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Temperature analysis and the effect of urban development on the outdoor thermal comfort and intensification of the Urban Heat Island phenomenon in the United Arab Emirates

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Abstract: This paper presents the temperature distribution and identification of Urban Heat Island intensity and outdoor thermal comfort conditions in a residential cluster in Dubai, UAE. Temperature and humidity data are collected during peak summer period and thermal imaging is further used as additional tool. From the analysis it is reported that the maximum temperature recorded in the cluster is 55 °C and the minimum is 22.9 ° C. The hottest day has an average temperature of 40.5 °C and the coolest day an average temperature of 36.1 °C. The highest temperatures during each day occur between 10am and 3pm and relative humidity peaks to 100% during night hours. The outdoor comfort is evaluated as a combination of the high temperatures and the relative humidity, and extreme discomfort is identified. Further analysis in the residential cluster, identified "hot spots" in specific areas where the spacing between the buildings is minimized. The temperature difference between these spots and other locations in the residential cluster can reach a maximum of about 12%. The temperature patterns in the cluster are also analysed with the use of CFD modelling and the results highlight the relation between the ventilation paths and the increased temperatures.
Keywords: Outdoor Thermal Comfort; Urban Heat Island; United Arab Emirates; Temperature Distribution

1. Introduction

Today's rapid urban development has led to a large increase of building energy use and subsequently fuel use and Greenhouse Gas emissions. Particularly in urban locations, the increase in energy related combustion and emissions, in combination with the specificities of the structural planning and materials used for construction, has had an increasing effect on heat concentration and ambient temperatures. This is the phenomenon described by scientists as Urban Heat Island (UHI) (Kolokotroni & Giridharan, 2008; Levermore, Parkinson, Lee, Laycock, & Lindley, 2017; Hassid, et al., 1999).

The United Arab Emirates is a country which during the last 40 years has experienced rapid growth and development, and statistics show that energy use has increased by more than 100% (The World Bank, 2014). The monthly average ambient temperatures have also experienced an increase of approximately 4 °C during the past 100 years (The World Bank, 2017). Due to this phenomenon, the increase in building's energy use due to the cooling systems has been significant, and it has been reported that almost 80% of the building energy use is for air conditioning (Indraganti & Boussaa, 2017).

Dubai in particular, is one of the 7 emirates that has experienced the most extreme development in the past 30 years. As an effect, the ambient environment has changed radically, leading thus to the observation of higher external temperatures in the city. (Taleb & Abu-Hijleh, 2013). Many researchers have focused on the impact of the increased external temperatures on the regional building energy use and thermal comfort (Brumana, Franchini, & Perdichizzi, 2017; Al-Sallal & Al-Rais, 2011). Outdoor thermal comfort in an exponentially advancing nation like the United Arab Emirates plays a major role in the growth of its economy and the satisfaction of its citizens. Furthermore, for external work environments, industries like construction, process and manufacturing, outdoor thermal comfort is a necessary aspect to be considered. Poor outdoor thermal comfort forces people to stay indoors and thereby increases the consumption of energy in buildings through air conditioning of interior spaces. Consequently, this energy produced generates greenhouse gases, which cause warming of outdoor air, contributing to higher outdoor air temperatures.

This paper presents a study of the temperature distribution in a residential cluster in urban Dubai. Data of air temperature and relative humidity are collected over a 3-week period during peak summer. The temperature distribution in the cluster is analyzed to identify the UHI intensity and highlight the parts where the heat intensity is higher. The analysis further deals with the outdoor comfort conditions of the cluster as a result of the harsh summer weather conditions. Moreover, through Computational Fluid Dynamics (CFD) analysis using ANSYS Fluent V17.2 software, the temperature and wind path and velocity in the cluster and their effect on the outdoor thermal comfort are discussed.

2. Methodology

2.1 Experimental Methodology

This paper evaluates the temperature distribution at a local microscale level in the residential compound of “The Sustainable City (TSC)” which is located southeast of the Dubai city center, as shown in Figure 1. The vision of TSC mainly encompasses the three pillars of sustainability: environmental, economic and social. According to the developers, the city’s master plan is technically very thorough, exceeding the best practices in environmental building technologies and innovative architectural typologies (Diamond Developers, 2017). The microclimate study conducted in this work seeks to identify and understand the formation of the temperature intensity and local hot spots created by the building topology in a selected building cluster within the The Sustainable City and how this affects the outdoor thermal comfort of the occupants.

The first part of the assessment is based on measured data and evaluates the distribution of the temperature and humidity within the cluster. The buildings have a “desert sand” color and are built in close proximity to some local vegetation of dessert bushes and palm trees used as a separation between the clusters. Furthermore, temperature records from the Al Maktum International airport (DWC) weather station, which is located in a suburban area approximately 60 km from the city center, were collected (Dubai World Central (DWC), 2017; Weather Underground, 2017). The airport data are used as a reference base for comparison with the measured data to establish the UHI intensity.

The 3-week experimental period spread from the 28th of May till the 11th of June 2017. All measurements were taken during sunny days with clear sky conditions. The original points of measurements used for the analysis of this paper are shown in Figure 2. Readings were taken with an interval of 5 minutes at each point. The readings included maximum, minimum and average temperature and maximum, minimum and average relative humidity. The readings were taken at points of approximately 2m height from the ground. The equipment used for the data collection is presented in Table 1.

Table 1, Experimental equipment used for data collection, source: (Gemini data loggers, 2017; Flir, 2017)

Equipment	Range
Tiny Tag View 2 TV 4500	Temperature : -25 °C to +70 °C with resolution of 0.02 °C
	Relative humidity 0 to 100% with resolution of 0.3%
Flir C2 thermal camera	-10 °C to +150 °C with accuracy of 2%.

Figure 1,The Sustainable City location in the Dubai emirate

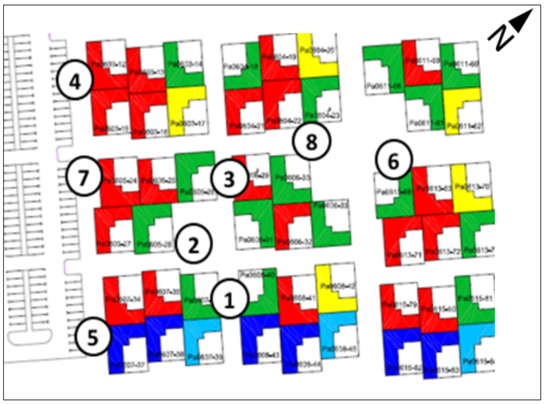


Figure 2,the position of the data loggers within the cluster

2.2 Numerical Methodology

Computational Fluid Dynamics (CFD) was further used as a tool to evaluate the temperature distribution and air paths and velocity in The Sustainable City cluster. The cluster model was developed and the flow around it was solved in ANSYS Fluent V17.2 software. The model was validated against the experimental data and the error was found to be approximately 8%. Thus it was proved to be a reliable tool to evaluate the effect of the UHI intensity on the cluster and the outdoor thermal comfort as a result of the cluster building topology and design, as well as a future guide for mitigation strategies.

The Dubai International Airport (DXB) wind data was used to determine the dominant wind speed and direction. The dominant wind speed and direction are 3.71 m/s and 220˚ and they were used in the present numerical simulation boundary conditions. The computational domain included residential cluster which was modelled as per the actual specifications. A tetrahedron meshing technique was applied on the geometry wherein the boundary conditions were applied on the edges and faces. The total mesh size comprised of 753,506 cells, 232,961 nodes, and 1,674,584 faces. The applied steady state boundary conditions included a reference velocity of 3.71m/s at a height of 1.7m. Direct solar radiation at the local coordinates was calculated by the software as 1423 W/m^2 and the diffuse solar radiation was 200 W/m^2. Different ambient temperatures were selected ranging from 30 °C to 45 ˚C.

3. Data on the temperature and humidity distribution

Overall for the cluster, it is observed in Figure 3 that during the data collection period a temperature variation exists. The hottest day is the 7th of June with an average daily measured temperature of 40.50 °C and the coolest day the 4th of June with average daily measured temperature of 36.08 °C.

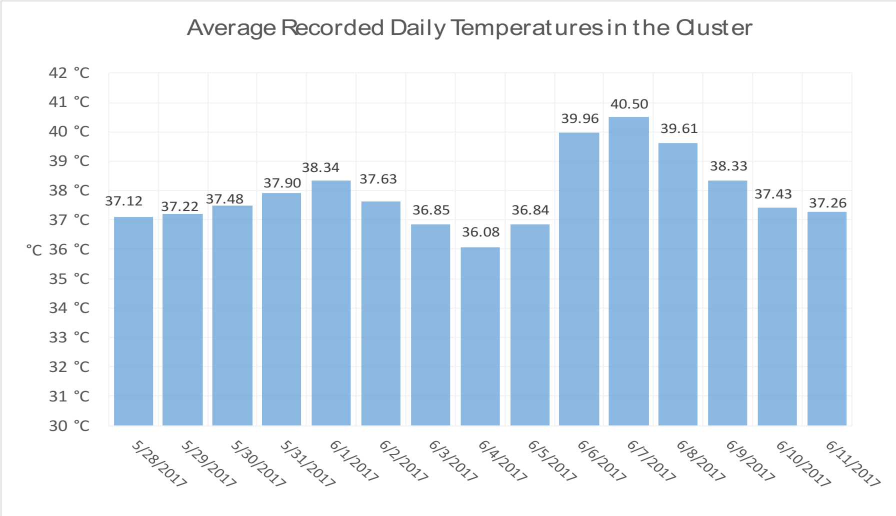


Figure 3, Average recorded daily temperatures in the cluster

Overall for the experimental period, the measured air temperature is higher than 30 °C for 75% of the time, as presented in Table 2.

Table 2, hours and percentages of temperatures above 30°C

Date	Total Hours above 30 °C	Night hours (9pm-6am)	Day hours (6am-9pm)	Night percentage	Day percentage
28-May	15.8	3.00	12.75	19.0%	81.0%
29-May	16.0	3.42	12.58	21.4%	78.6%
30-May	15.4	3.00	12.42	19.5%	80.5%
31-May	15.7	3.08	12.58	19.7%	80.3%
1-Jun	15.8	3.00	12.75	19.0%	81.0%
2-Jun	16.8	4.00	12.83	23.8%	76.2%
3-Jun	18.0	4.92	13.08	27.3%	72.7%
4-Jun	18.1	4.75	13.33	26.3%	73.7%
5-Jun	16.0	3.25	12.75	20.3%	79.7%
6-Jun	20.7	6.83	13.83	33.1%	66.9%
7-Jun	21.9	7.50	14.42	34.2%	65.8%
8-Jun	23.8	8.92	14.92	37.4%	62.6%
9-Jun	21.0	7.33	13.67	34.9%	65.1%
10-Jun	18.2	5.00	13.17	27.5%	72.5%

Figures 4 and 5 present the measured temperature and humidity data for each location in the cluster. As it is observed the different locations within the cluster present different temperature and humidity profiles. The minimum recorded temperature point in the cluster is 22.90 °C and the maximum recorded point is 55 °C. The maximum recorded temperatures on average in the cluster is 49.40 °C on the 6th June at 3pm. The minimum recorded temperature on average in the cluster is 25.13 °C on the 28th May at 5.40am.

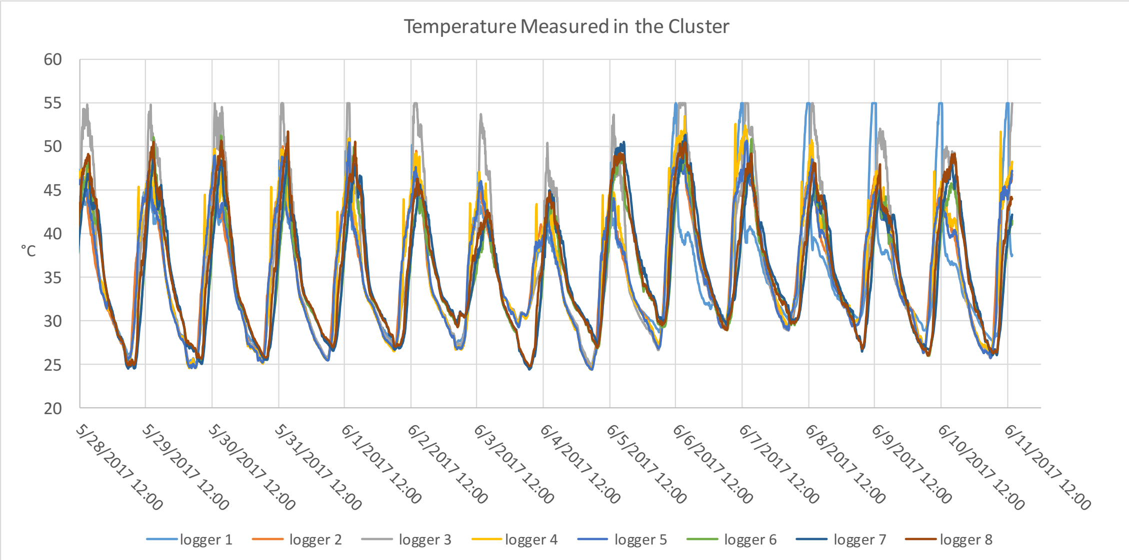


Figure 4, Temperature measured in the cluster

The minimum recorded relative humidity point in the cluster is 7.28% and the maximum is 100%. Overall it can be observed that the relative humidity presents the highest values until June the 3rd and then drops to peaks of around 70%. The maximum recorded on average in the cluster is 97% on the 2nd June at 6am. The minimum recorded humidity on average in the cluster is 12% on the 7th June at 3.20pm.

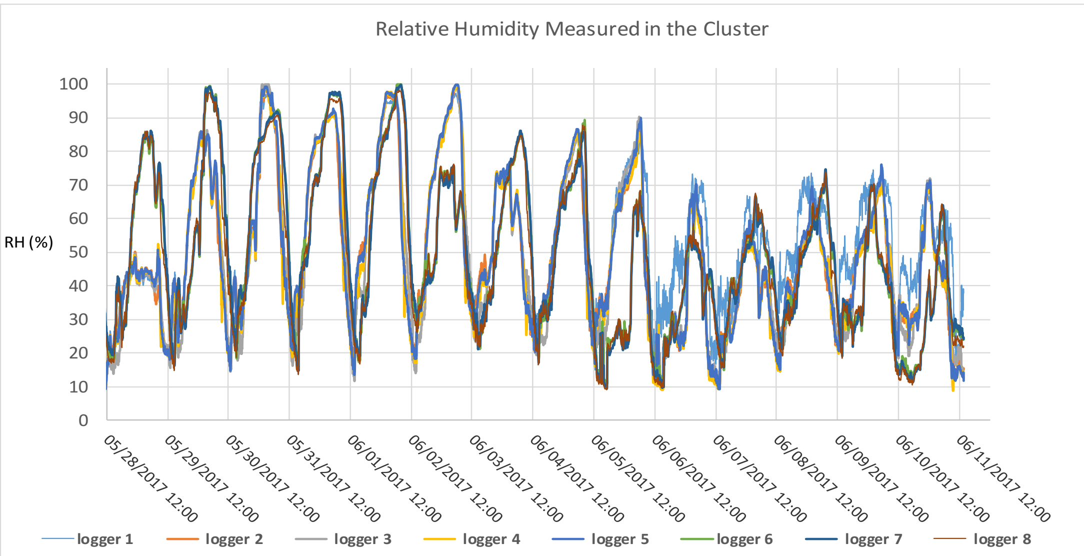


Figure 5, Relative humidity measured in the cluster

4. Analysis of the on the temperature and humidity distribution

For the duration of the experimental measurements, the hottest spot in the cluster is identified to be the logger 3 position with an average maximum temperature of 53.90 °C. The temperature recorded at the position of logger 3 does not drop below 24.50 °C for the whole experimental period and the maximum recorded temperature is 55 °C and this is reached for 10 days out of the 15.

The logger that presents the highest average relative humidity is that of position 1, with an average value of 53.90%. However, logger 3 presents the most relative humidity peaks of 100%. In the location of logger 3 both temperature and relative humidity peak more than in the other cluster locations. The average mean and maximum temperatures of the loggers positioned in the other locations are always smaller than the logger 3. Loggers 5, 6 and 7 present the lowest recorded temperatures overall in the cluster. Loggers 5 and 7 are located between the cluster, the parking areas, and a green space. The parking area provides free space on the south west side of the cluster, thus providing a clearer ventilation path. Logger 6 is placed in an open square formed by the cluster buildings and in a position where the surrounding buildings are in a greater distance than loggers 1, 2, 3, 4 and 8. The thermal imaging throughout the cluster, further confirms that logger 3 position is the hottest in the cluster. An example of a thermal image is shown in Figure 6.

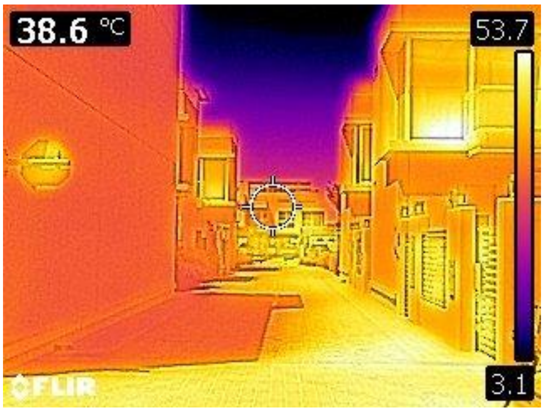
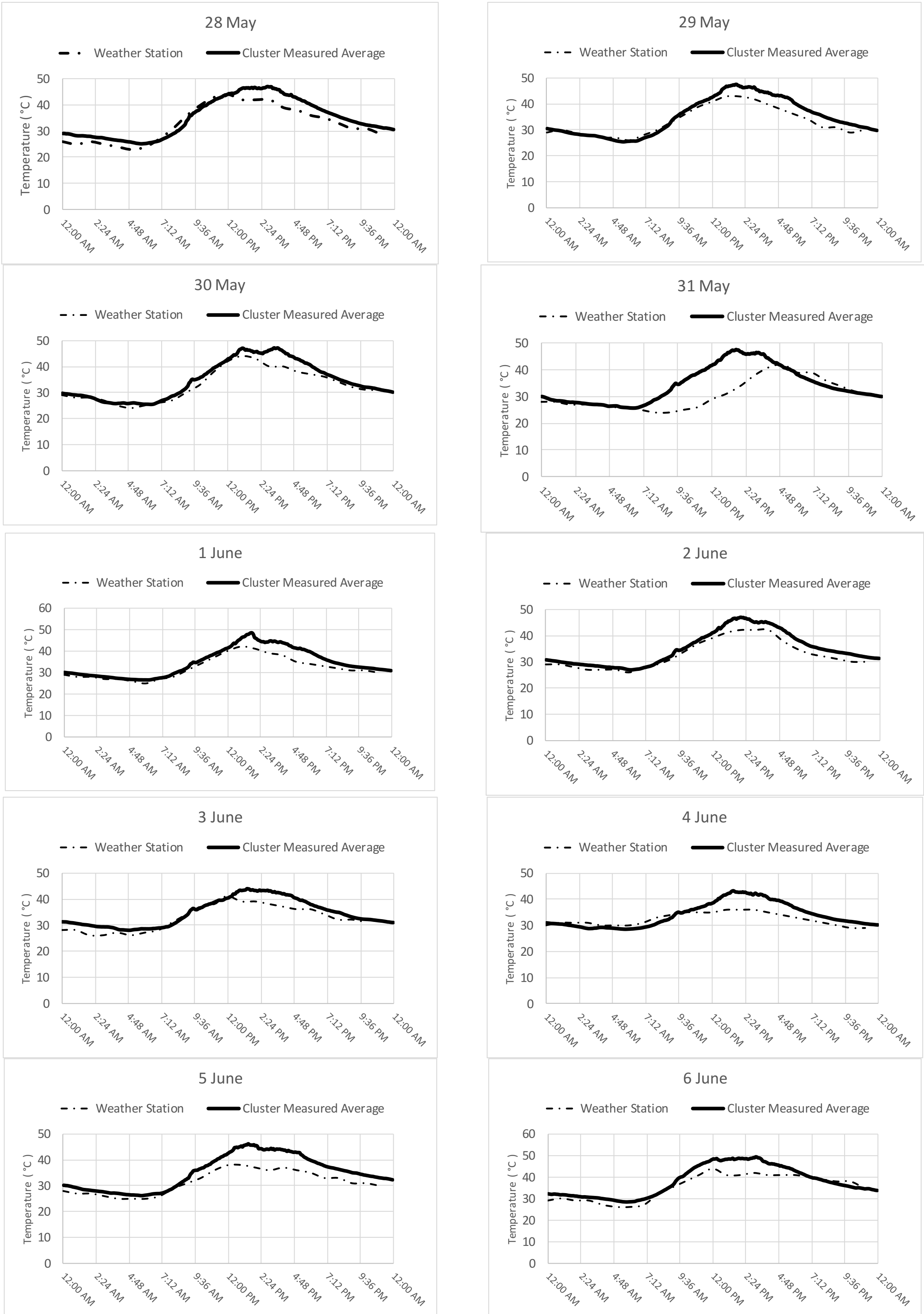


Figure 6, thermal imaging of the logger 3 location

Figure 7, presents the daily temperature difference between the measured temperatures as an average at the cluster and the temperatures recorded at Al Maktum weather station. It is observed that the temperatures measured at the cluster are constantly higher than the ones recorded at the weather station. On an average, the mean temperature difference throughout the cluster for the experimental period ranges between a minimum of 0.02 °C on June the 10th at 2am, and a maximum of 8.53°C on June the 5th at 2pm. The mean UHI intensity is calculated to be 2.44 °C. During night hours, between 9pm to 6am, the mean UHI intensity varies between 1.19 °C to 1.88 °C and between 6am to 9pm it varies between 1.33 °C to 5.39 °C. The extremely high temperatures and solar radiation during the day, could be the reason that the UHI intensity peaks during day hours. The relative humidity in the cluster is generally slightly lower than the relative humidity at the airport weather station. Overall, the relative humidity during the hours 9am to 9pm varies approximately between 10-60% and peaks during night hours.

Regarding the spatial temperature distribution in the cluster the hottest spot is identified in the area of logger 3 with 12% higher temperatures than the other loggers, followed by logger 1. Therefore, these are the parts of the cluster that greatest outdoor discomfort is expected for the occupants. The impact of relative humidity in combination with the high temperatures is further explored in the thermal discomfort evaluation, and presented in section 5. Furthermore, the reason of the creation of these hot spots of thermal discomfort is evaluated in section 6 with the use of CFD analysis.


28 May
29 May
30 May
31 May
1 June
2 June
3 June
4 June
5 June
6 June
Weather Station
Cluster Measured Average
Temperature (°C)
0
10
20
30
40
50
60
12:00 AM
2:24 AM
4:48 AM
7:12 AM
9:36 AM
12:00 PM
2:24 PM
4:48 PM
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9:36 PM
12:00 AM

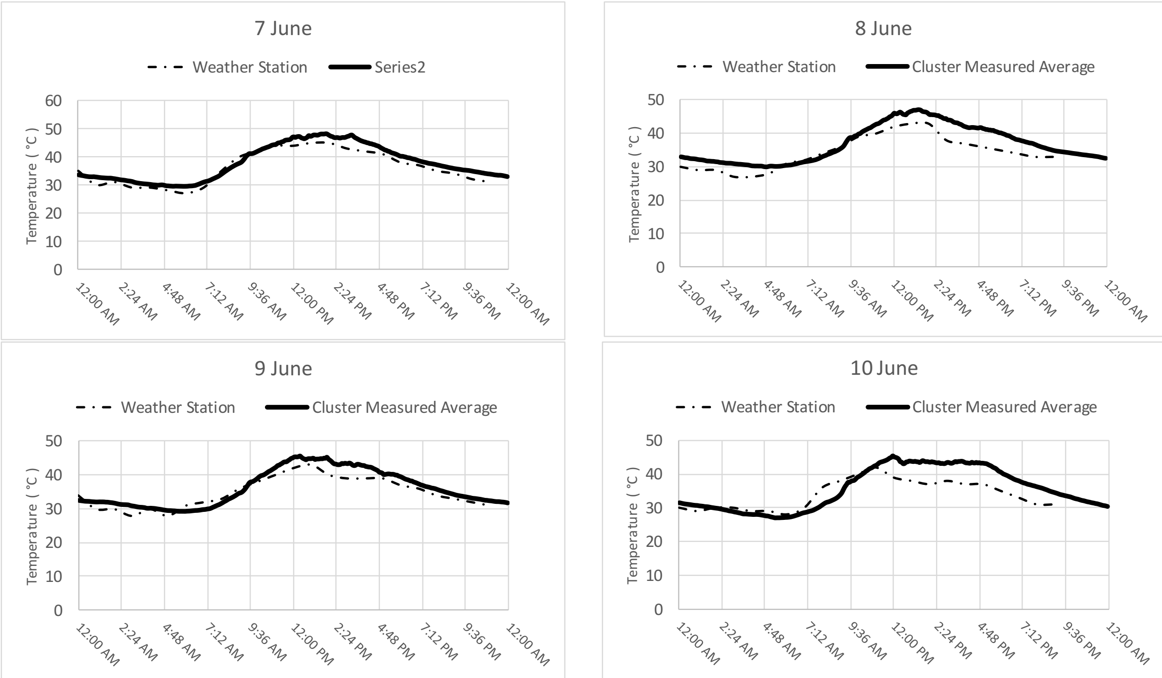


Figure 7, Comparison between the measured temperatures at the cluster and the temperatures recorded at Al Maktum weather station

5. Outdoor Comfort Conditions

As a further indication of the outdoor comfort, the temperature humidity index (THI) is calculated for the experimental period as an average for the cluster. The formula that is used is given in Equation (1):

$$THI = T - 0.55*(1 - RH)*(T - 58) \quad (1)$$

Where T is the air temperature measured in the shade in Celsius and converted in Fahrenheit, and RH is the relative humidity. If the THI is 70 or below, most inactive people are comfortable. If THI = 75, about half are uncomfortable, if THI = 79, nearly everyone is sweating and uncomfortable. In the case that THI is above 80 then extreme discomfort is present and if the THI values are as high as 90, then health and safety is of concern (Schlatter, 1987).

Figure 8 presents the THI in comparison to the temperatures and relative humidity measured in the cluster. As can be seen, the THI is always higher than 70 and in most cases even higher than 75. Considering the limit of 80 which is an indication of extreme discomfort as a benchmark, it is observed that it occurs for temperatures between 30 °C to 50 °C and a wide range of relative humidity values between 12.6% to about 90%. This situation is observed for about 80% of the time of the experimental period, and 100% of the day times. As a result, overall in the cluster, high discomfort is expected during the experimental period. This is not surprising as in the United Arab Emirates the summers are harsh and humid with very high temperatures.

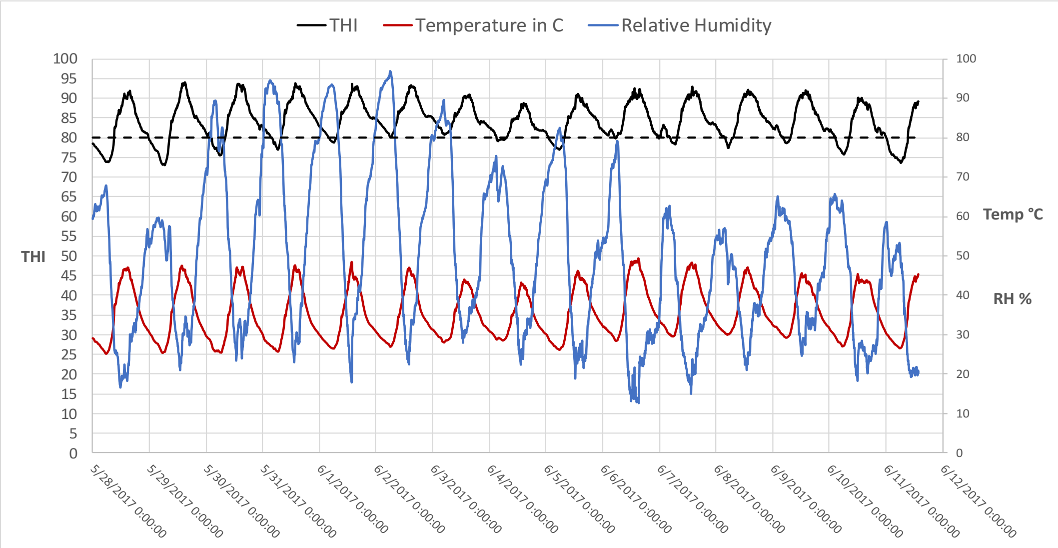


Figure 8, THI in relation to temperature and relative humidity

Further analysis for the data logging positions, indicates that the discomfort is greater in the positions where the measured temperatures are higher. As shown in Figures 9, 10 and 11 the location of logger 3 which has been identified as the hottest in the cluster, presents also the highest potential of discomfort, with an average THI of 84.46 for the whole experimental period. The location of logger 1, which is the second hottest and most humid in the cluster, presents the second highest discomfort, with an average of 84.43 for the experimental period.

In further agreement to the temperature distribution analysis, the position of logger 6 is found to be the one with the least discomfort conditions present, and an average THI of 83.22 for the experimental period.

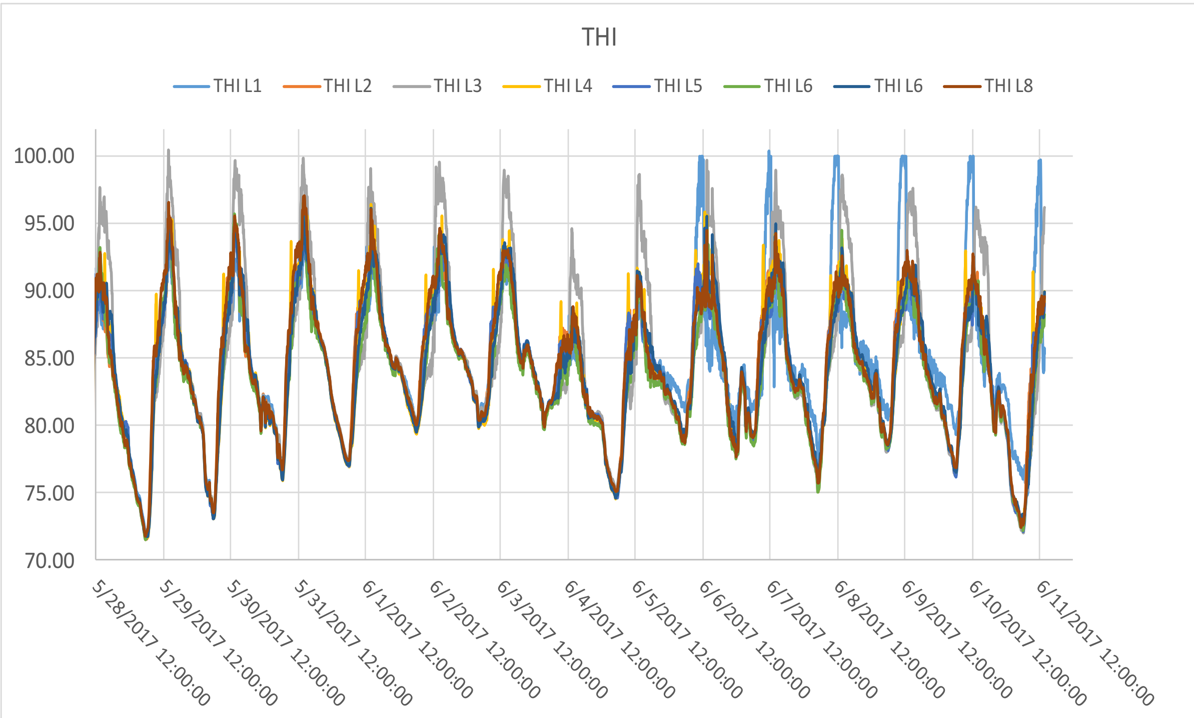


Figure 9, THI for each measurement position during the experimental period

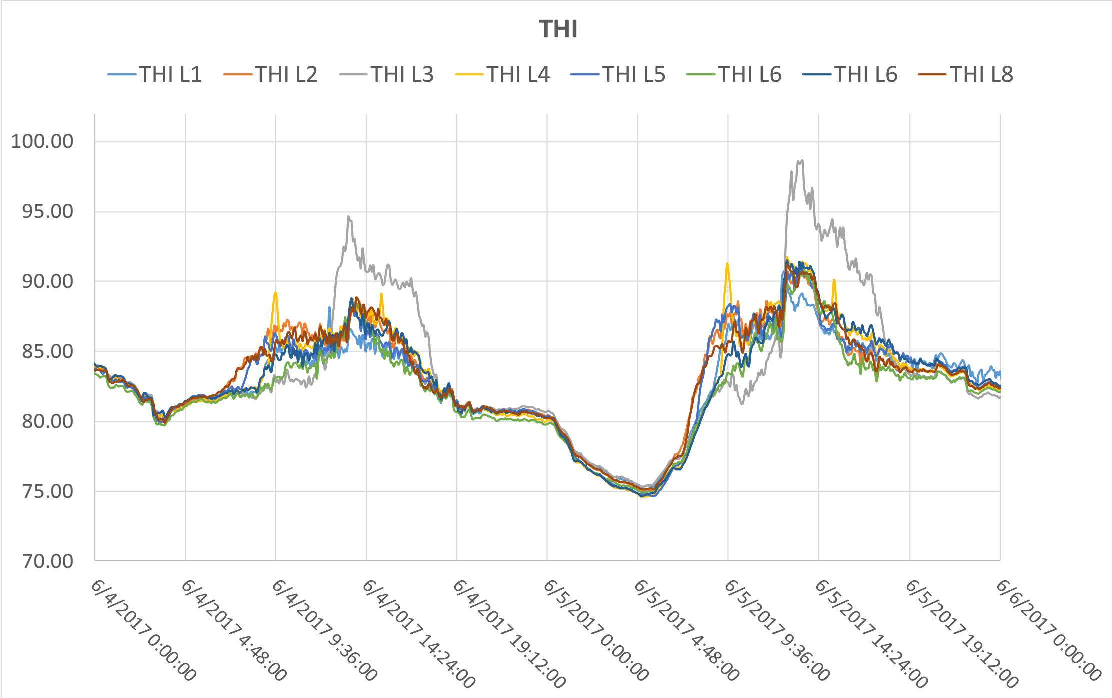


Figure 10, THI for each measurement position for the 4th and 5th of June

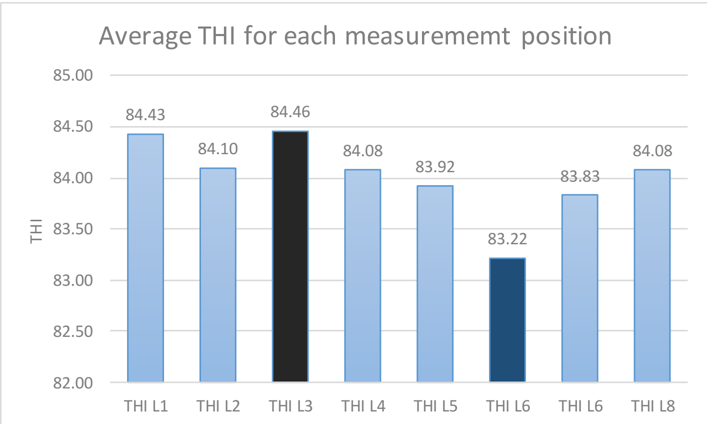


Figure 11, Average THI for each measurement position CFD Results

6. CFD Results

The CFD simulation of the microclimate is conducted for the selected building cluster. Air stagnation, as shown in Figure 12a, was observed at the backward of the building cluster where the temperature is much higher than other areas away from the building. The inlet speed applied to the model was 3.71m/s as per the weather data. Due to the high airflow in the central cluster region, the heat intensity was the lowest at those areas for all models. It was noted that local hot spots are strongly dependent on the geometries of the building cluster and construction materials.

Due to the atmospheric boundary layer around the cluster, the local air velocity at the building height was lower than the inlet boundary condition. Wind direction and speeds will have a significant impact on the hot spots as well. Figure 12b indicates the contour levels of static pressure around the cluster. As expected, higher air pressures are obtained at the windward locations of all the clusters local to the flow inlet, with the maximum pressure value of 3.8Pa. Negative pressure was obtained at the back of the clusters (leeward to the flow inlet) at approximately 2.5Pa.

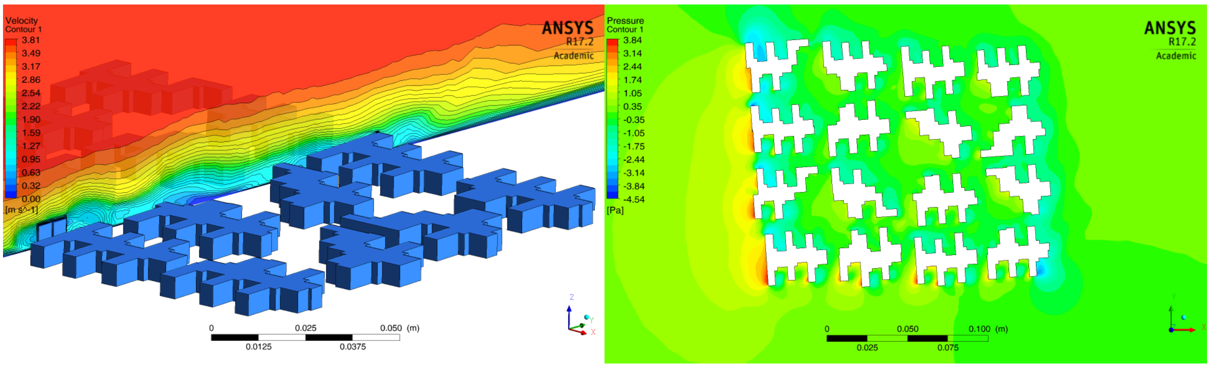
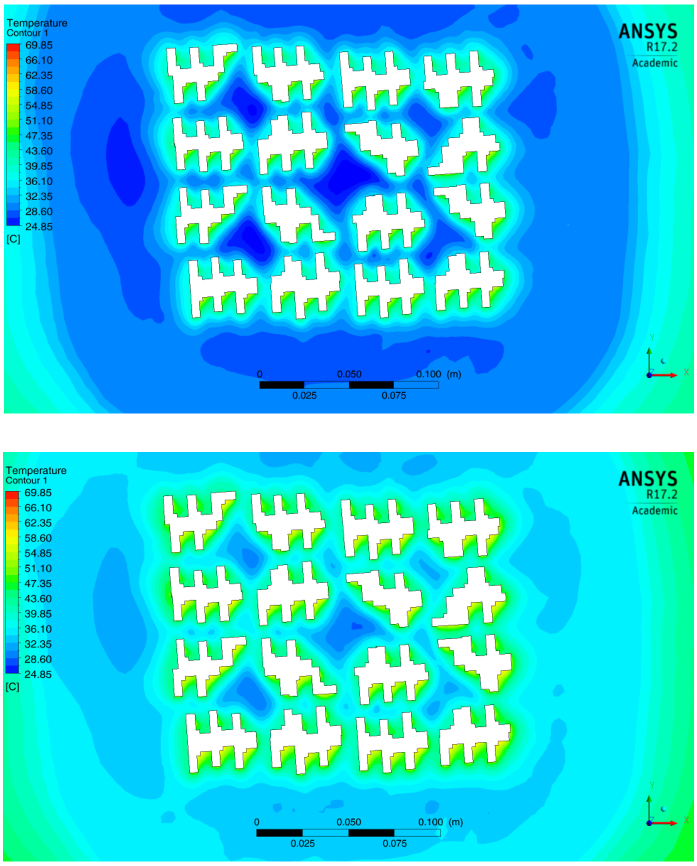


Figure 12, (a) Velocity and (b) static pressure contour levels across the cluster

The CFD results are based on ambient air temperatures of 30 °C, 35 °C and 40 °C to understand the temperature patterns around the cluster, and in accordance to the air temperature ranges of the experimental period. Figure 13 indicates a summary of the temperature findings. As can be observed, the heat intensity was found to be inversely proportional to the air movement through the cluster and the regions of hot spots were localised closer to the boundary walls.



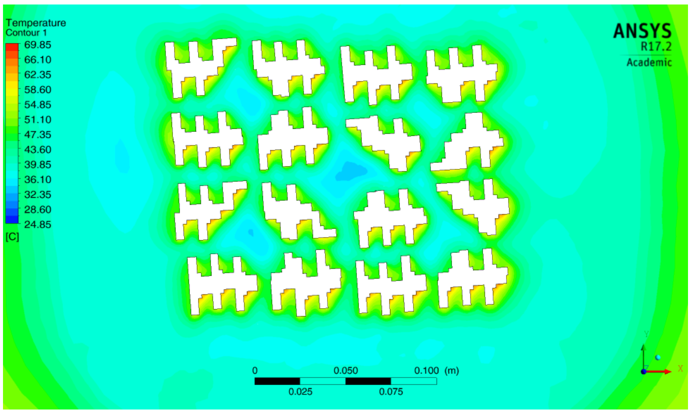


Figure 13, Plan view of the temperature contour levels

Figure 14 displays a quantified temperature profile along the axial direction of the cluster for ambient temperatures ranging between 30 °C and 40 °C. As displayed, the region of high and low heat intensities is consistent through the cluster and is independent of the ambient temperature. The least heat intensity is experienced by the central regions within the cluster (data logging point 6) due to accelerated air movement. However, the amplitude of heat intensity increases with increasing ambient temperature. A maximum temperature increase of 26% was noted when the ambient temperature was 30 °C. This was increased to 40% when the ambient temperature was 40 °C, thereby indicating that urban heat islands augment in magnitude with increasing ambient temperatures. This is a suggestion that under these climatic conditions of extremely high temperatures, the natural ventilation paths would need to be further assisted by other techniques in order to enhance outdoor comfort.

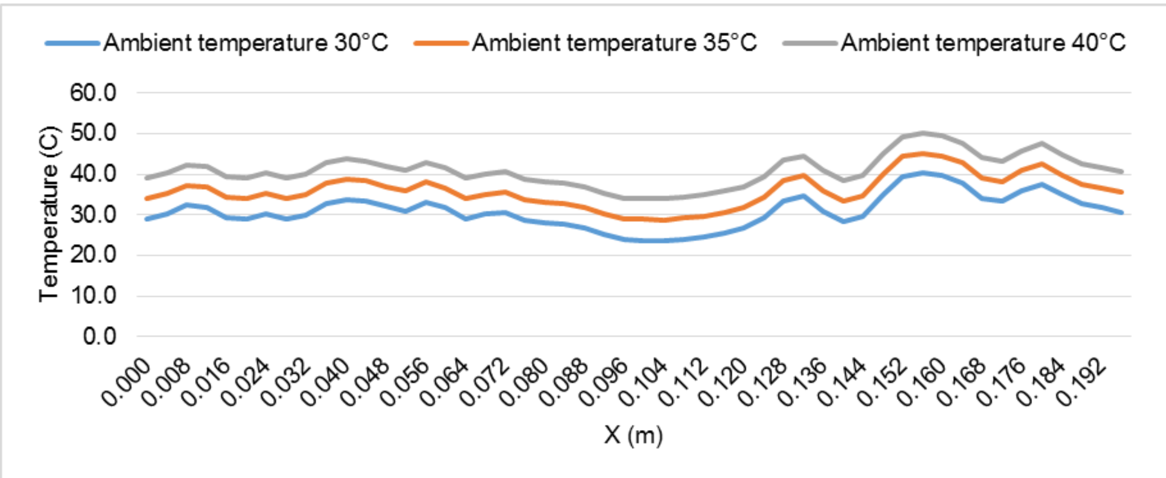


Figure 14, Temperature profiles along the axial direction of the cluster

7. Conclusions and Future Recommendations

This paper presents an analysis of the temperature distribution and its effect on outdoor thermal comfort in Dubai, United Arab Emirates. As Dubai is experiencing rapid urban development and population increase, it is important to evaluate how the residential buildings affect the ambient conditions and consequently the outdoor thermal comfort, particularly for the hot summer period.

A cluster in The Sustainable City residential compound was used as a case study, and air temperature and relative humidity data were measured during peak summer and indicate that 75% of the time temperatures are higher than 30 °C, with peaks of 55 °C. The minimum recorded temperature on average for the whole cluster was 25.13 °C. This extreme temperature range, in combination with the high relative humidity has an effect on outdoor thermal comfort. The temperature humidity index (THI) was calculated, and it was proved that for 100% of the day time and 80% of the overall experimental period, extreme discomfort is present. Furthermore, the hottest locations of the cluster, were also identified as the ones where the highest discomfort is experienced.

The outdoor comfort was further evaluated with a CFD model developed in ANSYS software. The model further indicated that the least heat intensity is experienced by the central regions within the cluster (data logging point 6) due to accelerated air movement as a result of the cluster spatial design and the broader space between buildings. Furthermore, the amplitude of heat intensity increases with increasing ambient temperature, thus eliminating the cooling effect of the ventilation paths within the cluster.

As a conclusion, mitigation strategies are necessary in order to improve this condition and result in lower air temperatures within the cluster. At the current state, The Sustainable City follows the local vernacular of the United Arab Emirates, with sand colored buildings, built at a close distance with limited vegetation present. Further work of the authors, will focus on evaluating the effect of increased green spaces around the cluster, external shading and different building coatings. Furthermore, the effect on a building cooling demand level will be evaluated with the use of IESVE software.

8. Acknowledgments

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