# A longitudinal field study of thermal comfort and air quality in naturally ventilated office buildings in UK

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## ABSTRACT

Natural ventilation has the potential to provide cooling and fresh air and cut 40% of the total energy consumption of European office buildings. While in the milder seasons natural ventilation is an obvious low-energy choice, if poorly designed it can cause overheating in summer and poor air quality in winter. In order to promote the use and design of naturally ventilated (NV) buildings, it is therefore important to understand how current NV buildings perform in terms of thermal comfort and indoor air quality. Only through long-term studies is it possible to evaluate seasonal variations in environmental performances and understand how they affect both occupant perception and adaptation. This is especially important in NV office buildings where high internal heat gains and occupant high density make it more difficult to ensure an optimal performance throughout the different seasons. However, longitudinal field studies are under-represented in the current literature. In this study we look at the performance of eight offices in four naturally ventilated buildings in the temperate oceanic climate of UK. Both objective (measurements) and subjective (surveys) data is collected through a long-term monitoring campaign of thermal comfort and indoor air quality. The results of the first six months of monitoring are reported in this paper. Air quality is found to be highly correlated to the outdoor weather conditions, with indoor air quality worsening in the winter months, especially in the office with the highest number of occupants and where a proper control strategy is not implemented. In terms of thermal comfort, middle floor offices are found to be the best performing spaces. The results of this preliminary analysis suggest that high density NV offices need to have a natural ventilation control strategy in place in order to ensure an optimal performance in terms of air quality. Concerns over overheating problems in roof-exposed offices are also highlighted.

## KEYWORDS

Long-term monitoring, thermal comfort, air quality, office buildings, natural ventilation

## 1 INTRODUCTION

The advent of mechanical ventilation and air conditioning in the middle of the 20th century has resulted in the progressive loss of the use of natural ventilation in non-residential buildings. Such a change has only been possible through considerable expenditure of energy. For example, 40% of the total energy consumption of European office buildings is due to heating, ventilation and air conditioning (HVAC) systems (Chenari *et al.*, 2016). Only recently, concerns over the impact of buildings' energy use on global $CO_2$ emissions have boosted the revival of natural ventilation (NV) as a possible solution for low-energy design: a successful NV cooling system has the potential to provide cooling and fresh air and halve a building's energy use (Carrilho da Graça and Linden, 2016). Researchers have also shown that occupants prefer natural ventilation and occupant controlled openings over mechanical ventilation, further favouring the upturn of natural ventilation (Seppänen and Fisk, 2002).

However, while in the milder seasons natural ventilation is the preferred low-energy choice, in the hotter and colder months there is a risk of overheating (Porritt *et al.*, 2011; Vellei *et al.*, 2016) and poor air quality (Yu and Kim, 2012), respectively. Deep floor plans, high internal heat gains, and a high density of occupants - characteristic traits of open-plan offices - represent a particular challenge when designing naturally ventilated office buildings (Carrilho da Graça and Linden, 2016). The risk of overheating is particularly of concern given that global average surface temperatures are predicted to rise as a consequence of climate change (IPCC, 2013).

To promote the use and design of naturally ventilated buildings, it is therefore important to understand how current NV buildings perform in terms of thermal comfort and indoor air quality. To expose the relationship between building performance and occupant satisfaction, the building's indoor conditions need to be coupled with occupant survey data. This is especially important if we consider that comfort and indoor air quality have been shown to be related to occupants' productivity, health and well-being (Lan *et al.*, 2010; Lorsch and Abdou, 1994; Al Horr *et al.*, 2016). Performance needs to be understood across seasons, and ideally over a number of years.

In the literature, such longitudinal field studies are very rare because it is usually very difficult to engage occupants for long periods. In view of this gap, a long-term monitoring campaign of thermal comfort and indoor air quality was carried out in four naturally ventilated office buildings in Bath, Bristol and Cardiff in UK. Eight different naturally ventilated offices were monitored in terms of air temperature, relative humidity and $CO_2$. To address the problem of occupant engagement, subjective responses were collected through a specially developed mobile phone survey application, with a non-intrusive reminder facility. Consequently, a large database of both objective (measurements) and subjective (survey) data was obtained for analysis.

In this paper, we report preliminary results for the objective data collected during the first 6-months (from August 2016 to January 2017), prior to the commencement of the co-incident subjective data collection, as a means of preliminary forensic analysis of building performance. Offices are compared in terms of thermal comfort and air quality in order to understand which are performing better and why.

## 2 METHODOLOGY

Data were collected from eight offices[1] situated in four buildings. All four buildings are located in South West UK, at similar latitudes, and characterized by similar outdoor environmental conditions. The Köppen Climate Classification subtype for this climate is Cfb, i.e. temperate oceanic climate (Kottek, 2006). The use of each building is also similar, they are offices for architectural and engineering practices and, therefore, a certain homogeneity in productivity and activity is expected.

### 2.1 Buildings' characteristics

The spread of offices and buildings including the indoor variables monitored in each are shown in Table 1. Building's characteristics for each office are described below. All the offices were visited, at least once each two weeks, by the first three authors of the paper.

[1] In this study we distinguish the concept of an "office" as a *single institutional entity* from the physical "building", which can be occupied by one or more offices.

Table 1: Variables monitored in each office.

| Building | Office | $CO_2$ | Temperature | Humidity |
|---|---|---|---|---|
| Bath | Fifth Floor | x | x | x |
| Cardiff | Ground Floor | x | x | x |
| | First Floor | x | x | x |
| Bristol (Listed) | Basement | x | x | x |
| | Second Floor | | x | x |
| Bristol (Annex) | Basement | | x | |
| | Ground Floor | | x | x |
| | First Floor | | x | |

2.1.1 Bath

The monitored office is on the 5th floor of a 6-storey building constituted of a masonry wall construction with no additional insulation and single glazed windows. The office setup is open-plan, with approximately 32 work stations and an internal plan area of roughly 115m$^2$. It is cross ventilated with windows on both sides of the building and a width less than 3 times the floor to ceiling height. This office has the greatest number of work stations of all the monitored offices.

2.1.2 Cardiff

Completed in 2010, the building was designed to be sustainable and provide high levels of comfort, with a BREEAM rating upon completion of 85.33% (outstanding). Features contributing to high building performance include structurally insulated laminated wood panels used for the walls, roof and floor, and double glazed windows. The green roof with a high thermal mass is designed to regulate temperatures. The building is comprised of 2 storeys, with each floor having an approximate internal plan area of 120m$^2$. The ground floor is predominantly a reception/lobby area, with a few work stations, while the first floor is the main open-plan office with a higher and more constant occupation (approximately 22 work stations). Natural ventilation is provided using a stack system, to allow warm air to be exhausted via openings operated by the building management system.

2.1.3 Bristol

The buildings studied in Bristol consist of a listed building and its adjoining annex. The listed building was built in the 1800's and the annex was built in the 1950's, both have since had several refurbishments. The listed building is 4-storey, including the basement and attic, constituted of limestone ashlar with high thermal mass. Windows are single glazed. The annex is a lightweight structure with double glazed windows and insulated walls. Both are naturally ventilated. The basement offices of both buildings have restricted direct solar influence, due to adjacent obstructions. The number of work stations for each floor of the annex building is 28, and it is similar for the old building, except for the basement which has only 16 work stations.

## 2.2 Physical measurements

Wireless air temperature, humidity and $CO_2$ sensors reported data to a university-hosted database every 5 minutes over a 6-month period from August 2016 to January 2017. The manufacturer-stated accuracy of the sensors is given in Table 2. Sensors were placed at several locations in each office and it was ensured, as far as possible, that sensors were placed at a height approximately of one meter from the floor, at least one meter away from the radiators, not less than half a meter away from any external wall, where they could not be hit by direct solar radiation and away from any local sources of radiation such as computer monitors. A mean value from all the measurements is used, representing each office.

Table 2: Sensors used.

| Sensor | Range | | | Accuracy |
|---|---|---|---|---|
| DS18B20 temperature | −10°C | to | +85°C | ±0.5°C |
| RHT03 humidity | 0% | to | 100% | ±2% |
| K30 Senseair $CO_2$ | 0ppm | to | 5000ppm | ±30ppm |

For each building, outdoor temperature data was used to see its influence on indoor parameters. In Bath, outdoor data was collected from a weather station fitted on the roof of the monitored building. Data for Cardiff and Bristol were downloaded from online sources (WU, 2017).

### 2.3 Data preparation

Data was recorded at intervals of 5 minutes, however only the hourly and daily mean values are used for the analysis. Additionally, data is filtered to only include times when the buildings are in use: working hours are assumed to be from 8am to 6pm, and weekends and bank holidays are excluded.

For naturally ventilated buildings, it is important to know if and when any heating or cooling is provided so that internal conditions can be properly compared against external data. A free running building is one in which indoor conditions are primarily influenced by outdoor environmental conditions, without the use of mechanical heating/cooling or ventilation systems. By inspection of the temperature data over time, it is evident that heating was switched on the middle of October in all the buildings. For the outdoor data, the mean daily temperature is taken as the mean over the 24-hour day, whereas for the indoor data, the mean is taken for only the working hours.

## 3 STANDARDS

The two most commonly used standards for evaluating indoor environmental conditions in free-running buildings are the ANSI-ASHRAE Standard 55 (ASHRAE, 2013) and the European EN-15251 (EN-15251, 2007). They both consider the process of thermal adaptation as a black box and integrate occupant thermal expectations and adaptive actions in a single linear equation predicting indoor comfort temperature from outdoor temperature. For each standard, the temperature limits must be defined for the appropriate category: as the monitored buildings are offices with normal expectations, moderate activity level and no especially sensitive equipment, Category II is used for BS EN 15251 and 80% acceptability is used for ASHRAE 55.

Within the ASHRAE adaptive thermal comfort model, the upper and lower allowable indoor operative temperature limits ($T_{upper}$ and $T_{lower}$) for 80% acceptability are given by equations:

$$T_{upper} = (0.31T_{out} + 17.8) + 3.5, \text{ and} \quad (1)$$
$$T_{lower} = (0.31T_{out} + 17.8) - 3.5 \quad (2)$$

While for the European model, $T_{upper}$ and $T_{lower}$ for Category II are given by equations:

$$T_{upper} = (0.33T_{out} + 18.8) + 3, \text{ and} \quad (3)$$
$$T_{lower} = (0.33T_{out} + 18.8) - 3 \quad (4)$$

where $T_{out}$ is the prevailing mean outdoor air temperature which can be approximated by the running mean temperature (ASHRAE, 2013). In this paper $T_{out}$ is calculated from 30 sequential days prior to the day in question, as:

$$T_{out} = (1 - \alpha)[T_{e(d-1)} + \alpha T_{e(d-2)} + \alpha^2 T_{e(d-3)} + \alpha^3 T_{e(d-4)} + ... + \alpha^{29} T_{e(d-30)}] \quad (5)$$

where α is set to 0.8 as suggested in the standards, $T_{e(d-1)}$ is the mean outdoor temperature of the day before the day in question, and $T_{e(d-2)}$ is the mean outdoor temperature of the day before that, and so on. The ASHRAE limits are valid when $10<T_{out}<33.5$°C while the European model applies when $10<T_{out}<30$°C for the upper limit and $15<T_{out}<30$°C for the lower limit.

The limits are valid for when the building is free-running, when the building is heated, in winter, set values are based on the PMV-PPD model (Fanger, 1970). According to EN 15251, the recommended level of $CO_2$ for Category II is 500ppm above outdoor levels. If the outdoor level is taken as 400ppm, this gives us a threshold of 900ppm. According to EN 15251, acceptable relative humidity levels for Category II are between 25% and 60%.

# 4 RESULTS

## 4.1 Air quality

Figure 1 and Figure 2 show that air quality worsened in the colder winter months in the Bath office which has the highest occupancy among the surveyed offices. In Cardiff, the fact that the building has implemented a Building Information Modelling (BIM) controlled stack ventilation strategy allowed the stabilization of lower $CO_2$ levels in the winter months compared to the office in Bath. On the other hand, the Bristol listed building basement had poor air quality even in late summer. This is because indoor temperatures were very low (see Section 4.2), forcing the occupants to keep windows closed to reduce the heat losses. Finally, the lower occupancy of the basement of the listed building in Bristol might have helped to keep winter $CO_2$ levels relatively low compared to the office in Bath.

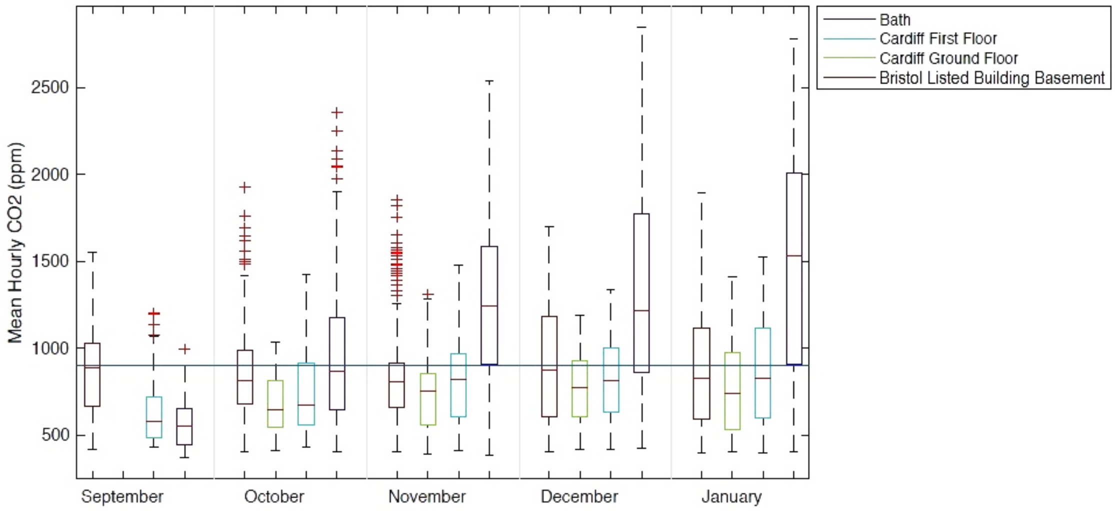


Figure 1: Boxplot of the mean hourly $CO_2$ for each month in each office with indication of the 900ppm threshold (EN-15251, 2007).

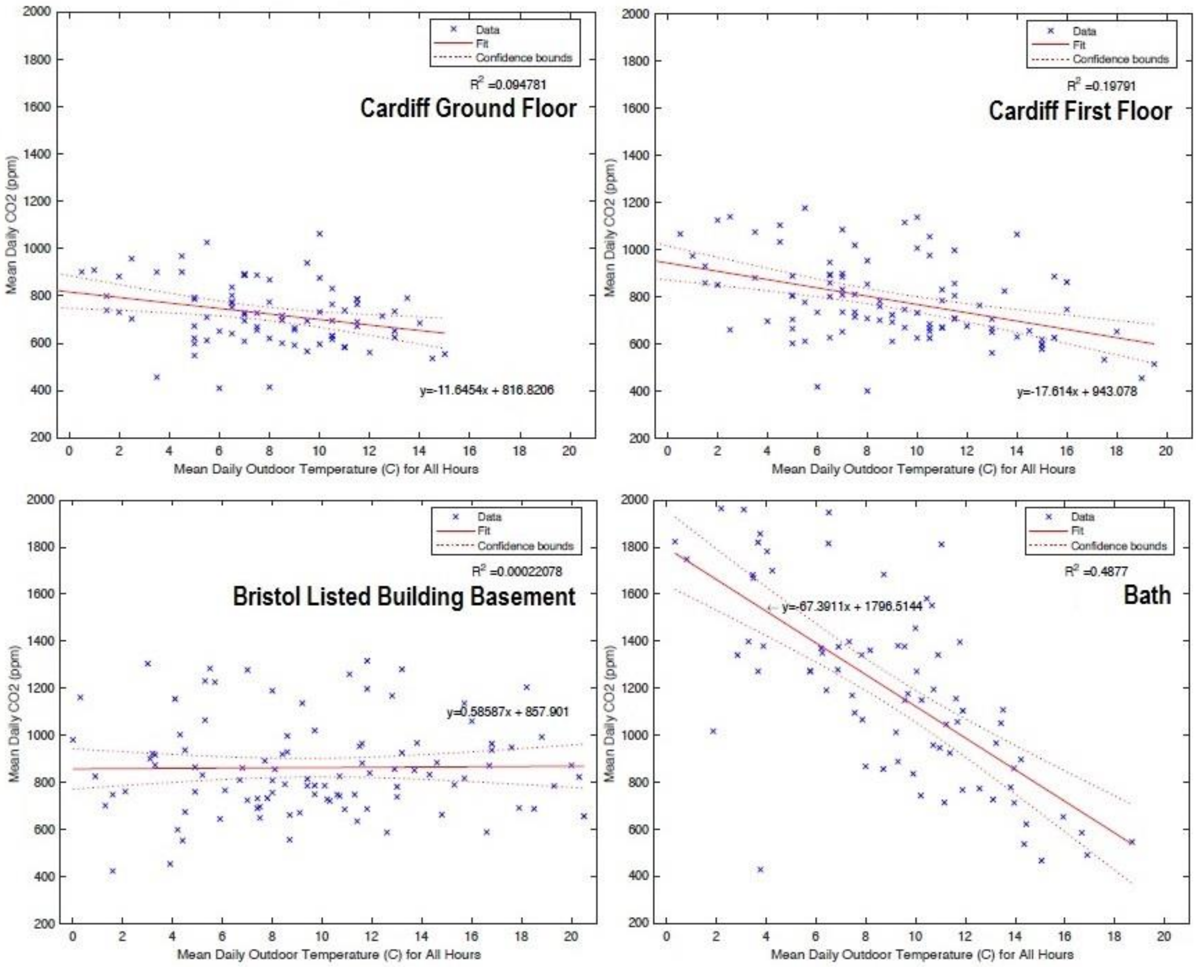


Figure 2: Fitted linear regression model and 95% confidence band for the relationship between mean daily indoor $CO_2$ and mean daily outdoor temperature.

## 4.2 Temperature

Mean daily indoor temperatures are within the limits of both the ASHRAE and European adaptive standard for all the monitored offices during the free running period, except for the basement of the listed building in Bristol (Figure 3). The low temperatures monitored in this office are due to the fact that the office has very little exposure to direct solar radiation and probably high heat losses through the floor. It is also noteworthy that, in the Bristol listed building, there are large differences (around 3°C) between the mean temperatures monitored in the basement and roof-exposed offices during the free-running period (see Figure 4). These differences are attenuated in the Annex and Cardiff Buildings, although it is evident that roof-exposed offices are the warmer ones in the late summer (when the buildings are free-running) and, therefore, at a higher risk of overheating.

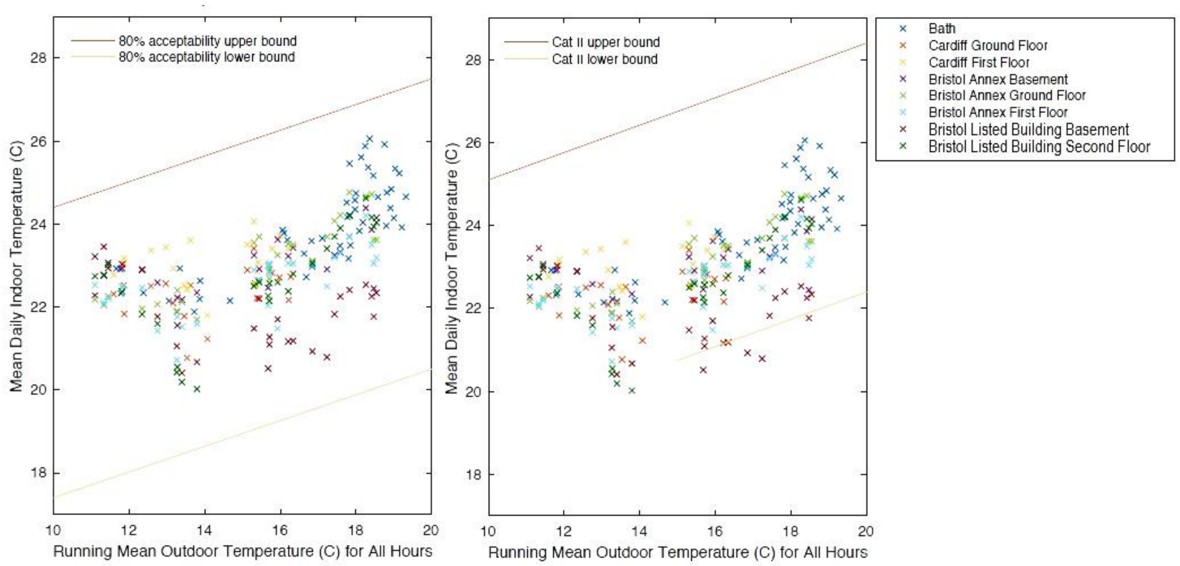


Figure 3: Acceptability of mean daily indoor temperatures based on ANSI/ASHRAE Standard 55 (ASHRAE, 2013) and EN 15251 (EN-15251, 2007), for when the buildings are free running.

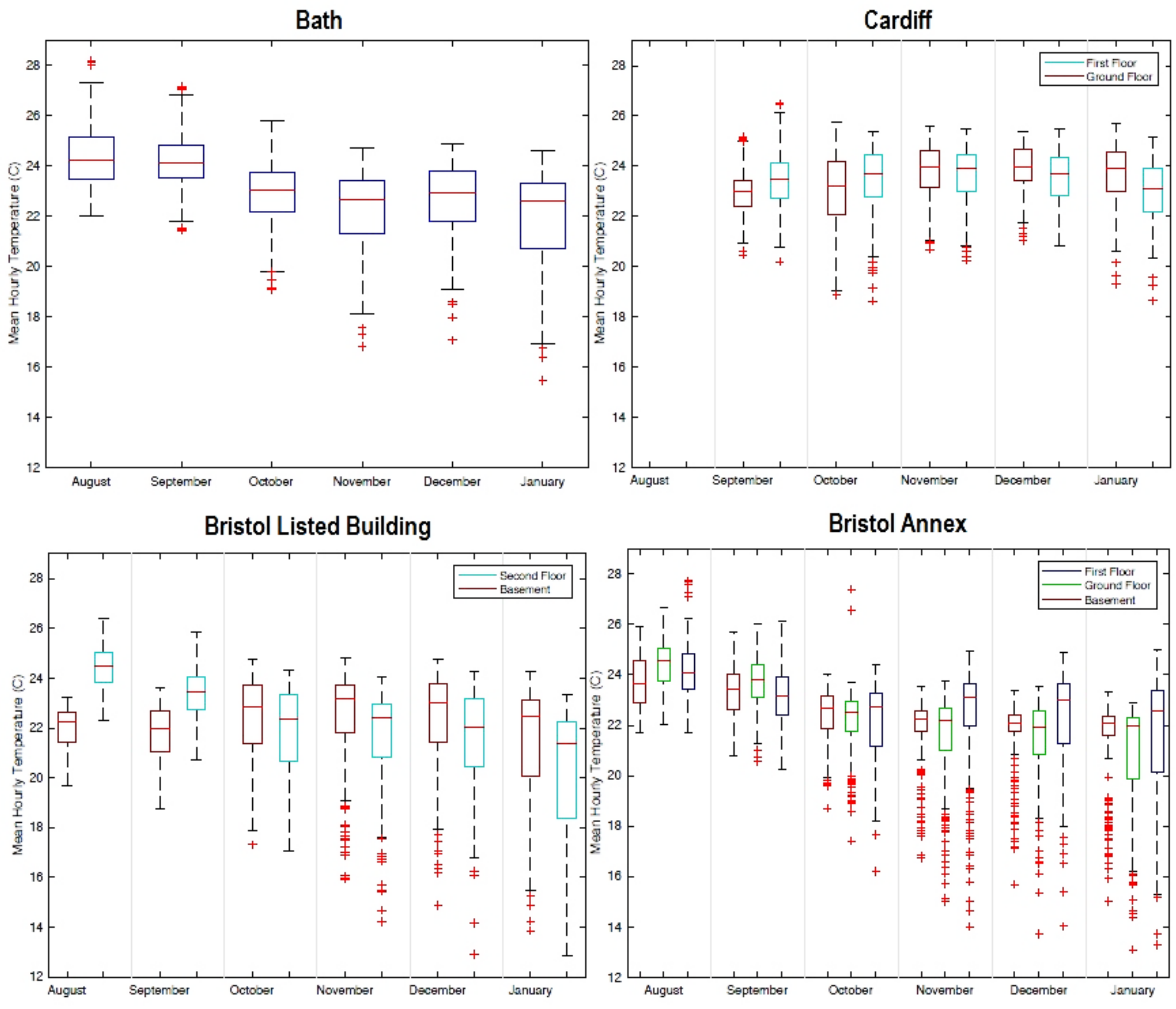


Figure 4: Boxplot of the mean hourly temperatures for each month in each office.

## 4.3 Relative humidity

Figure 5 shows that relative humidity is within the European limits except for the basement of the Bristol listed building and of the ground floor of the Bristol Annex where relative humidity above 60% are monitored. It can also be observed that relative humidity decreased during the heated winter months (November, December and January), with the lower levels monitored in January.

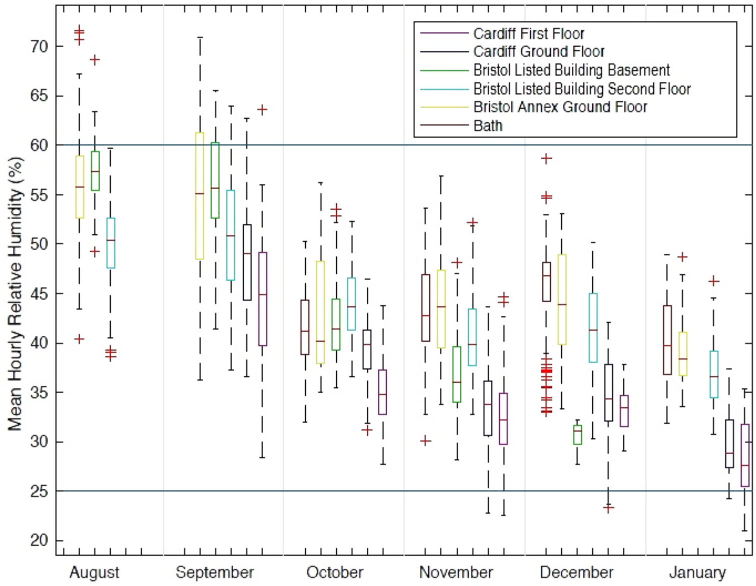


Figure 5: Boxplot of the mean hourly relative humidity with indication of the limits set by EN 15251 (EN-15251, 2007).

## 5 CONCLUSIONS

A long-term monitoring campaign of thermal comfort and indoor air quality is being undertaken in eight naturally ventilated office buildings in Bath, Bristol and Cardiff in UK. Offices are monitored in terms of air temperature, relative humidity and $CO_2$. We report results from the first six months of the monitoring campaign. The long-term monitoring effort allowed us to track seasonal variations in the environmental performances of the different offices. We found that middle-floor offices are performing the best, the offices in the last floor (under the roof) are at higher risk of overheating, while the basement offices experience temperatures below the threshold of the European Standard and relative humidity above the European humidity limits. In terms of air quality the new BIM controlled stacked ventilated office is the one with better air quality. Air quality is found to worsen in the winter months in all the offices, especially in the most overcrowded one where a proper ventilation control strategy is not implemented. Future analysis will look at both objective measurements and coincident occupant survey data to understand the implications of these conditions on health, comfort and productivity.

## 6 ACKNOWLEDGEMENTS

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