



This is the final peer-reviewed manuscript as accepted for publication by the publisher ('the post-print').

PLEA 2017 EDINBURGH

Design to Thrive

A novel approach to predict real-time urban heat island effect and indoor overheating

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Abstract: Quantifying urban heat island effect often requires the observation of air temperature distribution over the whole city. Satellite or aircraft mounted radiometers, car mounted temperature sensors and GPS loggers or fixed point monitoring have been employed in previous studies for urban heat island effect analysis. Above methods often are very expensive, labour intensive and have its own limitations. This paper proposes a novel approach to measure in real-time, and most importantly to predict urban heat island effect and indoor overheating through weather forecast data feeds services, such as the UK Met Office DataPoint service, which releases 3-hourly site-specific forecast for nearly 6,000 locations in the UK. The geographic high resolution weather forecasts are made available for over 300 locations around London, which provides rich dataset for urban heat island effect study and indoor overheating study. In this paper, authors have compared the observed temperatures with next 24-hour forecasts from 7 different forecast providers. The relatively small difference (often less than 1°C) provides us confidence in creating 'true' temperatures for locations that do not have weather observation stations. This enables built environment researchers and industrial partners to predict indoor temperature and mitigate indoor overheating risks effectively.

Keywords: weather forecast, urban heat island, prediction, overheating, modelling

Introduction

Overheating risks under changing climate has been identified by a number of research projects in the UK. Since 2009, the Adaptation and Resilience in the Context of Change network (hosted at ECI, Oxford) has facilitated the networking and synthesis of research in adaptation and resilience of buildings and infrastructure to climate change. The network integrated the findings from a number of EPSRC research projects to help ensure that policy and practice have the best available evidence. These EPSRC projects include DeDeRHECC (EP/G061327, Prof Short, Cambridge), LUCID (EP/E016375, Prof Davies, UCL), SNACC (EP/G060959, Prof Gupta, Oxford Brookes), COPSE (EP/F038178) and SCORCHIO (EP/E017398, Professor Levermore, Manchester), PROMETHEUS (EP/F038305, Prof Coley, Bath), PROCLIMATION (EP/F038151, Prof Hanby, Loughborough), Decision support for building adaptation in a low-carbon climate change future (EP/F038240, Prof Banfill, Heriot-Watt).

These projects provided the growing evidence of overheating occurring more frequently in hospital, homes(both new and existing), and especially in smaller, single-aspect dwellings where cross ventilation is more difficult to achieve. The Good Homes Alliance report highlighted 30% of flats and elderly care homes built after 2000 overheated. In hospital, medium-rise ward block built in late 1960s would be deemed too hot by 2030s based on

HTM03-01 criterion (Short et al., 2012). Rodrigues et al. (2012) studied summer overheating potential in a low-energy steel frame house in future climate scenarios, and Adekunle and Nikolopoulou (2016) did similar study for a prefabricated timber housing. At national scale, Beizaee et al. (2013) conducted the survey of summer temperatures and overheating risk in English homes. Taylor et al. (2016) mapped indoor overheating risk modification across the UK using historical design summer year and data from CIBSE.

Jenkins et al. (2014), Liu et al. (2016) and Du et al. (2012) developed future weather data tools for assessing the long term risk of overheating in buildings for future climates. The building performance modelling using future weather data (Ji et al., 2014) shows that overheating could occur in pre-1919 Victorian property as early as 2020s based on CIBSE Guide A and adaptive comfort criteria BS EN 15251.

The Joseph Rowntree Foundation report (Gupta et al., 2016) highlighted that there was a mismatch between long term overheating prediction in climate modelling and those measured through environmental monitoring. Researchers at UCL modelled (Oikonomou et al., 2012) and monitored (Pathan et al., 2017) indoor overheating in London domestic building stock. These are clear evidences showing the link between indoor overheating and urban heat island effect. The urban heat island intensity in Manchester has a highly significant rising trend which by the end of the century could add 2.4 °C to the average annual urban temperature, on top of the predicted climate change increase (Levermore et al., 2017). A framework is proposed (Lazos et al., 2014) to utilise a range of weather variable predictions in order to optimise certain commercial building systems.

Opportunities and novelty

All previous studies mentioned above required the observation of air temperature distribution over the whole city to quantify urban heat island effect. Satellite or aircraft mounted radiometers, car mounted temperature sensors and GPS loggers or fixed point monitoring have been employed in previous projects for urban heat island effect analysis.

Above methods often are time consuming, expensive, labour intensive and have their own limitations. Satellite imaging needs to be conducted at clear sky condition, however urban heat island effect tends to occur at night when the city were covered by stable cloud and still air. Car mounted data collections require a certain number of personnel at the same time to perform a transect measurement and are not suitable for longer term measurement. Fixed point monitoring has been seen the most accurate method, however it needs to install significant number of temperature sensors and data loggers or data acquisition system around urban environment. This often involves high capital/labour cost and difficulties of getting permissions to install monitoring equipment in desirable locations. The study for Great Manchester (where 59 temperature data loggers were installed) had involved 8 different local councils which took almost a year to negotiate with.

Since 1973, researchers (Corpening et al., 1973) have begun to develop statistic models to predict summer peak energy load. The accuracy of weather data has always been a weak point for many years. However the accuracy of weather forecasts has been improving significantly over the past 3 decades. A four-day forecast today is more accurate than a one-day forecast in 1980 (Met Office, 2016). This paper proposed a novel approach to measure in real-time, and most importantly to predict urban heat island effect and indoor overheating risks through weather forecast Application Programming Interfaces (APIs) service. The UK Met Office DataPoint API service releases 3-hourly site-specific forecast data feeds for nearly 6,000 locations in the UK which covers population centres, sporting venues and tourist

attractions in all cities. For London, the geographic high resolution weather forecasts are made available for over 300 locations (yellow dots in figure 1), which provides rich datasets for urban heat island effect study and indoor overheating study.

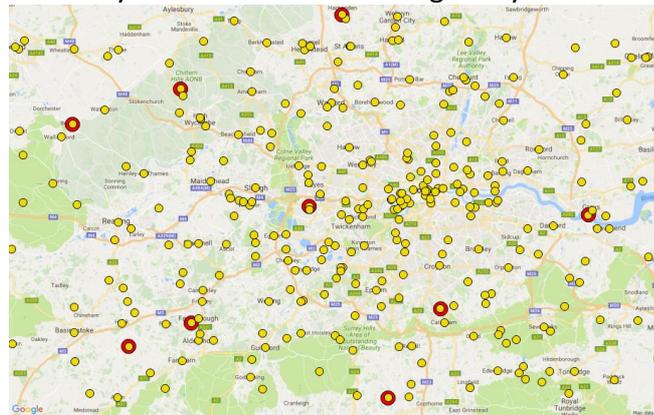


Figure 1 Weather observation stations (red dots) and locations with weather forecast available (yellow dots)

The method reduces the distance between the location of building and the location of weather data from hundreds/tens of kilometres to hundreds of meters or few meters, therefore it increases the accuracy of building performance prediction, and most importantly, its geographic high resolution next 5-day 3-hourly forecasts can be used for predicting building indoor environmental condition, energy demands and renewable generations for next few days at individual building, urban and national scale.

A number of weather forecast APIs currently available for public to use around the world due to the popularity of smart phone and weather forecast APPs. There are at least 7 API providers (listed in table 1) offering cost free service for the public. However there are often restrictions attached, such as the total number requests, and/or maximum frequency of requests (see table 1). These APIs offer worldwide opportunities for researchers and industrial partners to explore weather adaptation solutions in built environment.

Table 1. Cost free weather forecast API providers and their limitations

API provider	Calls limit	Max call frequency	Forecast	Data source
datapoint.metoffice.gov.uk	5000/day	100/minute	5-day 3-hourly	XML/ JSON
api.openweathermap.org	None	60/minute	5-day 3-hourly	XML/ JSON
api.weatherbit.io	None	45/minute	5-day 3-hourly	JSON
api.darksky.net	1000/day	None	7-day hourly	JSON
api.wunderground.com	500/day	10/minute	10-day hourly	XML/ JSON
api.apixu.com	5000/month	None	10-day hourly	XML/ JSON
api.met.no	None	None	10-day 3-hourly	XML

Method

The main aim of the paper is to demonstrate the novel approach of predicting urban heat island effect and its impact on indoor overheating through linking near future weather forecasting and building performance simulation. To achieve this aim, following eight working tasks were conducted in sequence by using numerical programming tool Matlab, building energy simulation tool EnergyPlus and geographic information system tool QGIS.

Task 1: Regularly capture next 24-hour forecasts and observations for the locations interested in this study from different weather forecast API providers. This was achieved through scheduling Matlab tasks 4 times a day to download the latest next 24-hour forecasts and past 24-hour observation in the file format of .xml or .json over 7 months period starting from April 2016. In this study, the rolling next 24-hour forecasts for 302 locations in London

and forecasts for Cardiff, Belfast, Edinburgh and Heathrow airports were recorded. The observations from weather stations at Cardiff, Belfast, Edinburgh and Heathrow airports and other 8 locations around London (red dots in figure 1) were also recorded 4 times a day for the same period. This involves sending over 1.8 million requests to different API providers and saving the corresponding data files.

Task 2: Convert the received data files into a Matlab data file. The files returned from APIs are normally in .xml or .json format. A bespoke Matlab script was developed to combine the individual observation or forecast files into time series data matrix, and cubic spline interpolate data for any gap shorter than 3 hours.

Task 3: Compare the weather observation at four UK capital cities with next 24-hour forecasts made for the same location, and identify the best forecast provider for the UK. This study is essential to understand the data quality of forecasts from different API providers. Note that each data provider may have strength in creating forecasts for a particular region. For example, the UK Met Office has better understanding of UK weather, whereas the Norwegian Meteorological Institute might do better job in their geographical coverage area.

Task 4: Understand the distribution of the difference between next 24-hour forecast and observations obtained from weather stations. This was based on the statistical analysis of a relative long term dataset (7 months period in this study). It provides evidence for quantifying the forecast accuracy of the particular weather forecast provider.

Task 5: Once the confidence of weather forecast was established, the sensitivity of forecast in relation to geographical distribution was tested through comparing the forecasts made available for a number of locations in the same city. In this paper, the forecasts for 302 locations around London were studied.

Task 6: Above testing and comparisons with observation provide qualitative evidences in creating the next 24-hour temperature mapping for a city, in this paper, London. This enables researcher and industrial partners to predict outdoor temperature at city centre and fringe, to map urban heat island effect and qualify urban heat island intensity numerically.

Task 7: Outdoor temperature forecasts for different parts of the city were translated into indoor warmness through building performance modelling in this task. EnergyPlus Version 8.6 were used in this task. It has been tested against ANSI/ASHRAE Standard 140-2001 and are widely used by both practitioners and researchers internationally. A single zone high mass building for free floating temperature test - Case 900FF 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 overheating 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 m² of south facing windows. The building is of heavy weight construction with wall U-value of 0.512, roof U-value of 0.318 and floor U-value of 0.039 W/m²K. There is no mechanical heating or cooling system. Please refer ANSI/ASHRAE Standard 140-2001 for further details of model drawing and settings.

Task 8: The indoor temperatures for the 2 identical case study buildings located at city centre and fringe were compared against CIBSE overheating benchmarks CIBSE Guide A 2006 and CIBSE TM52/BS EN 15251 adaptive thermal comfort standard. Results of comparison studies and modelling results of case study buildings were reported in the following section.

Results and discussions

The task 1 and 2 are the designed for generating raw data for the following study, and there are no statistical or graphic outputs. This section illustrated the results from task 3-8 and the subheadings are named accordingly.

Results – Task 3: Selection of weather APIs

The Root Mean Square Errors (RMSEs) between observation and forecasts from 7 different weather APIs were calculated to quantify how close these forecasts are to observations from weather stations. Figure 2 shows that the UK Met Office has the best forecast for the UK over the testing period. In general, the difference between UK Met Office forecasts are less than 1 °C. The relatively small difference provides us confidence in creating ‘true’ temperatures for locations that do not have weather observation stations. Hence, all the following studies used the UK Met Office forecasts.

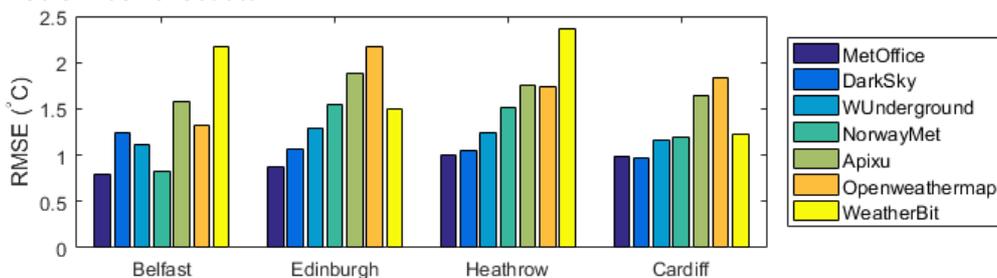


Figure 2. RMSE between observation and forecasts from 7 different weather APIs (1st to 6th April)

Results – Task 4: Comparison between observation and forecast

The observed temperature and 24-hour ahead forecast at London Heathrow from the UK Met Office during the period of 1st May to 31st December 2016 was shown in figure 3. It confirms that the forecast is very close to observation. The blue line in late July, early September and early October was due to missing forecast data which was caused by shutdown of data collection computer. Figure 4 illustrates the distribution of the difference between forecasts and observations for additional 8 locations in London. The central red line indicates the median of difference which are very close to zero. The bottom and top edges of the box indicate the 25th and 75th percentiles of difference distribution, respectively. This means that, for over half of testing period, the difference between forecast and observation are less than 0.5 °C for most of sites. Occasionally the difference could reach 2-3 °C.

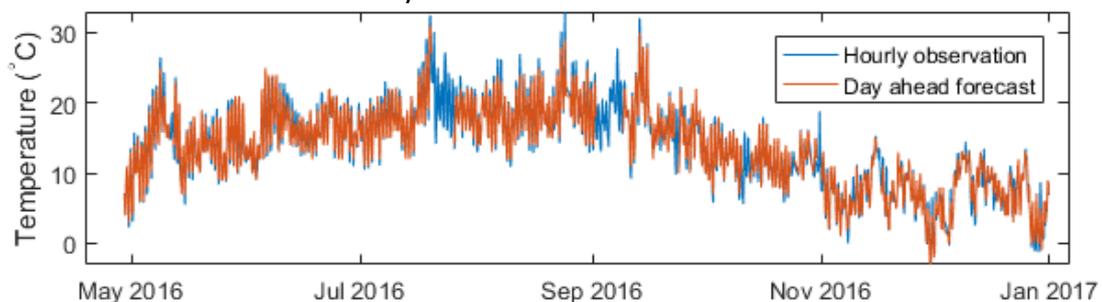


Figure 3. Observed temperature and 24-hour ahead forecast at London Heathrow (1st May to 31st Dec 2016)

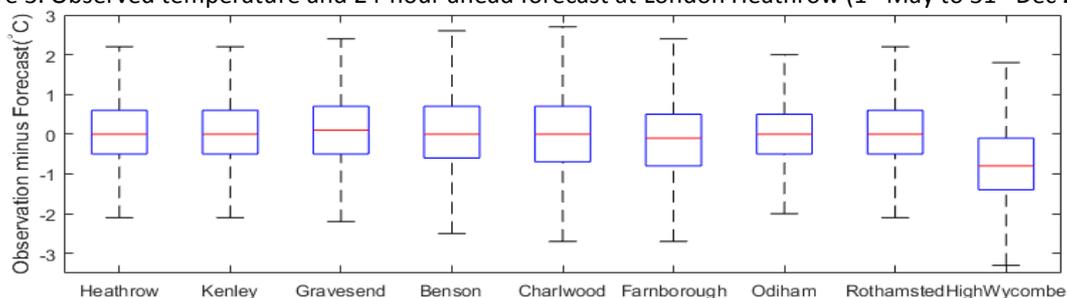


Figure 4. The distribution of the difference between observed temperatures and forecasts at the eight weather stations around the London

Results – Task 5: Weather forecast sensitivity testing

The Met Office forecast claims that their UK Site Forecasts are generated through the UK High Resolution Unified Model 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 and 70 layers vertically for about 40km high. In order to understand whether the forecasts are location sensitive enough to capture urban heat island effect, the average forecasted temperature for 302 locations around London during the period of 1st May to 31st December 2016 was shown in figure 5 Left. It shows that the difference of average temperature could be up to 3 °C over the 7 months period.

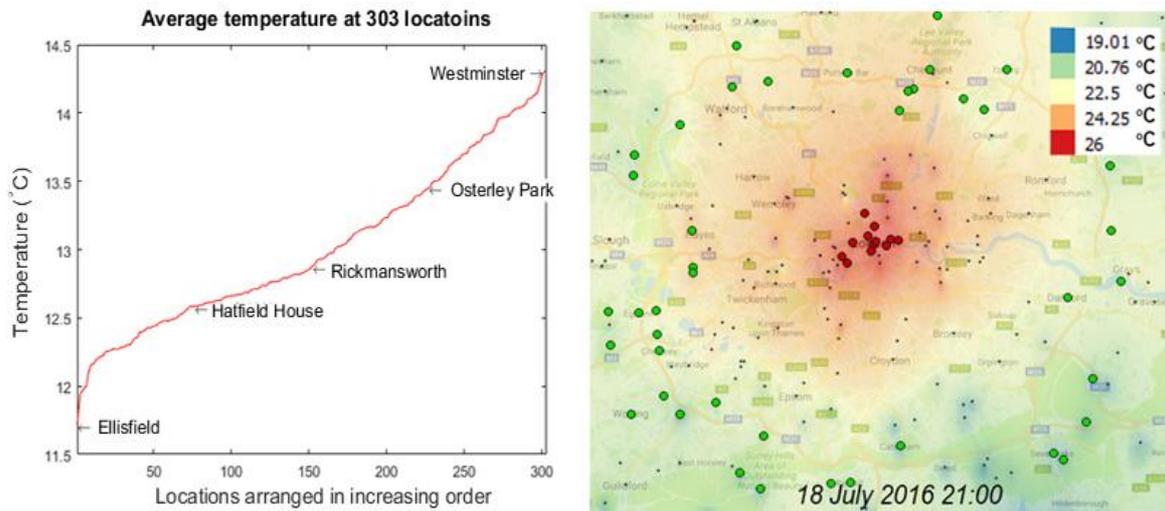


Figure 5. Left: Average temperatures at 302 locations around London over the period of 1st May to 31st Dec 2016; Right: Forecasted urban heat island effect in London at 9pm on 18th July 2016

Results – Task 6: Urban Heat Island Intensity

The predicted temperatures distribution (at 21:00 18th July 2016) around London were mapped using forecasts (made at 23:00 17th July) 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 5 Right) shows the central London is general 3-5 °C warmer than its boundary area.

The calculation method of UHI Intensity (UHII) in this paper has been defined in authors’ previous study (reference omitted for blind review). In short, it is the temperature difference between the average temperature of the central cluster (red dots in figure 5 Right) and the average temperature of boundary at each specific time step (green dots in figure 5 Right). The UHIIs over the period of 1st May to 31st December 2016 were illustrated in figure 6. In general, it ranges from 1 °C to 4 °C and tends to reach the peak at night.

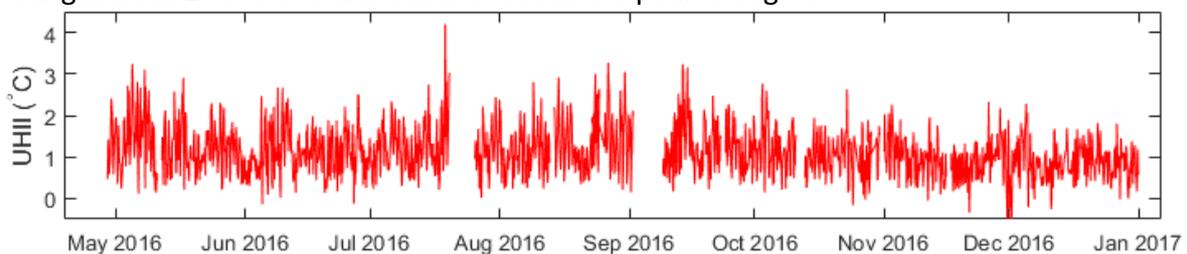


Figure 6. 24-hour ahead UHI Intensity forecast over the period of 1st May to 31st December 2016

Results – Task 7: Indoor temperature modelling

To explore the impact of UHI on indoor overheating, 2 identical buildings (Case 900FF) located in city centre (Westminster) and city boundary (Tanners Hatch YHA, southwest outside London M25) were selected to conduct building performance modelling in EnergyPlus for the week starting from 13th July 2016. The results (figure 7) shows that rooms in city centre is always warmer than the same room at city boundary, however outdoor temperature is only one of factors influencing indoor temperature.

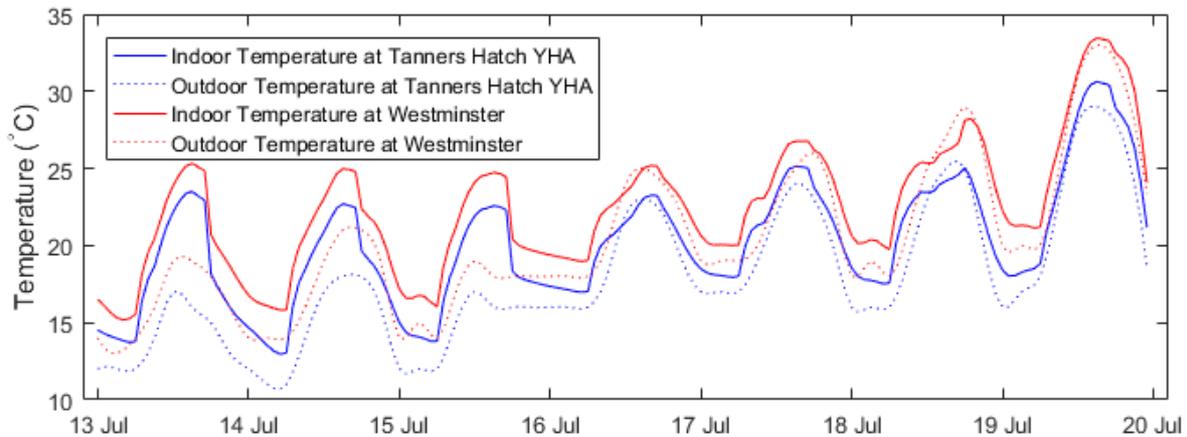


Figure 7. Predicted indoor (solid line) and outdoor temperature (dot line) at city centre (red) & boundary (blue)

Results – Task 8: Indoor overheating benchmarking

The indoor temperatures for the 2 identical case study buildings located at city centre and fringe over the 7 months period were compared against CIBSE overheating benchmarks CIBSE Guide A 2006 and CIBSE TM52/BS EN 15251 adaptive thermal comfort standard. The results in table 2 shows that rooms in city centre is significant warmer than rooms at city fringe. Therefore, the mitigation of the urban heat island in city centre is the key. Different strategies to reduce UHI effects can be adopted, based on properly designing the urban texture in order to obtain the health benefits, examples including, the increase of urban surface reflectivity and urban vegetation (green roofs, street trees, and green spaces).

Table 2. Indoor overheating risks comparing against CIBSE 2006 and CIBSE TM52/BS EN 15251

Benchmark	CIBSE 2006		CIBSE TM52/BS EN 15251		
	Number of hours > 26 °C	Number of hours > 28 °C	Criterion 1 Hours of Exceedance	Criterion 2: Number of days Daily Weighted Exceedance over 6	Criterion 3: Upper Limit Temperature shall not exceed 4K
Tanners Hatch YHA	270	131	101	15	7.18
Westminster	510	279	187	24	8.87

Conclusion

The paper demonstrated a novel approach to predict real-time urban heat island effect and indoor overheating using near future weather forecast. The Met Office DataPoint API service provides a great opportunity for building and industrial partners to predict short term building performance. Authors' research shows that the DataPoint API provides accurate real-time weather data for the locations in the UK that do not have weather stations, and most importantly, its next 5-day 3-hourly forecasts can be used for predicting indoor temperature at individual building, urban and national scale.

In this paper, authors have compared the observed temperatures and next 24-hour forecasts from 7 different data providers. The UK Met Office has better forecast of UK weather, whereas the Norwegian Meteorological Institute might have better estimations of

the weather in their geographical coverage area. Authors identified a number of equivalent weather forecast API providers outside the UK, such as openweathermap.org, weatherbit.io, darksky.net, [AerisWeather API](http://AerisWeather), wunderground.com, apixu.com. They offer the access of current and next 5-day 3-hourly forecasts weather data for over 200,000 cities around world.

The immediate beneficiary of this research will be building management system providers, who could get free access to forecast data and prediction algorithm. For example, Google Nest Thermostat will be able to decide when to pre-cooling the building to avoid overheating by considering tomorrow's weather in your area. Building integrated renewables system, such as solar air conditioning will be able to forecast their generation and demand from buildings, therefore optimise system performance.

Acknowledgment

This study is funded by the Welsh government's Sêr Cymru (Stars Wales) program. The authors thankfully acknowledge weather forecast data provided by the UK Met Office, api.openweathermap.org, api.weatherbit.io, api.darksky.net, api.wunderground.com, and api.apixu.com and api.met.no.

References

- Adekunle, T. O. and M. Nikolopoulou (2016). "Thermal comfort, summertime temperatures and overheating in prefabricated timber housing." *Building and Environment* 103: 21-35.
- ASHRAE (2001). ANSI/ASHRAE Standard 140-2001: Standard Method of Test for the Evaluation of Building Energy Analysis Computer Programs. Atlanta, ASHRAE.
- Beizaee, A., et al. (2013). "National survey of summertime temperatures and overheating risk in English homes." *Building and Environment* 65: 1-17.
- Corpening, S. L., et al. (1973). "Experience with Weather Sensitive Load Models for Short and Long-Term Forecasting." *IEEE Transactions on Power Apparatus and Systems PAS-92(6)*: 1966-1972.
- Du, H., et al. (2012). "Generating design reference years from the UKCP09 projections and their application to future air-conditioning loads." *Building Services Engineering Research & Technology* 33(1): 63-79.
- Gupta, R., et al. (2016). *Care provision fit for a future climate*. York, Joseph Rowntree Foundation.
- Jenkins, D. P., et al. (2014). "Developing a probabilistic tool for assessing the risk of overheating in buildings for future climates." *Renewable Energy* 61: 7-11.
- Ji, Y., et al. (2014). "Assessing overheating of the UK existing dwellings – A case study of replica Victorian end terrace house." *Building and Environment* 77: 1-11.
- Lazos, D., et al. (2014). "Optimisation of energy management in commercial buildings with weather forecasting inputs: A review." *Renewable and Sustainable Energy Reviews* 39: 587-603.
- Levermore, G., et al. (2017). "The increasing trend of the urban heat island intensity." *Urban Climate*.
- Liu, C., et al. (2016). "Future probabilistic hot summer years for overheating risk assessments." *Building and Environment* 105: 56-68.
- Met Office (2016). "Developing the science for long range weather forecasts." from <http://www.metoffice.gov.uk/news/in-depth/long-range-forecasting>.
- Oikonomou, E., et al. (2012). "Modelling the relative importance of the urban heat island and the thermal quality of dwellings for overheating in London." *Building and Environment* 57: 223-238.
- Pathan, A., et al. (2017). "Monitoring summer indoor overheating in the London housing stock." *Energy and Buildings* 141: 361-378.
- Rodrigues, L. T., et al. (2012). "Summer overheating potential in a low-energy steel frame house in future climate scenarios." *Sustainable Cities and Society*.
- Short, C. A., et al. (2012). "Building resilience to overheating into 1960's UK hospital buildings within the constraint of the national carbon reduction target: Adaptive strategies." *Building and Environment* 55: 73-95.
- Taylor, J., et al. (2016). "Mapping indoor overheating and air pollution risk modification across Great Britain: A modelling study." *Building and Environment* 99: 1-12.