Generating High Resolution Near-Future Weather Forecasts for Urban Scale Building Performance Modelling

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Introduction

The EU committed to lower greenhouse gas emissions 40% by 2030 from 1990 baseline. Building sector is the largest contributor to global greenhouse gas emissions emitting approximately a third of total emissions. To achieve the target, the United Kingdom (UK) Government's Department for Business, Energy & Industrial Strategy and the Government's regulator body for gas and electricity markets (Ofgem) is developing strategy to enable and enhance the use of demand-side response, energy storage and distributed generation. The Government's research funding body - the Engineering and Physical Sciences Research Council has identified energy efficiency and security, reliable infrastructure as priority areas for strategic development in its Delivery Plan 2016-20.

For implementing these changes and successfully managing the transition in building energy sector, quantitative tools and dataset are needed to understand and predict the dynamic demands from buildings and generations (particularly those from renewables) at urban and national scale. They are crucial elements for informing decision making within building and energy network control system.

Traditionally, understanding the performance of buildings requires high quality local weather data for building simulation and evaluation. The weather data are often 'secondary' data obtained from nearby airport weather station or through local measurement. The 'secondary' data are often so-called Typical Meteorological Year (TMY) data in the USA, or Test Reference Years (TRY) in Europe. TMY/TRYs were chosen from past 20-30 years data using the Finkelstein-Schafer statistic method. They reflect the most 'typical' conditions over a long period (decades), which are not suitable for understanding current building performance (recent months or a year). Local weather stations are often very expensive to install, particularly for urban scale modelling, and it takes long time and significant effects to collect data.

For demand-side management and energy storage system, predicting building and energy system performance is crucial and challenging. Various statistical models were developed based on historic data. They are robust, however not capable to deal with changing future factors, such weather. With help of future weather data, dynamic building energy simulation tools offer a potential to predict energy demands.

Opportunity

As a part of the United Kingdom Government's Open Access movement, the UK Meteorological Office (Met Office) made site-specific forecast data available to the public through the Met Office DataPoint service Met Office (2016b). The DataPoint service is an Application Programming Interface (API) that provides last 24-hour land and marine observations, and more importantly 3-hourly weather forecast for next 5 days. This provides a channel for smart phone APPs to access weather forecast reports for a specific location.

Next 5-day 3-hourly weather forecasts are issued 24 times per day, at approximately 55 minutes past each hour for approximately 6,000 locations around the UK including population centres, sporting venues and tourist attractions. These are significantly more than the number of observations stations and weather files available for buildings simulation. Currently there are around 140 temperature and humidity observation stations (figure 1 left) and 3 solar radiation observations stations around the UK. For building simulation, only 14 sites are available from the Chartered Institution of Building Services Engineers for practitioners.

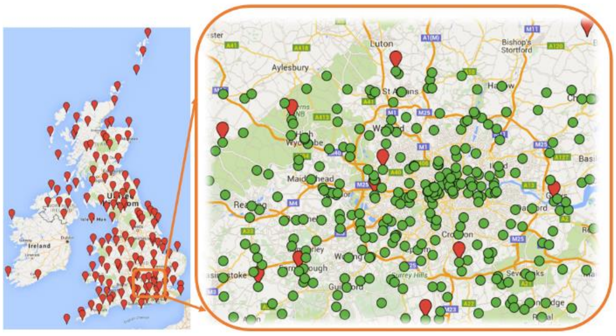

Figure 1 140 observation stations in the UK (red) and 302 forecast locations (green) around London

The Met Office DataPoint service provides a great opportunity for building performance simulation professionals in the following 2 aspects:

1. It provides forecast for 6,000 locations, 40 times higher density than observation stations. If the forecasts are accurate enough, they can be used to conduct building simulation for those locations do not have weather stations. For example, for buildings

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in London, practitioners normally use historical weather data from Heathrow or Gatwick airport for building simulation. With the help of the Met Office DataPoint service, weather data from more than 300 locations are potential available (shown in figure 1 right). It reduces the distance between the location of building and the location of weather data from tens of kilometres to several hundreds of meters or few meters, therefore it increases the accuracy of building performance prediction.

2. The Met Office forecast are made available for next 5 days, therefore they can be used for predicting building energy demands and renewable generations for next few days at individual building, urban and national scale. This is particularly important for understanding the implication of future weather and make response to it.

For both aspects, one of key question immediate raised is the accuracy: how close are they comparing with observations?

Met Office forecast and its accuracy

Authors' previous studies (Du et al., 2016b, Du et al., 2016a) have compared the forecasts with observation for London, Cardiff, Edinburgh and Belfast independently to the institute making the forecasts. The results show that the next 24-hour forecast temperature, relative humidity, wind speed and wind direction are very close to observations, often less than 1 ºC difference in temperature, 5% difference in relative humidity, 1.5m/s difference in wind speed and 25 degree difference in wind direction. This provided a reasonable level of confidence in creating 'true' weather data for locations that do not have weather observation stations, and in conducting building performance prediction.

Instead of repeating the previous findings, this section mainly addresses the accuracy question from physical modelling perspective: how does the Met Office forecast work?

The Met Office forecasts are generated through a number of models (*Figure 2*) that covers different scale and grid length. The Met Office runs a 25 km global weather forecasting model, which is able to represent the large-scale weather patterns, A 25 km model can also resolve regions weather activity; however, there are still many important weather phenomena which take place on more local scales and require a more detailed model. For this reason, the Met Office runs a version of the Unified Model over the UK with finer grid. It claims that weather phenomena, such fog filling valleys, enhanced rain over mountains and more importantly for this study, higher temperatures in cities, are included.

The UK Site Forecasts are generated through the UK High Resolution Unified Model calculations on Met Office's Cray Supercomputer that is capable to do 16000 trillion calculations a second. The High Resolution Unified Model has a fine grid of 1.5km by 1.5km horizontally (for inner domain, 4 km for outer, Figure 3) and 70 layers vertically for about 40km high.

The World Meteorological Organisation compares similar statistics among national meteorological services around the world. Their results show that the UK Met Office is consistently one of the top two operational services in the world (Met Office, 2016a). The Met Office publishes its accuracy regularly by comparing forecasts to the actual values observed at a list of 119 sites across the UK. Over past 3 years, 95.2% of temperature forecasts are accurate to within +/- 2°C on the current day. Their reports shows that the accuracy of forecasts has been improving significantly over 3 decades. A four-day forecast today is more accurate than a one-day forecast in 1980.

Figure 2 Met Office Numerical Weather Prediction models coverage areas (Met Office, 2016c)

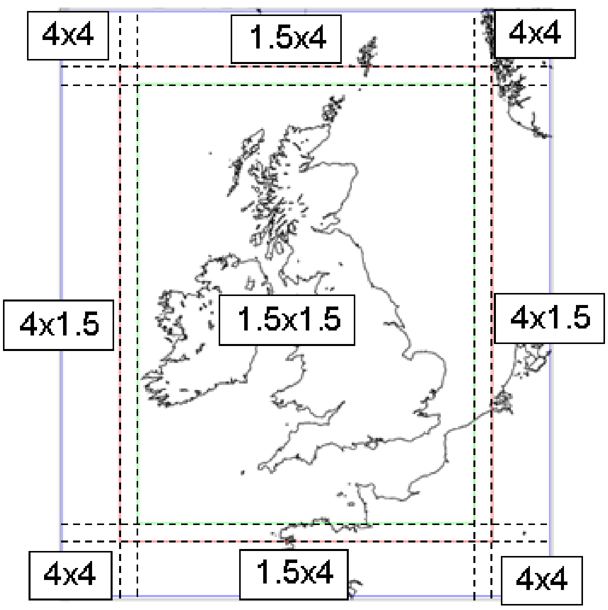

Figure 3 UK 1.5km Resolution Unified Model (Met Office, 2016d)

On behalf of the UK Government, the Department for Business, Energy and Industrial Strategy is spending approximately £117 million per year on Met Office Public Weather Service to help the UK public make informed decisions about day-to-day activities using weather forecasts. Energy and building sector should make use of such valuable resources for demand and generation prediction.

Methodology

This paper proposed a novel approach to predict urban heat island effect impacts on building heating and cooling energy consumptions using dynamic building simulation packages. To deliver the aim, 4 working packages were conducted:

1. Repeatedly gathering next 24-hour forecast and observation weather data for interested locations on rolling basis from 1st January 2016 to 30th November 2016 when this paper was drafted. This was achieved by running the following Matlab script 3 times a day at 00:45am, 02:45am, 12:45noon to gather most recent forecast from the Met Office DataPoint API and avoid any missing value.

```
%% To get a three-hourly five-day forecast for locations in
column C 'forecast'
load forecast %loading weather forecast location and observation
station names and their station IDs
for id=1:size(Forecast_unique,1)
    datapointURL='http://datapoint.metoffice.gov.uk/public/data/'
    ; % MetOffice DataPoint API URL
    locationId=num2str(Forecast_unique(id));
    locationName=char(txt(Forecast_index(id)+1,5));
    resource=strcat('val/wxfcs/all/xml/',locationId,
    '?res=3hourly'); % get 3 hourly data
    APIkey='[redacted]'; % Private key
    datapointURL=strcat(datapointURL,resource,'&key=',APIkey);
    FileName=[locationName,'_Forecast_',datestr(now,
    'dd-mmm-yyyy hh'),'.xml'];
    urlwrite(datapointURL,FileName); % get XML file from
    MetOffice DataPoint API
end
```

Figure 4: Matlab script to gather forecast data from Met Office DataPoint API (personal key number is omitted)

2. Constructing weather files in EPW format which are ready for use in building simulation. Quality control and calculating missing weather parameters were the key tasks within this working package. A Matlab script was developed to converting the Extensible Markup Language file (.xml, which were received from the API) into readable weather files and calculated wet bulb temperature and diffuse, direct and global horizontal solar radiation. The direct and diffuse solar radiation are important components for simulation; however, the forecasts did not have this readily available. In this paper, authors follow Duffie and Beckman (1980)'s method to calculate them using the forecast relative humidity and calculated sun position. A validation against observed data was conducted, and the results were shown in Solar radiation section of this paper.
3. With the gathered next 24-hour temperature forecasts above for 302 points around London, the changing temperatures distributions were mapped against time using QGIS 2.18 (qgis.org, 2016) and its Inverse Distance Weighting (IDW) interpolation plugin. It is one of the most popular interpolation techniques for spatial interpolation application (Bhattacharjee et al., 2013). The Urban heat island Intensity (UHII) was then calculated in Matlab and plotted against time to demonstrate its intensity. The results were shown in UHI effect section of this paper.
4. In order to test the energy implications of predicted urban heat island effects on buildings at different locations of the city, authors conducted dynamic building energy simulation using simulation engine EnergyPlus Version 8.6 (US Department of Energy, 2016) to explore the heating and cooling energy consumptions in a summer week and in a winter week. EnergyPlus software has been tested against ANSI/ASHRAE Standard 140-2001 and are widely used in both practitioners and researchers in a number of countries. A single zone building - Case 640 (figure 5) in ANSI/ASHRAE Standard 140-2001(ASHRAE, 2001) was chosen as the case study building due to its simplicity and it has been widely used for comparative studies. The building is a rectangular single zone (8 m wide x 6 m long x 2.7 m high) with no interior partitions and 12 m^2 of south facing windows. The building is of lightweight construction with wall U-value of 0.514, roof U-value of 0.318 and floor U-value of 0.039 W/m^{2}K. Heating and cooling set points were applied in the model to test energy implications of urban heat island effect. For further details of model drawing and settings, please refer ANSI/ASHRAE Standard 140-2001. Due to the natural of testing, following changes have been made in the Case 640 model:
   - Location of buildings => London
   - RunPeriod: 1st of May to 30th November 2016
   - Schedule:Day:Hourly- Zone Heating Setpoint All Days => 22 ºC; Cooling Setpoint remain 27 ºC

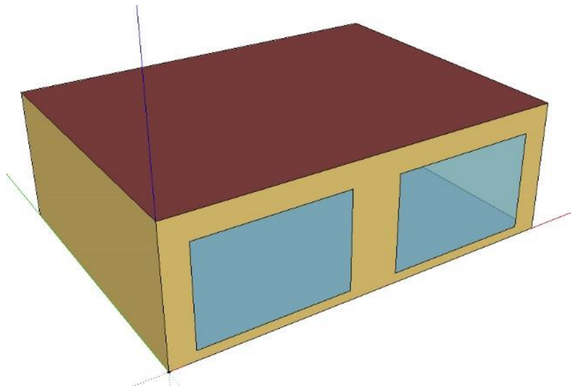

Figure 5: A single zone building - Case 640 defined within ANSI/ASHRAE Standard 140-2001

Solar radiation

As the Met Office DataPoint API currently do not offer solar radiation forecast data freely for public, solar radiation needs to be calculated from location and weather conditions. Previous research (Dimas et al., 2011, Spokas and Forcella, 2006) has demonstrated that solar radiation could be calculated using relative humidity and sun position. The accuracy is linked to the determination of beam atmospheric transmittance, which was assigned based on humidity, and a determination matrix. Dimas et al. (2011)'s research shows that their correlation coefficient between predicted and measured is 0.9 (R=0.95). Therefore, this approach is adopted and described as bellow.

The horizontal direct (beam) radiation (G_{Bh}) was calculated via the following equation (Duffie and Beckman, 1980).

$$G_{Bh} = G_{oh}\tau\, cos\theta_z \qquad (1)$$

Where τ is the atmospheric transmission, $G_{oh}$is the solar constant taken as 1360 W/m2, θ_z is the zenith angle. The value of τ was determined from the relative humidity using the relationship shown in Table 1.

Table 1: Atmospheric transmission determination matrix using RH. (Dimas et al., 2011)

RH condition (%)	τ value
RH ≤ 40	0.69
40 < RH ≤ 45	0.67
45 < RH ≤ 55	0.57
55 < RH ≤ 65	0.47
65 < RH ≤ 75	0.41
75 < RH ≤ 85	0.3
RH > 80	0.2

The diffuse component G_{Dh} was calculated via the following Liu and Jordan (1960) 's method.

$$G_{Dh} = 0.3\,(1 - \tau^m)G_{oh}\, cos\theta_z \qquad (2)$$

Where m is the optical air mass number, which can be calculated from the following equation (Dimas et al., 2011)

$$m = \frac{Pa}{101.3\, cos\theta_z} \qquad (3)$$

Where Pa is the atmospheric pressure (kPa) which was approximated from the elevation α (m).

$$Pa = 101.3\, e^{-(\frac{\alpha}{8200})} \qquad (4)$$

The calculated globe solar radiations were compared with observations from Fair Isle weather station in the UK (longitude 1.628, latitude 59.527). The hourly solar radiation observation data are from the Global Radiation Observations database from the Centre for Environmental Data Analysis (CEDA, 2016), which is based within the UK Science and Technology Facilities Council's Rutherford Appleton Laboratory. Fair Isle is one of three locations having hourly solar radiation data within the database. The relative humidity and pressure data are from UK Hourly Weather Observation database, also from CEDA.

As shown in figure 6, there is significant scatter indicated by the large R^2 value of 0.66 and there is a tendency for the calculation method to underestimate the global radiation. Figure 7 shows one-week time series comparing the observed and calculated global solar radiation. It can be seen that the calculated values were underestimated in most of days during the week.

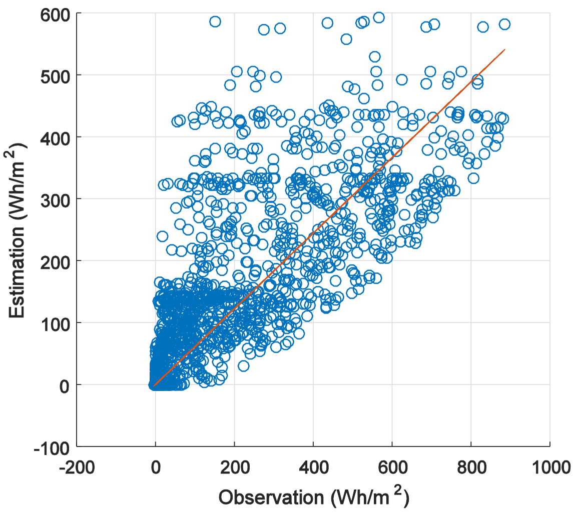

Figure 6: Comparison of observed and calculated global solar radiation for Fair Isle. R^2 of 0.66.

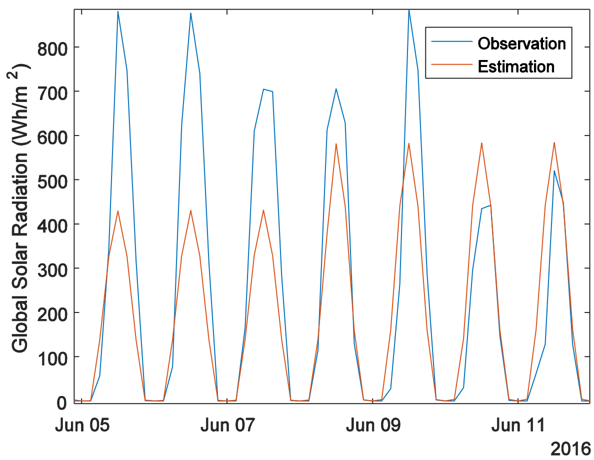

Figure 7: Comparison of observed and calculated global solar radiation time series.

Comparing with the previous, above method is able to generation both direct and diffuse solar radiation; however, the accuracy is not as good as previous study. Given the fact of less accuracy of above solar radiation model, the building simulations were conducted with the same set of solar radiation data for all sites near London. A time series of beam and diffuse radiation are shown in figure 8 and they are been used for the following heating and cooling energy consumption simulation.

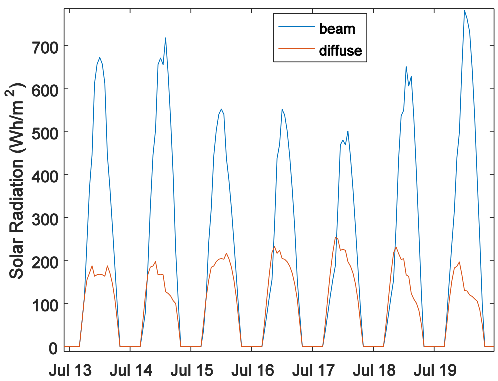

Figure 8: Time series of solar radiation for London used in the building simulation weather data.

Predicted Urban Heat Island effect

To understand the temperature difference between different locations in the nearby area, a comparison study was conducted using observed temperature data from 9 weather stations around London. Locations of these stations are shown as red dots in the right map of figure 1. Heathrow is the warmest place comparing with others as shown in figure 9. The difference could be 2 ^{o}C on average over the 10-month period starting from 1st January 2016.

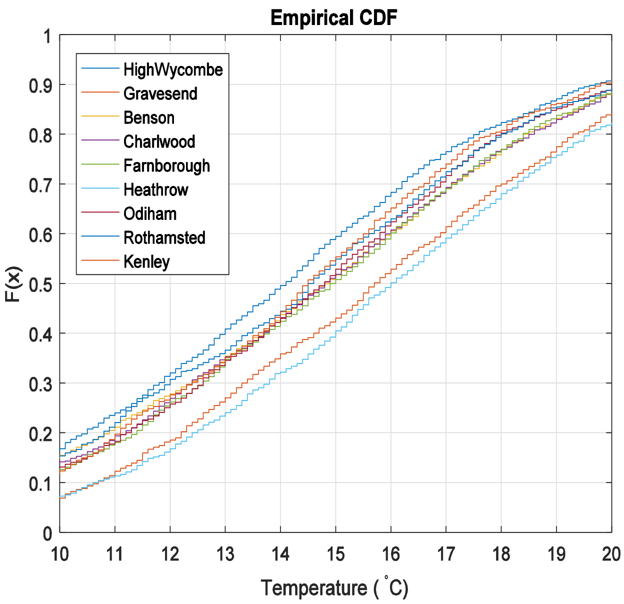

Figure 9: Cumulative frequency distribution of observed temperature over 10-month period from 1st January 2016

The density of observed data points is not enough to map the temperature distribution around London, particularly because of the lack of data points in the central London. Quantifying urban heat island effect often requires the observation of air temperature distribution over the whole city with either moving or fixed monitoring devices, or satellite or aircraft mounted radiometers. Above methods often are very expensive and labour intensive. With the availability of forecast data from the 302 locations around London (green dots in the right map of figure 1), the temperature distribution could easily be obtained.

The predicted temperatures distributions (at 9am, 12noon and 3pm on 2nd November 2016) around London were mapped using next 24-hour temperature forecasts (made at 00:55am on 2nd November 2016) from 302 data points around London in QGIS 2.18 software. The software's Inverse Distance Weighting (IDW) interpolation method calculates the temperature values for locations do not have forecast data. The results (figure 10-12) shows the central London is general 2-3 ^{o}C warmer than its boundary area, but it also depends on the incoming warm air and its moving direction.

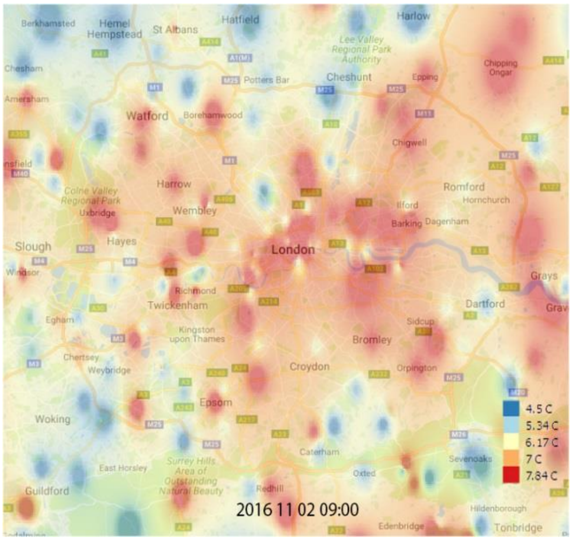

Figure 10: Predicted urban heat island effect at 9am 2nd November 2016

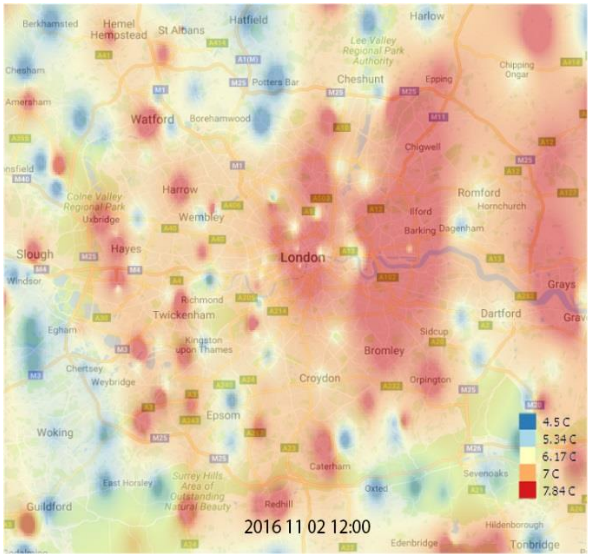

Figure 11: Predicted urban heat island effect at 12noon 2nd November 2016

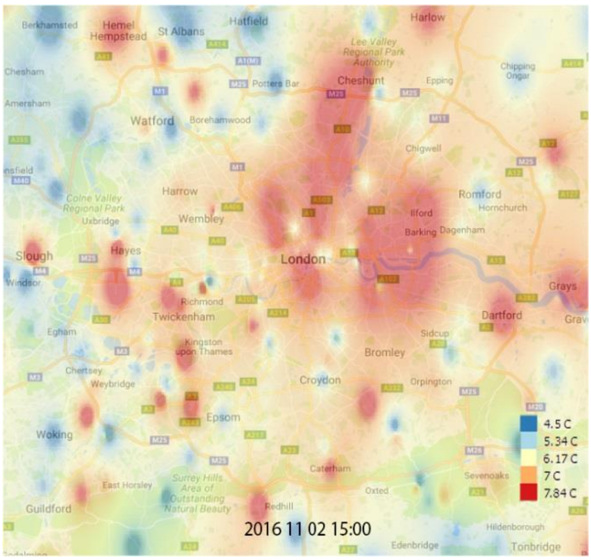

Figure 12: Predicted urban heat island effect at 3pm 2nd November 2016

To quantify UHI effect, this paper defines the UHI Intensity (UHII) as the temperature difference between the average temperature of the central cluster and the average temperature of boundary at each specific time step.

$$UHII = \frac{\sum_{i=1}^{n} T_{ci}}{n} - \frac{\sum_{i=1}^{m} T_{bi}}{m} \quad (5)$$

where T_c and T_b are temperatures of the cluster and the boundary, respectively. n and m are the number of points at the centre and boundary.

Out of total 302 locations around London, a group of 12 points (red dots in figure 13) was chosen as the central cluster and another group of 43 points (blue and yellow dots around M25 Orbital Motorway) was selected as boundary due to their geographic distribution and around to M25 - the natural boundary of London.

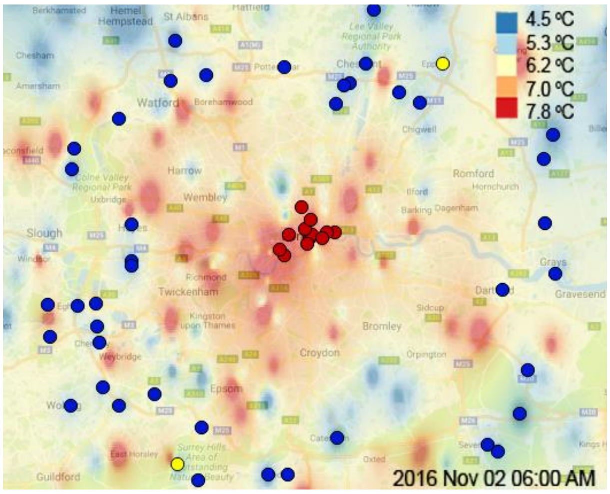

Figure 13: Predicted urban heat island effect and core (red)/boundary data points (blue and yellow)

The similar definition has been applied in previous studies (Zhou et al., 2013, Debbage and Shepherd, 2015), although natural city centre and boundary M25 are employed in this preliminary study instead of applying the City Clustering Algorithm (Rozenfeld et al., 2008) and computing boundary (Peng et al., 2012).

The calculated UHI Intensity for first week of November 2016 is shown in figure 14 (blue bar). It ranges from 0.4 to 2.3 ºC during this period and often reaches peak at early morning and when temperature of boundary (yellow line in figure 14) drops. This is in line with the common understanding that city centre tends to hold the heat when temperature of the city drops. Further study of other time periods shows that UHI effect is evident all year around and peaks in both summer and winter.

Energy implications

The temperature difference between city central and outside boundary is evidenced through above study. It is important to understand its energy implications on heating and cooling of buildings. As discussed in the methodology section, this section present the EnergyPlus simulation results of a rectangular single zone building (8 m wide x 6 m long x 2.7 m high) with 22 ºC heating setpoint and 27 ºC cooling setpoint.

Authors assumed that the same building is located at 2 places in city centre and 2 places at the boundary of London. Boundary points are highlighted as yellow dot in Figure 13. The exact locations of testing points are listed in Table 2. They were randomly chosen from central cluster and boundary groups to represent buildings at city centre and city boundary.

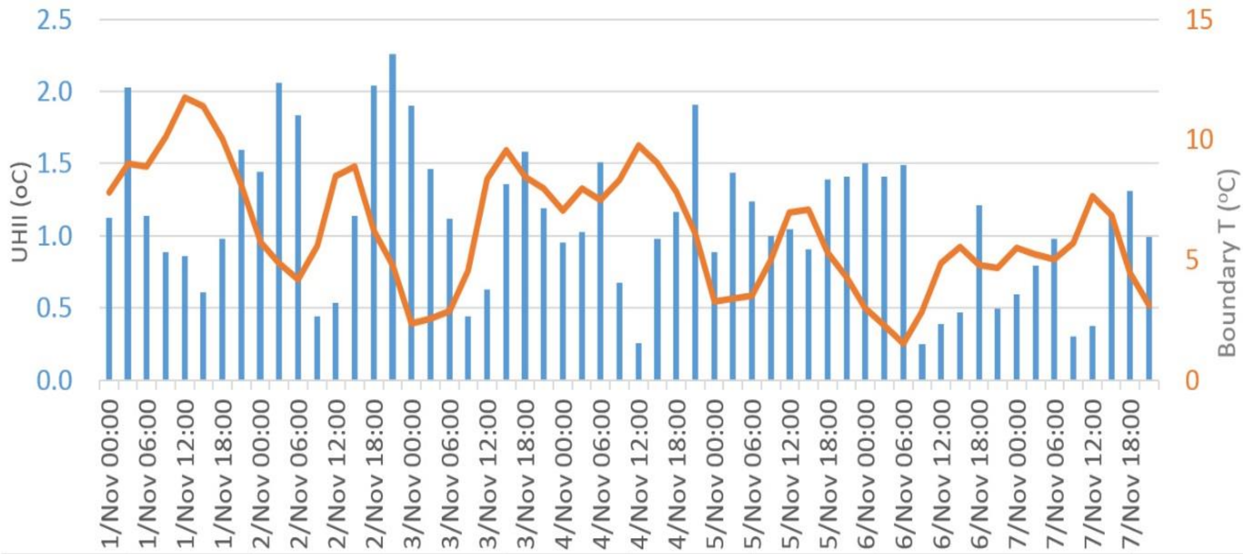

Figure 14 Predicted UHI intensity over a week starting from 1st Nov 2016

Table 2: Locations of test buildings

Type	ID	Location	Lat.	Lon.
Boundary	351389	Epping	51.70	0.11
	353811	Tanners Hatch	51.25	-0.37
Central Cluster	324386	Horseguards Parade	51.50	-0.13
	351301	Earl's Court	51.49	-0.18

To represent summer and winter weather conditions, the week starting from 13th July 2016 and a week starting from 1st November 2016 were chosen for building heating and cooling energy simulation respectively.

The simulation results (Table 3) show that the buildings at city centre need 42% more energy for cooling in summer comparing with the same building located at city boundary due to urban heat island effect.

However benefiting from the warmer weather, buildings in city centre consume approximately 32% less energy for heating in summer and 12% less energy for heating in winter.

Table 3: Heating and cooling energy demand in a summer week (13-19 Jul 2016) and a winter week (1-7 Nov 2016)

Testing	City Boundary		City Centre	
	351389	353811	324386	351301
Summer Heating	36.7 kWh	+6%	-33%	-30%
Summer Cooling	27.8 kWh	-9%	+41%	+42%
Winter Heating	201.4 kWh	-1%	-12%	-12%

Discussion

The approach of using open access weather forecasts provides a great convenience for building simulation professionals. It not only reduces the distance between locations of weather data to buildings, but also offers a new way of construct weather data which could be used to map the predicted demand of buildings, generation from renewables and living conditions (comfort).

There is an argument that it would be better to use the measured data from weather stations and use spatial approximation algorithms to get data for certain locations. However, this often involves expert knowledges of local environment. The accuracy study (Du et al., 2016b, Du et al., 2016a) has shown that forecasts are reasonable close to observations. This approach reduces the possibility of human error when shifting the weather using tools like METEONORM.

The solar radiation model applied in this study underestimates global radiation value. It could be improved by redeveloping atmospheric transmission determination matrix for UK sites or use conventional meteorological models of solar radiation described by Muneer (2007) or Perez et al. (1990). In addition to relative humidity, solar UV index, visibility, precipitation probability and weather code within the forecast data could be used to develop the atmospheric transmission.

The UHI study reflects previous empirical study that London's UHI is most intense near the centre of the city, during night-time, in summer, under stable, anticyclonic weather (Wilby, 2003). The higher cooling energy demand was also mentioned in Graves et al. (2001)'s study. This paper provides quantitative model and data to support this argument. The method proposed here also outlines a potential to quantify the benefits of the building and urban design countering the UHI effects.

Conclusion

This paper focuses on building performance modelling using high spatial resolution weather forecasts from the UK Met Office. The UK Met Office makes weather forecast through a High Resolution Unified Model with 1.5km grid density over the UK. The model considers detailed weather phenomena, such fog filling valleys, enhanced rain over mountains and higher temperatures in cities. The forecast data were made available through the Met Office DataPoint API service. The public could access both real-time observation weather data for about 140 stations and next 5-day 3-hourly weather forecasts for nearly 6,000 locations in the United Kingdom. The forecast is reasonable accurate comparing with observation. This paper explores the method to gather these data regularly on daily basis and convert it into a format that is used for urban heat island effect study and building dynamic simulation. A model of calculating solar radiation was examined in this study.

The results shows that the predicted UHI Intensity for London is ranging from 0.4 to 2.3 ºC during a week period and often reaches peak at early morning. The warmer weather in city centre of London would cause 42% more energy usage for cooling comparing with the same building located at the city boundary. For heating, the UHI effect could help reduce 32% energy consumption in summer and 12% in winter.

Future research

Due to the importance of forecast for building energy management system and renewable energy system, future research could be conducted in many disciplines. For example, by 2030 exceeding 50% capacity of the EU power network will be various renewables sources, the outputs from which highly depends on changing weather factors, therefore it is important to establish stable and forecast-based controlled energy systems to match the changing demand. The development of predictive control algorithms will be the immediate future research topic.

As demonstrated in this paper, high-resolution weather forecasts can be used to model building energy demand. A systematic approach of conducing such study at urban and regional scale needs a development of bottom-up urban energy model, which supports multiple weather inputs.

Although this study is UK-focused and forecast data is only available for UK locations, the same method can be applied to locations outside the UK as long as there is a suitable weather forecast API provider.

Authors have already identified a number of equivalent weather forecast API providers outside the UK, such as AccuWeather API, OpenWeatherMap API, NOAA API, AerisWeather API, Wezzoo API and so on. For example, Openweathermap.org is global weather API provider, which is supported by NOAA GFS model and Environment Canada data. It offers the access of current and next 5-day 3-hourly forecasts weather data for over 200,000 cities around world based on models and measurements from 40,000 weather stations. Therefore, future research will be an extension of this paper to help global users to get access to reliable weather data for building simulation and optimisation. In case of the breakdown of single data source, multiple APIs could be employed at same time to increase system stability.

Acknowledgements

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