The influence of urban microclimate vertical variations on the building performance of a high-rise office building at different floors

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Abstract. This paper explores the urban microclimate effects on the building performance of high-rise office buildings of different heights. In general, the environment section of buildings’ performance calculation relies on weather station data located in rural areas which are quite different from the actual urban microclimate. How the accuracy of urban microclimate modelling affects the building performance simulation is not understood. We have previously explored horizontal elements’ effects on high-rise office building performance. In this research, wind and temperature vertical variations’ effects on performance at different heights is explored. Compared with the wind in rural areas, the urban wind has more barriers and is more turbulent. The temperature profile in urban areas is also different from that in rural areas because of Urban Heat Island effects. How do these features of urban microclimate influence the performance? Is the influence significant enough and worth modelling? From this research, vertical temperature gradients are a more significant influence on energy use than vertical variation of wind speed and urban boundary layer depth. If the building is extremely high the accurate modelling of wind speed profile may matter as well because the influence of vertical variations on natural ventilation increases with height.

1. Introduction
Modelling real urban microclimate needs to include the features of urban microclimate, such as Urban Heat Island (UHI), urban wind, Lapse Rate, Urban Boundary Layer (UBL) and so on. However, not all the features have a similar level of influence on the building performance simulation results. Is the influence of each parameter significant and therefore worth modelling? Earlier research has demonstrated the necessity of modelling UHI and urban wind [1]. This paper primarily studies the strength of urban microclimate vertical variations, like wind speed profile exponent, boundary layer thickness and temperature gradient coefficient. Follow on stages are planned to report the relative effect of the Urban Heat Island and the necessity of stratified urban microclimate modelling to deal with its effects. Then, the research will examine the differences between one regional climate and another. This paper uses London as the case study location.

1.1. Urban wind profile
The Atmospheric Boundary Layer (ABL) is the air layer near the earth surface which is affected by the earth’s surface. As well as with heat from the surface and evaporation of water, the ABL is characterized by turbulence when the air flows close to the rough earth surface. The height of the boundary layer is based on the surface-generated turbulence [2]. The Urban Boundary Layer (UBL) is the turbulent layer of air over a city which is characterized by the turbulence influenced by the roughness of urban areas. The depth of the UBL above the ground is characterised by the roughness length. The UBL is deeper in the city than in rural areas and the lower portion of UBL extends up to 10% of the depth of boundary layer [3]. The urban wind profile described in this paper is the vertical distribution of wind speed within...
the lowest part of UBL. There are generally two mathematical models used to represent mean wind speed at different height: the logarithmic law and the power law [4].

1.2. Reliability of logarithmic and power-law wind profile
Johnson (1959) analysed the relative accuracy of logarithmic and power-law wind profiles. The power-law represented the data better than the logarithmic law [5]. In Drew et al.’s research, the log wind profile was shown to be valid in the inertial sublayer [6]. Cook considered the log wind profile represented reality better than power-law between 10 m and 20 m height [7]. From 20 m to 100 m, both can predict the mean wind speed. However, above 100 m height, the power-law estimated the mean wind speed within the ABL more reliably [7]. Tieleman and Cook considered the logarithmic law wind profile does not produce as reliable predictions of wind speed as the power law above around 200 m height [8], [9]. With a typical inter-floor height of 4m, it can be concluded that the power law estimate should be used for buildings over 5 storeys in height.

2. Methods
A prototypical energy model of a high-rise office building has been proposed based on the range of new tall buildings in London. It is 72m*50m*154m high and 35 storeys tall [1]. Urban microclimate data is not widely available. Hence, the effect of the urban environment on the microclimate must be calculated from nearby rural weather data. The research examines energy performance of the prototypical building based on rural weather data and on urban weather data.

2.1. Urban wind profile of London
The original wind data of London is the weather data collected from the Gatwick weather station in rural areas. To convert the wind data from rural areas, the first step is to consider the 20-30% reduction as a result of urban surface roughness [10]. The second step is to replicate the vertical distribution of urban wind speed according to observation data [6].

In Drew et al.’s research, a Doppler lidar is used to obtain weather data during an 8-month period in London city centre. The wind data was investigated to develop the mean wind speed profile of central London and it gives an exponent of the mean wind speed profile of central London for around 2500 m height of 0.4237 [6]. However, the trendline does not match the observed data from 1000 m to 2500 m. The exponents 0.3962 for 1000 m and 0.3996 for 500 m heights are extremely similar and trendlines match well with data. In this research, 0.4 is taken as the exponent of London wind profile. This experimentally determined value is quite different than the value of 0.33 recommended in the ASHRAE Fundamentals [11]. It suggests the need for caution in accepting such general guidance in design.

2.2. Urban atmospheric boundary layer thickness/depth of London
The boundary layer thickness over urban areas is substantially higher compared with rural areas as a consequence of increased turbulence caused by higher terrain roughness [12]. In 1988 it was found the mixing height London City centre is 50-100 m higher than 50 km far away in rural areas [13]. In contrast, Rigby and Toumi’s study suggest the boundary layer depth of London city centre increased around 100 m compared to rural areas [12]. In the 20 years since then, hundreds, of high-rise buildings have been built in London. The urban boundary layer thickness of London is therefore expected to be even greater in parts. Bohnenstengel et al., determined the UBL of London to be approximately 400 m to 500 m deep and relatively invariable [14]. The ASHRAE hand book of Fundamentals suggests a similar value: 460m [11].

2.3. Urban temperature profile of London
Similar to the wind data, the temperature data for London is also collected at the Gatwick weather station in a rural area. To convert the temperature data from rural areas to city centre, the first step is to consider the 10% increase monthly average as a result of Urban Heat Island [1]. The second step is to replicate the vertical distribution of urban temperature according to observation data [15]. Kukkonen et al (2014) determined the temperature gradient coefficient to be around 0.002K/m which means the temperature decreases 2 K for every 1000 m increase in height[16].
2.4. Vertical variation settings of the London microclimate

Table 1 summarises the vertical variation parameters from the above review. Each group of parameters has a serial number. S from serial number means suburb and U means urban.

| Location                | Wind Speed Profile Exponent | Wind Speed Profile Boundary Layer Thickness (m) | Air Temperature Gradient Coefficient (K/m) | Serial Number |
|-------------------------|-----------------------------|-----------------------------------------------|-------------------------------------------|---------------|
| Suburb-Gatwick Airport  | -                           | -                                             | 0.0065                                    | S1            |
|                         | 0.14                        | 270                                           |                                           | S2            |
|                         | 0.14                        | 270                                           |                                           |               |
|                         | 0.14                        | 270                                           |                                           |               |
|                         | 0.22                        | 370                                           |                                           | U2            |
|                         | 0.33                        | 460                                           | 0                                         | U3            |
|                         | 0.4                         | 400                                           | 0                                         | U4            |
| Urban-London City Centre| 0.4                         | 460                                           | 0                                         | U5            |
|                         | 0.4                         | 500                                           | 0                                         | U6            |
|                         | 0.4                         | 500                                           | 0.002                                     | U7            |
|                         | 0.4                         | 500                                           | 0.0065                                    | U8            |
|                         | 0.4                         | 500                                           | 0.01                                      | U9            |
|                         | 0.4                         | 500                                           | 0.0065                                    | U10           |

3. Results

An Energyplus analysis has been conducted in order to examine the results of the strength of these vertical variations in temperature and wind speed. The analysis reports the differences of the thermal load of a prototypical office at 1st, 17th and 33rd floors.

3.1. Vertical variations effects on thermal load in suburb and rural areas

This simulation results compare the thermal load with vertical variation (S2, U8) and without vertical variation (S1, U1). S1 is based on the original rural weather data and U1 uses a converted urban weather file of London. The differences at 1st, 17th and 33rd floors are shown in Figure 1.

![Figure 1. Thermal load changes with vertical variations in suburb and urban areas of London; differences in energy use as % for rural (Gatwick) and City locations between the normal “London” weather file (wind at 10m, temperature at 2m) and energy use on the 1st, 17th and 33rd storey.](image)

From Figure 1, the upper 3 lines show the vertical variations’ effects on buildings performance in suburban areas and the lower 3 lines show urban areas. The effects of vertical variations at suburb areas
increases with height which is less than 6%. However, in urban areas the effects are much bigger than in rural areas. The 33rd floor almost reaches 10% difference, a level likely to make a difference in a design decision.

3.2. Effects of wind speed profile parameters on thermal load in urban areas
Using London city central weather data without vertical wind speed variation Figure 2 reports the influence on energy performance at levels 1, 17 and 33 of UBL thickness and of the Power Law coefficient for the increase of wind speed with height. The coefficient and thickness combinations studied were: 0.14 with 270 m (U2), 0.22 with 370 m (U3), 0.33 with 460 m (U4) and 0.4 with 500 m (U7).

![Figure 2. Effects of exponent and relative boundary layer thickness on thermal load changes in the urban area of London; differences in energy use as % between the normal “London” weather file and energy use on the 1st, 17th and 33rd storey.](image)

From Figure 2, the differences of thermal load are small at lower levels no matter what the exponent value and relative boundary layer thickness are. However, the differences significantly increase with height of the building. At the 1st and 17th floor, the differences of thermal load between different exponent and thickness is less than 5%. At the 33rd floor, the influence can reach 10%.

Then, the effects of varying boundary layer thickness are explored by comparing the London City central weather data with a wind speed exponent of 0.4 and 400 m UBL thickness (U5) with a UBL of 460 m (U6) and a UBL of 500 m (U7) which are shown in Figure 3.

![Figure 3. Effects of boundary layer thickness on thermal load changes in the urban area of London; differences in energy use as % between the normal “London” weather file and energy use on the 1st, 17th and 33rd storey.](image)

The effects of wind speed profile boundary thickness on buildings’ thermal load are extremely small with less than 1% difference (Figure 3) which can be ignored. Even though the difference is small, the difference of thermal load increases with boundary thickness and height.
3.3. Effects of temperature gradient coefficient on thermal load in urban areas

There is some debate in the literature about the lapse rate. The influence on load of values from the literature are examined in Figure 4: 0.002 (U8), 0.0065 (U9) and 0.01 (U10). The baseline for the differences reported in Figure 4 is the Gatwick Airport data taking 0 temperature gradient coefficient as (U7).

![Figure 4. Effects of temperature gradient coefficient on thermal load changes in the urban area of London; differences in energy use as % between the normal “London” weather file and energy use on the 1st, 17th and 33rd storey.](image)

From Figure 4, no matter what the temperature gradient coefficient it is, the differences increase with height. At all three floors floor, the differences increase with the temperature gradient coefficient. The influence of temperature gradient plus height can produce an EXTRENE difference of thermal load.

3.4. Effects of vertical variation on natural ventilation in urban areas

In this part of research, U1 and U8 are modelled with natural ventilation. Taking without vertical variations of wind and temperature as comparing group (U1), the effects of vertical variation with 0.4 roughness length, 500 m UBL thickness and 0.002 temperature gradient coefficient (U8) are shown in Figure 5.

![Figure 5. Effects of vertical variations on thermal load changes with natural ventilation in the urban area of London; differences in energy use as % between the normal “London” weather file and energy use on the 1st, 17th and 33rd storey](image)

In Figure 5, the thermal load changes are compared with or without wind and temperature vertical variation. Under the condition of natural ventilation, the change rates increase with height. At the 33rd floor, the influence can reach 10% in April and 20% in May. Values in July are extremely high because the base value is very small. The absolute value which should not be reference.

4. Conclusions

The basic conclusion from this study is that it is necessary to model the microclimate vertical variations in urban areas.

- Modelling wind speed profile at all, is more important than modelling it accurately.
- The accuracy of the boundary layer thickness also has a very slight influence on the buildings’ performance simulation.
It is necessary to model the temperature gradient coefficient accurately because the simulation results are very sensitive to the value of the temperature gradient coefficient.

The vertical variations’ influence on natural ventilation is slight at lower floor and significant at higher floor.

This research has shown that modelling vertical variation of wind is essential to represent tall building energy performance accurately. The precise value of the wind profile is less significant, provided it is modelled. However, it is very important to model temperature vertical variations accurately. This has a strong influence on natural ventilation modelling.

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