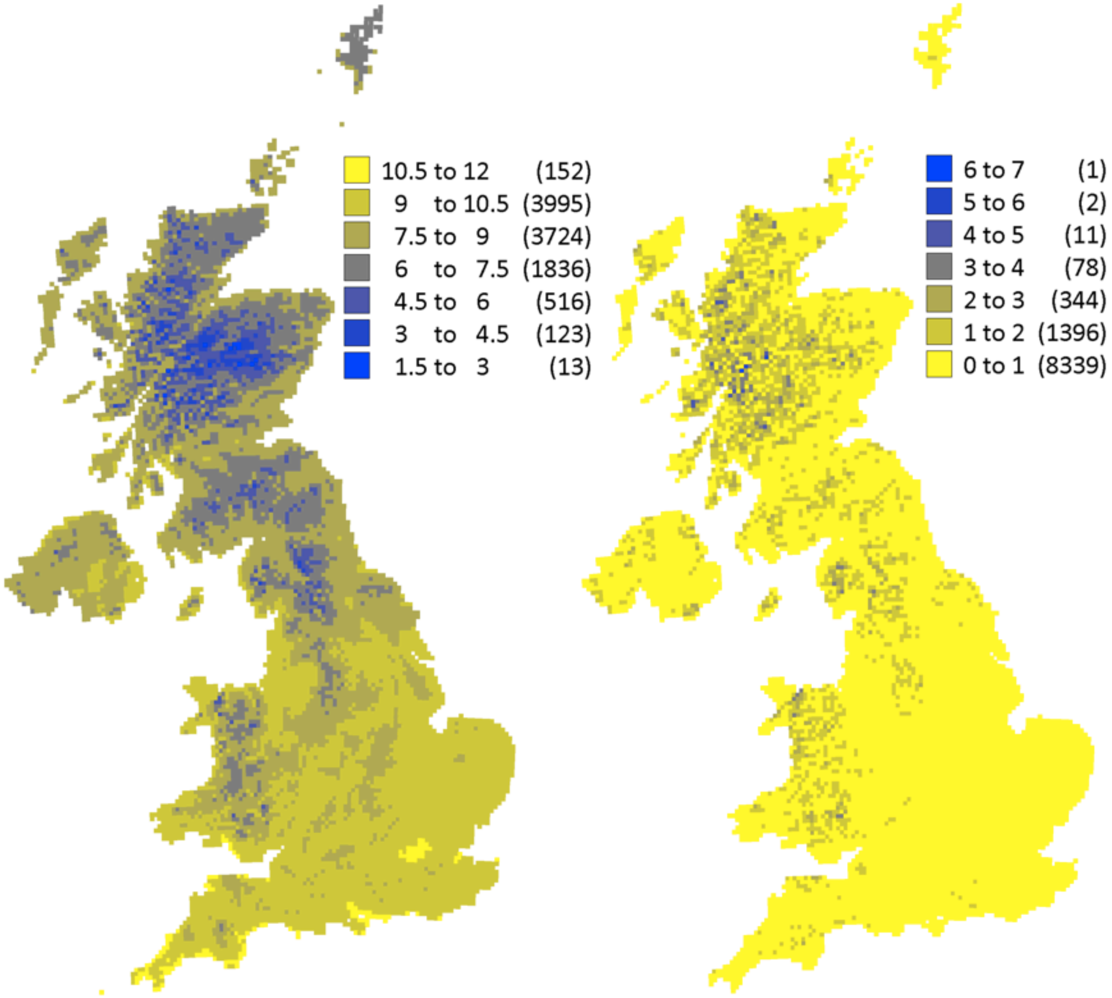

Figure 1 Maps showing mean annual air temperature from the Perry and Hollis data set on a 5 km grid for the whole of the UK (σ = 1.36 °C) (left), and absolute difference between adjacent grid squares (σ = 0.70 °C) (right). Data shown for the period 1961-1990 (1970s). The numbers in brackets represent the number of grid squares within that range.

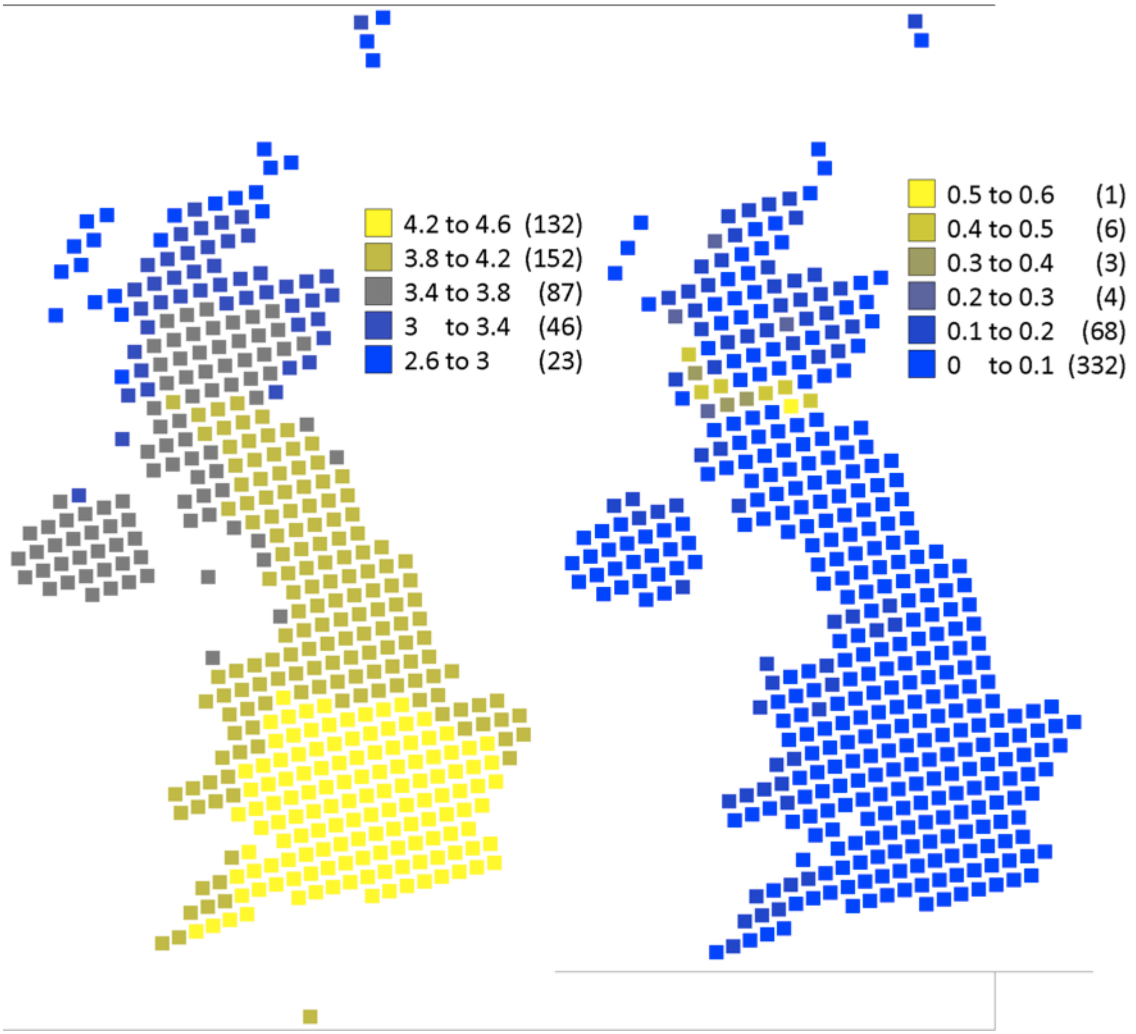

Figure 2 Maps showing predicted change from current mean annual air temperature (σ = 0.07 °C), left, and absolute difference between adjacent squares (σ = 0.44 °C), right, on a 25 km grid for the whole of the UK. Data shown for the 2080s under the A1FI emissions scenario at the 50th percentile. The numbers in brackets represent the number of grid squares in that range.

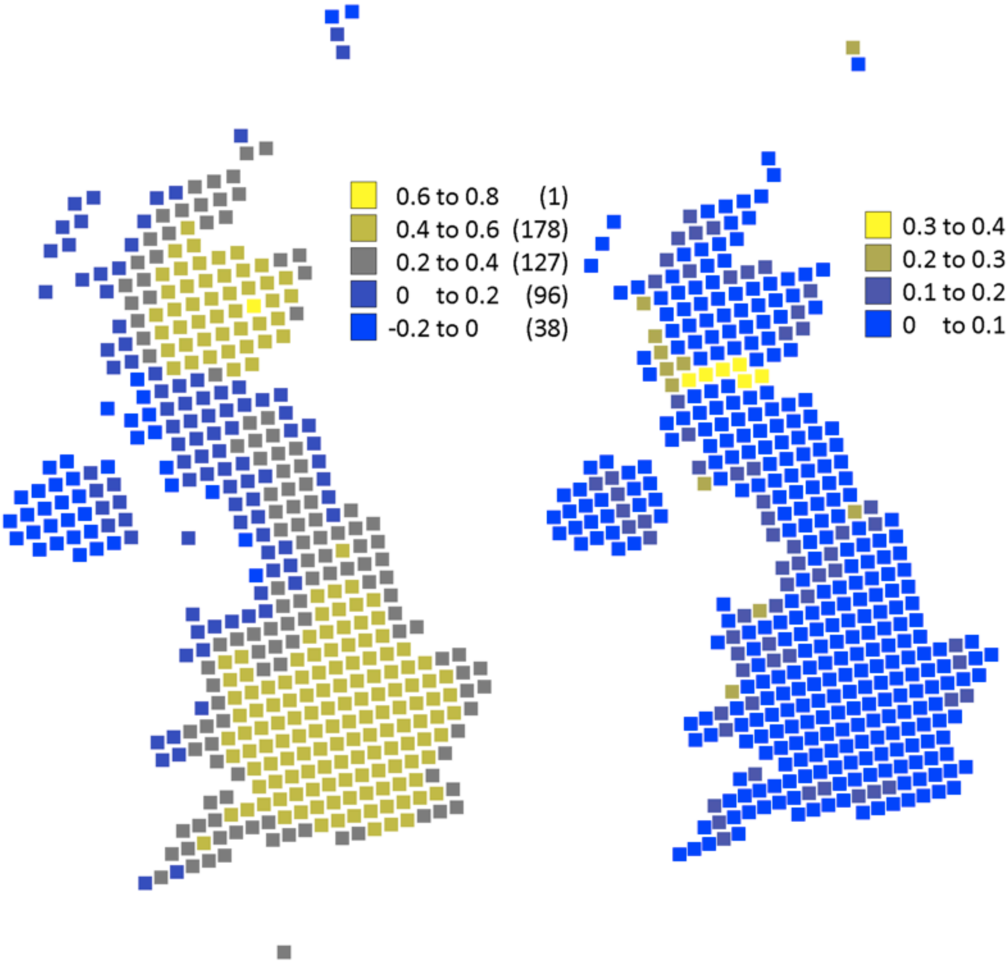

Figure 3. Maps showing the predicted change in annual mean diurnal temperature swing (σ = 0.20 °C), left, ($\Delta T_{max} - \Delta T_{min}$) and the absolute difference between adjacent squares (σ = 0.06 °C), right, on a 25 km grid for the whole of the UK. Data shown for the 2080s under the A1FI emissions scenario. The numbers in brackets represent the number of grid squares in that range.

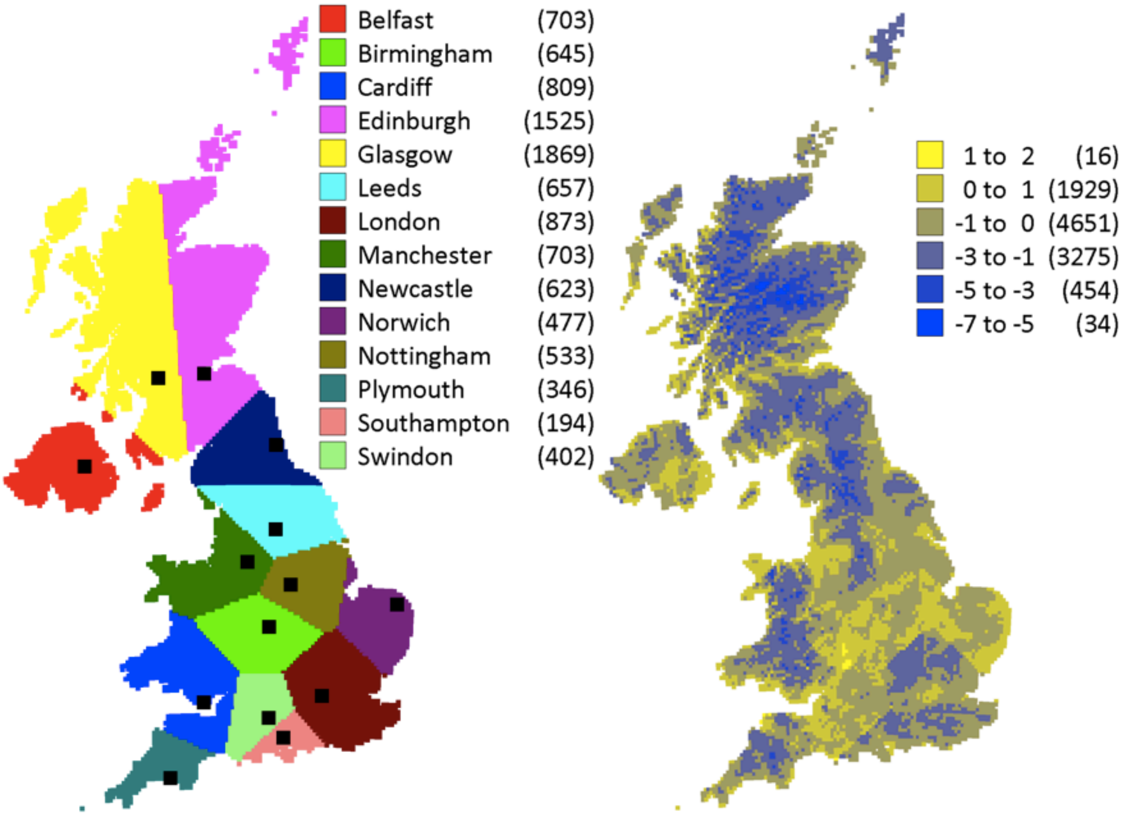

Figure 4. Map of the areas of influence of the 14 weather stations with the weather stations marked as a square (left) and the difference between mean annual air temperature (σ = 0.96 °C) at a point and that at the geographically closest point in the 14 station data set used for compliance modelling on the 5 km grid (right). Data shown for the period 1961-1990 (1970s). The numbers in brackets represent the number of grid squares in that range.

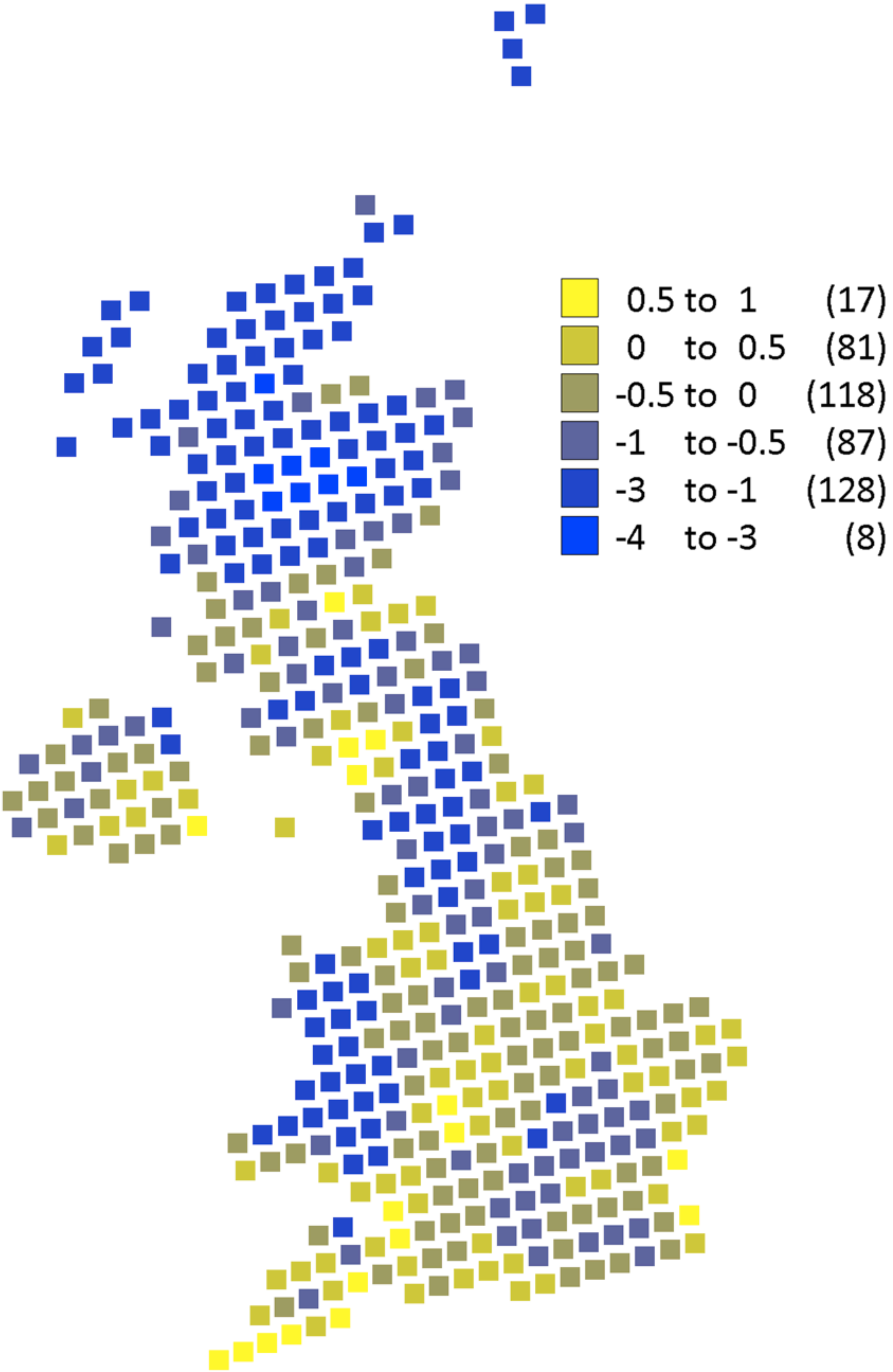

Figure 5. Map of the difference between mean annual air temperature (σ = 0.79 °C) at a point and that at the geographically closest point in the 14 station data set used for compliance modelling on the 25 km grid. Data shown is for the 2080s under the high emissions scenario and 50th percentile created by combining the 25 km Perry and Hollis data set with the relevant climate change projections. The numbers in brackets represent the number of grid squares in that range.

Figure 6 Illustration of the 5 km grid overlaid on the two chosen transects (arbitrarily numbered) shown on the Google Maps™ UKCP09 weather generator user interface.