Urban Climate xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Urban Climate

journal homepage: www.elsevier.com/locate/uclim

Analysis of urban heat in a corridor environment – The case of Doha, Qatar

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ARTICLE INFO

Keywords:
UHI index
Corridor environment
Arid cities
Thermal comfort
Built environment
Qatar

ABSTRACT

Doha, Qatar is one of the arid coastal cities of the Gulf Cooperation Council (GCC) countries. Like similar cities, temperatures can vary widely throughout, with rapid and extensive development that has contributed to micro-climate changes. While numerous studies since the 1950s have assessed urban micro-climates, few have offered insights into urban corridor environments. This research is one of few projects to examine temperature records along two major roadways and identify factors that explain variation. The research uses vehicle-based air temperature traverses during late spring and summer 2016 using a Type T fine gauge thermocouple mounted in a white plastic tube and supported above the vehicle on the passenger-side window. The data were assessed in terms of four factors that may impact temperature along the corridors, including: distance from the coast, traffic volume, vegetation density, and building volume density from 50 m up to 400 m (in 50 m intervals) from the centerline of the traverse. Results indicated that the two most critical variables that predict air temperature patterns along the corridors are the distance to the coast and the traffic volume. This knowledge can be incorporated into urban planning and design practice for extreme arid environments to maintain temperatures that reduce heat-related stress.

1. Introduction

The city of Doha, the capital of Qatar, has witnessed the emergence of oil-wealth in the last few decades that has transformed the city from a small fishing, pearling, and trading settlement to a modern city with numerous examples of international architecture, an urban core of high-rise offices and apartments, and a growing number of hotels, museums, and other facilities for hosting international events. The transformation has changed the fabric of the society due to the vast influx of workforce to serve the expanding city. The global competition and the increasing numbers of the population demand massive expansion in infrastructure and urbanization that have changed the overall built environment of the city (Adham, 2008; Wiedmann and Salama, 2012). The exceptional form and pace of urbanization in desert cities, like Doha, Qatar, highlight the need for an experimental detailed study of its potential impact on local microclimate change. Sustaining an adequate quality of life for this increasing population in Doha may be contingent, to a critical extent, on our understanding of the climatic changes induced by urbanization (Charabi and Bakhit, 2011; Pearlmutter et al.,

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http://dx.doi.org/10.1016/j.uclim.2017.08.008
Received 6 April 2017; Received in revised form 3 August 2017; Accepted 22 August 2017
2212-0955/

2006).

The Urban Heat Island (UHI) has been investigated as one of the most stimulating climatic phenomenon of cities. It can be conceptualized as “the rise in temperature in any man-made area, resulting in a well-defined, distinct “warm island” among the “cool-sea” represented by the lower temperature of the area's nearby natural landscape” (Arrau and Pena, 2016). The main cause of UHI formation is the differential cooling rates of built and natural surfaces, which is most apparent during nighttime (Oke, 1982). Built surfaces comprise a high proportion of water-resistant, low albedo and low emissivity construction materials. Urban areas have been found to have 2–5% lower albedo and 1–2% lower emissivity than surrounding croplands (Jin et al., 2005). As a result, they absorb short-wave radiation, that is released afterwards as heat. Numerous studies have revealed that urban areas, compared to non-urbanized areas in their surroundings with less artificial surfaces, record higher local temperatures as a result of the UHI effect (Arnfield, 2003; Taha, 1997; Wong et al., 2016). The effect of the UHI is not limited to the adjacent urban environment, but also has effects on the global environmental quality. Jin et al. (2005, p. 1552) argue that “land–atmosphere–biosphere interactions cause significant mesoscale circulation anomalies, and these anomalies can propagate to large scale.”

In studying the specific causes and patterns of the UHI for different locations, a number of approaches, measurement methods and scales have been investigated, including ground-based stationary or mobile surveys (Blankenstein and Kuttler, 2004; Yan et al., 2014) of ground-level air or surface temperature (Voogt and Oke, 2003) at scales ranging from the local to *meso* scale up to continental or global studies (Jin et al., 2005) and at levels of the urban canopy layer or urban boundary layer as distinguished by Oke (1976). Remote sensing has also been found to be important, particularly for city-wide, regional or larger scale studies (Jin et al., 2005; Nichol et al., 2009; Streutker, 2002; Voogt and Oke, 2003).

While many urban climate studies have been documented for mid-latitude cities (Arnfield, 2001; Oke, 1986), fewer studies can be found for cities in arid tropical or sub-tropical regions (Lazzarini et al., 2013; Pearlmutter et al., 1999; Sofer and Potchter, 2006), which are perhaps some of the most challenging climate regimes for thermal comfort. Research in the desert city of Muscat, Oman used mobile traverses to examine the UHI in selected sites. Results indicated that UHI magnitude is greatest in summer and that it is located along narrow roads with low ventilation, multi-storied buildings, high business activities and heavy road traffic (Charabi and Bakhit, 2011). Another study in the arid desert city of Phoenix, Arizona examined the seasonal relationship of urban plant cover, land use, and micro-climate in the city. Near-surface temperatures were measured along several transects. Land use was identified as the most evident impact on microclimate, especially during summer, with residential and agricultural land uses recording the lowest air temperatures, while industrial and commercial land uses recorded the highest temperatures (Stabler et al., 2005).

2. Study background

Doha is the most densely populated city in Qatar with approximately 40% out of a total population of 2.4 million in 2015 (Qatar Ministry of Development and Planning Statistics, 2015). For this study, the climate of Qatar is significant in that it constitutes the combined effects of extremely hot, and sometimes humid summers, a coastal location, and the formation of the UHI induced by rapid urbanization (Golden, 2004; Ferwati et al., 2016). Due to its hot climate from mid-April through November and the expanding infrastructure, residents experience a high degree of thermal discomfort during this part of the year. For example, summer outdoor temperatures frequently exceed 40 °C, whereas humans are most comfortable during summer with ambient temperatures ranging from 23 to 27 °C (Epstein and Moran, 2006; ASHRAE, 1992). Of course, an individual's perception of thermal comfort is much more complex and dependent on physical parameters other than the ambient air temperature alone. This topic has been widely researched to increase the understanding of the physical parameters that impact thermal comfort leading to the development of numerous models for both indoor and outdoor comfort (Coccolo et al., 2016; Cheung and Jim, 2017; Rupp et al., 2015).

Summer heat will be intensified by the effect of the UHI, and this is likely to have negative impacts on the welfare and health of city residents, making it important to examine the factors that contribute to increased temperatures in such a city. A previous study in Doha, which found a maximum UHI intensity of 3.5 °C in summer and 1.5 °C in winter, attributed the UHI effect to the desert environment, heat exhaust emitted by vehicles and air conditioning, reductions in vegetation, as well as heat that is trapped by buildings and other built surfaces (e.g., roads and pavements) during the day and then released at night (Sasidharan et al., 2009). Other studies have highlighted the role that land use types have on the thermal pattern of the UHI (Feizizadeh and Blaschke, 2013; Hart and Sailor, 2009; Middel et al., 2014) as well as the wall-to-wall distance and height of buildings, leading to formation of urban canyons that, in some locations, constrain the rate of escape at night of sun energy absorbed by construction materials during the day.

Remarkably, earlier research identifies transport corridors and roadways, in general, as major contributors to urban heat (Sasidharan et al., 2009; Wong et al., 2016). Yet, at the same time, we have not fully identified the characteristics of urban corridors that are responsible for generating such acutely higher temperatures. Corridors offer an immediately fruitful opportunity to impact the growth of rapidly urbanizing regions. They are larger than an individual parcel/tax lot, and smaller than city-wide analysis, but offer the possibility of examining a range of building densities, configurations, land uses, and traffic patterns within a well-defined spatial element. Rapidly urbanizing regions require particular attention to the scale of corridors for three reasons: (1) many rapidly developing cities are composed of sprawling areas of low-density and often irregular, minimally planned growth patterns; (2) they are often the first to be planned; and (3) they attract future development. Therefore, a central aim of this research is to explore the UHI patterns that emerge from urban corridors, and develop methods of analysis and planning that may offer insights for reducing heat trapping design that are consistent with rapidly changing cities.

This study utilizes a fine-scale approach of mobile air temperature traverses for studying the thermal regimes in two major urban corridors of the city. In particular, these major corridors are long, nearly straight roads, running from the coast to more than 20 km inland, which provide a distinct opportunity for studying coastal influences compared to other built environment variables. The study

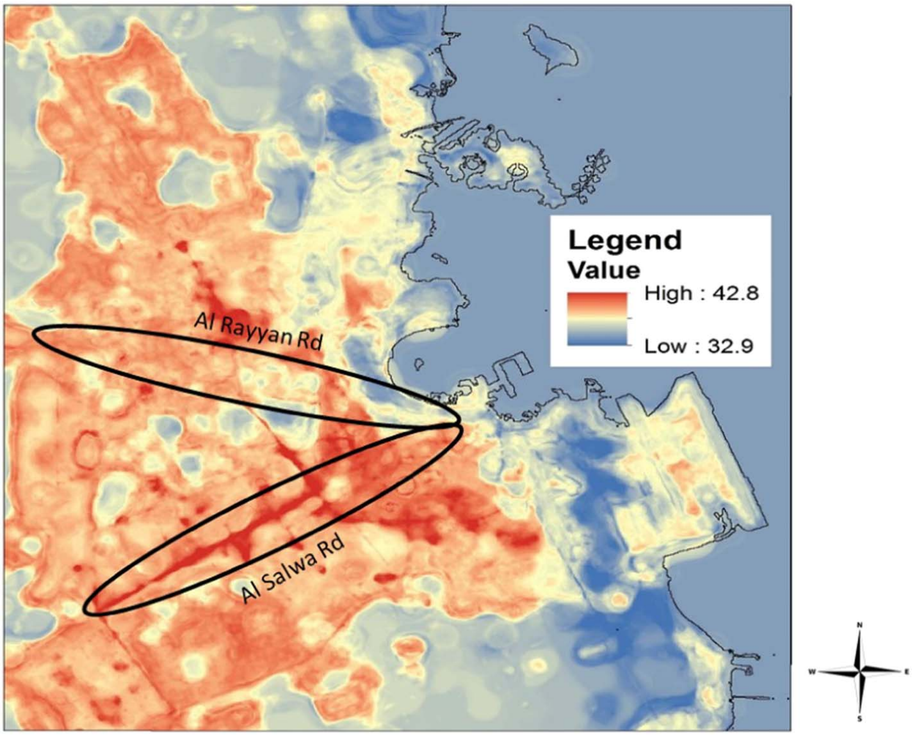

Fig. 1. Predicted surface map (unit is in °C) for 9/8/2014 7 PM.

investigates the relative importance of the following four built environment variables in contributing to increased air temperatures: building density, vegetation cover, distance to the coast, and traffic volume. Based on the results, recommendations are made for future planning in hot, arid urban corridor environments.

3. Methodology

3.1. Selection of study areas

A previous study in September 2014, which comprised traverses for almost all parts of Doha city, resulted in development of a spatial description of temperature variability for one day in September 2014 at 7 PM (Makido et al., 2016). The predicted surface map highlighted Salwa Road as a distinct high temperature surface (Fig. 1). Another major corridor, Al Rayyan Rd., does not appear as distinctly as a high temperature surface.

The completion of an earlier city-wide assessment, and the observation that some corridors (and specific areas within each) have heightened temperatures, while others do not, forms the basis for this study. Indeed, the selected corridors - Salwa Road and Al Rayyan Road - are typical of major arterial asphalt roads in greater Doha, yet they differ in their temperatures throughout the day (Makido et al., 2016). The detailed analysis of microclimate variation at the street level may offer insights about how to better design major thoroughfares for improving thermal comfort. The corridors were selected to cover the spread of the greater Doha metropolitan area, in order to include varied patterns of land use, and evaluate both the urban core and the urban fringe of the city. Given that they both begin from a near-coincident point near the coast and run inland for at least 10 km, but appear to exhibit different temperature patterns along these segments, they were found to be useful cases for comparison (Table 1). The corridor traverses included areas of heavy to moderate traffic and do not have a uniform width. Only street level roads were traversed; tunnels and flyovers were avoided.

3.2. Mobile air temperature traverses

The main approach to data gathering was to employ mobile traverses (average speed of 40 km/h) across the corridor with automobile-mounted sensors. Following a protocol established by Hart and Sailor (2009), air temperature was measured using a Type T fine gauge (30 gauge) thermocouple mounted in a white plastic tube measuring 12 cm long and 2.5 cm diameter and supported above the vehicle roof on the passenger-side window, extending approximately 25 cm. In each mobile traverse, air temperature was measured at a height of approximately 1.8 m (road surface to thermocouple height) and frequency of once per 3 s. At the same time a GPS device was recording in 1-second increments for geo-referencing and estimation of altitude (Makido et al., 2016) (Fig. 2). A shapefile was digitized in ArcGIS 10.3 of the coastal outline and used to determine the distance to the coast from each measured air temperature point.

Table 1
Summary of corridor characteristics.

Corridor characteristic	Al Rayyan Rd	Salwa Rd
Orientation	Relatively straight line from the NW corner of the M'sheireb Downtown Doha project inland to the Education City area and then ends at the Dukhan Highway which then continues W-NW to the city of Dukhan, a city that is furthest to the West in Al Rayyan Municipality	Relatively straight line from the SW corner of the M'sheireb Downtown Doha project inland to the Industrial Area District and eventually to the border crossing with Saudi Arabia as national highway 5
Traffic patterns	Represents a modern street, with few parallel service roads. Significant traffic flows, which at certain points experiences heavy traffic congestion during working days	Represents a modern street, with parallel service roads and significant traffic flows, particularly noted for extreme traffic congestion during working days
Width	Two lanes in each direction near the coast but widening to three lanes and then narrowing back to two as it moves inland	Two lanes in each direction near the coast and widening to 3 lanes in each direction
Intersections	It intersects with several of the city's Ring Roads: some are on-grade with traffic lights, while a few remaining on-grade roundabouts are currently being replaced with traffic lights	It intersects with the city's Ring Roads: some are on-grade with traffic lights, some are on-grade roundabouts, and some are fully grade-separated interchanges
Surrounding land use	It has different adjacent land uses ranging from commercial, residential, and institutional with different development densities	It has different adjacent land uses, primarily large commercial and offices, with some residential and with different development densities
Materials	The materials include asphalt for all street pavements, CMU (concrete masonry unit) and stucco plaster for buildings, and precast concrete pavers for pedestrian areas. Both side of the road are commercial stores with an average of 60% class walls.	The materials include asphalt for all street pavements, CMU with stucco (Portland cement plaster) for the buildings, and precast dry-lid concrete pavers (light gray or brick color) for sidewalk, both sides of the roads are residential.
Wind effects	When the wind direction is from the East, the roadway corridor may channel prevailing breezes into the inner urban areas	When the wind direction is from the North-East, the roadway corridor may channel prevailing breezes into the inner urban areas

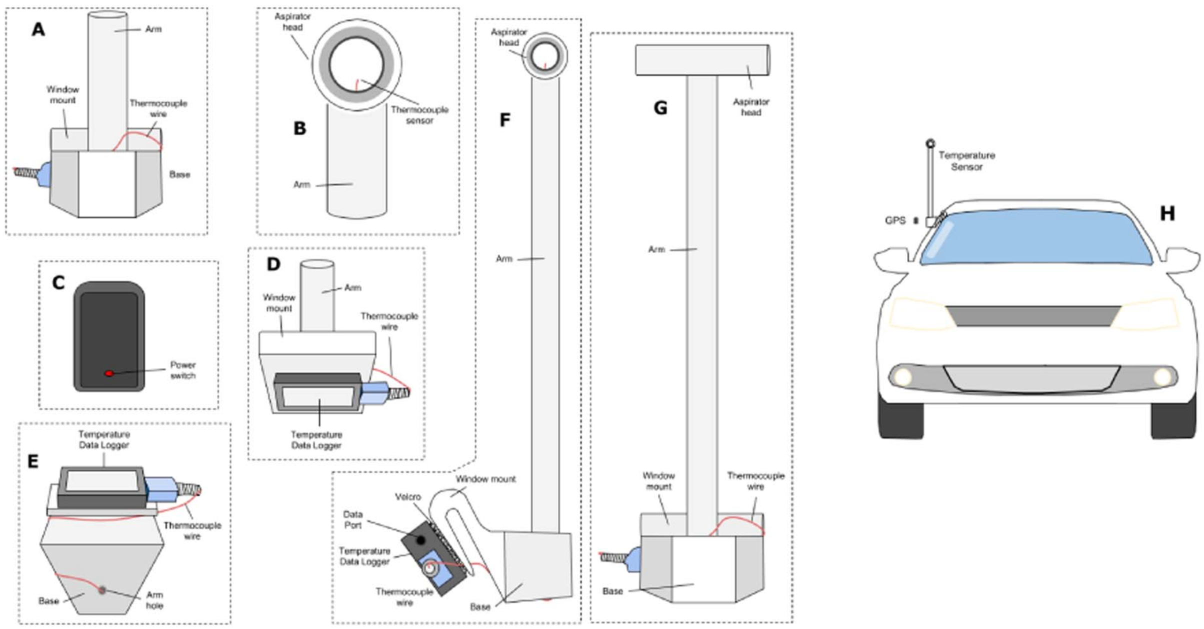

Fig. 2. Rendering of sensor setup. 2a: Front of base. 2b: Aspirator detail. 2c: GPS unit. 2d: Back of base. 2e: Bottom of base. 2f: Profile of device. 2g: Front of device. 2h: Approximate scale of device and GPS unit (GPS unit kept inside of vehicle).

Early morning (6 AM), afternoon (1 PM), and evening (7 PM) near-surface temperatures were measured along both the Al Rayyan and Salwa Road corridors during April and late July/early August 2016. Data for vehicle speeds of less than 5 km/h were discarded to avoid oversampling when the vehicles were stopped (e.g., in traffic or at traffic lights). To optimize the accuracy of mobile measurements, three meteorological stations are monitored for sub-hourly air temperature. The three stations are located near to the studied corridors - one near the coast and the other two inland (Fig. 3).

The background change in the temperature between the starting point and the endpoint of each traverse was examined and accounted for so that any warming or cooling trends in the data would not be overstated. For example, between 6:00 and 6:30 AM on April 26th, the temperature increased by approximately 1.5 °C. A linear correction was applied to account for this background change, using the average temperature change of the two weather stations (one inland and one coastal) (Fig. 3).

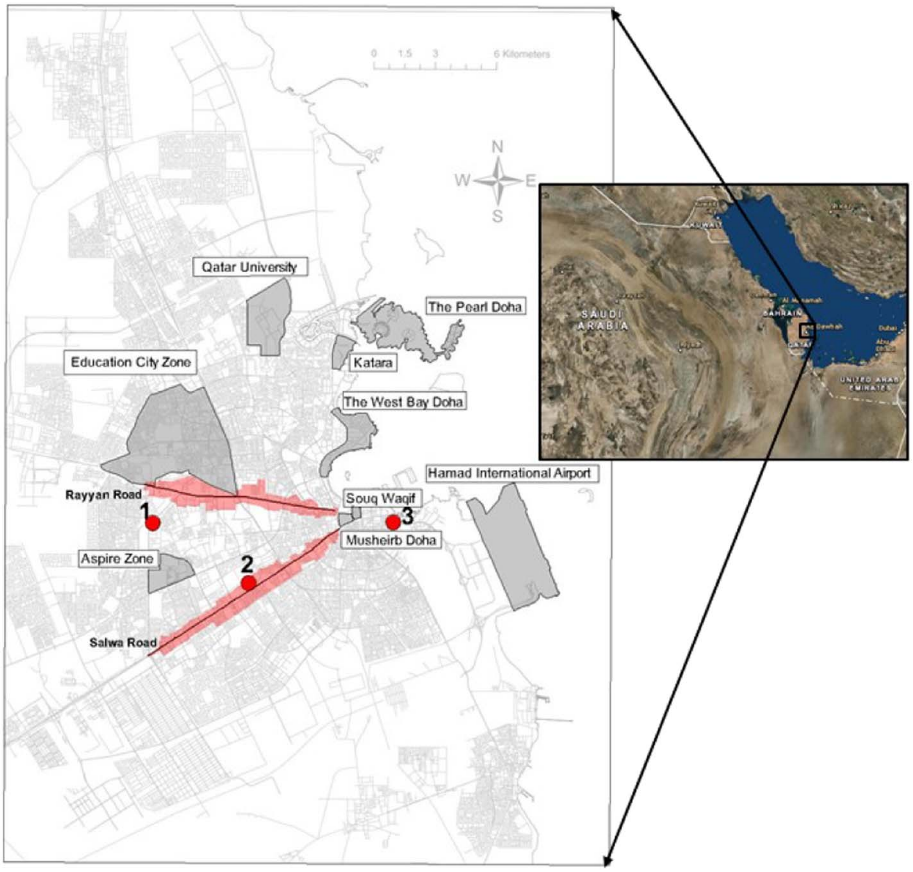

Fig. 3. Map of the Doha metropolitan area with the Al-Rayyan and Salwa Rd. corridors highlighted and the locations of the three weather stations (1 – Al Rayyan, 2 – Al Waab, 3 – Al Khulaifat).

3.3. Built environment data

3.3.1. Building height and density data

An AutoCAD dataset of plot boundaries overlaid with a point set of height measurements provided the descriptions about buildings surrounding the corridors (Ministry of Environment, 2013a, 2013b). The data was geo-referenced and converted to shapefile format in ArcGIS 10.3. Because the height measurements were determined to be sea level to top of buildings, a second point cloud of Digital Elevation Model (DEM) heights was used to calibrate the physical dimensions of the built structures around the corridor (Ministry of Environment, 2013c). In order to estimate actual building height, the height taken from the DEM dataset was subtracted from the height in the original buildings dataset. Total building volume per plot was normalized by plot area to create a new variable, which subsequently was converted into a gridded raster format at 1 m. This conversion to a density raster allows for the most unbiased assessment of total buildings in various proximities to the traverse data.

3.3.2. Vegetation data

A vegetation dataset was synthesized from the European Space Agency's Sentinel-2 Earth observation mission data. Sentinel-2 data contains 12 spectral bands of varying wavelength between 0.443 μm and 2.190 μm. Spatial resolution of these visible near infrared bands used in this study are 10 m × 10 m resolution; temporal resolution is approximately 5 days (i.e. new imagery is captured every 5 days for the planet). Data was obtained for July 24th, 2016 at approximately 7 AM UTC (10 AM Doha time). In order to classify high-vegetation pixels, a normalized difference vegetation index (NDVI) was created from band 8 (near infrared/0.842 μm/10 m GSD) and band 4 (visible red/0.665 μm/10 m GSD) using the following formula:

$$\mathrm{NDVI} = \frac{\mathrm{NIR} - \mathrm{red}}{\mathrm{NIR} + \mathrm{red}}$$

where:

NIR = band 8.

Red = band 4.

This formula resulted in a new raster dataset with values between − 1 and 1, with higher numbers indicating higher levels of

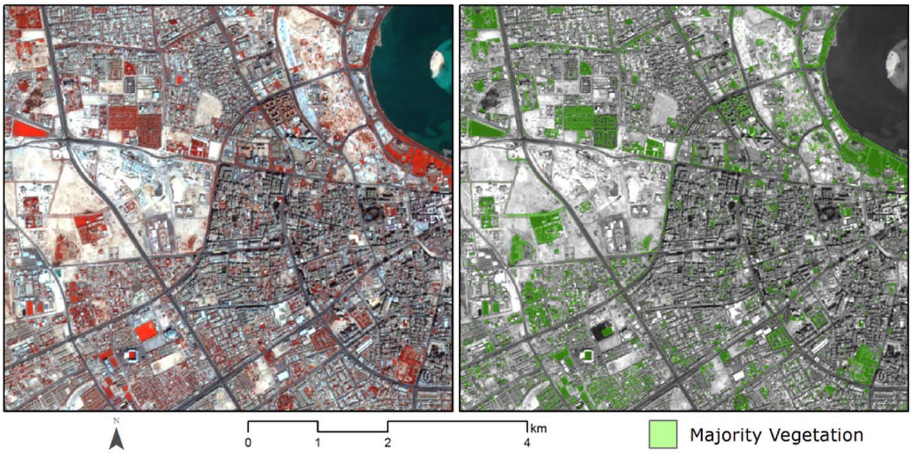

Fig. 4. Left: false color infrared imagery (composite of Sentinel-2 bands 8, 3, and 2), wherein the color red represents areas with photosynthetic activity; right: the previously described extracted areas of vegetation (green) as an overlay over a black and white image. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

photosynthetic activity. A sensitivity analysis of the NDVI data determined that a threshold of 0.055 sufficiently indicated pixels that were majority-vegetation. A final vegetation raster was created by assigning all NDVI pixel values greater than or equal to 0.055 (those that primarily contain vegetation) a value of '1', and all else a value of '0' (Fig. 4).

3.3.3. Traffic data

Traffic data were obtained through Qatar University from a project on traffic count modeling for Qatar (Ghanim, 2016). The counts were determined through traffic models developed for Qatar and estimated at major intersections for morning, midday, and evening, in both eastbound and westbound directions. For each of the three periods, total traffic count (regardless of direction traveling) variables were calculated. Next, a series of spatially located raster datasets were created by interpolating traffic counts between each point using an inverse distance weighting (IDW) algorithm. The resulting raster (Fig. 5) covered the entire study area with a resolution of 1 m × 1 m, and its pixel values represented an estimate of traffic counts as a spatially continuous variable.

3.4. Statistical analysis

Following the collection and preparation of datasets described in Section 3.3, the independent variables generated were tested for ability to predict air temperature for each traverse through the use of Random Forest modeling (RF) in R. While Ordinary Least Squares regression (OLS) is a common approach to analysing the strength of independent variables and their predictive ability for dependent variables, in the type of dataset developed in this research (a corridor with point measurements in a nearly straight line), it can be difficult to overcome the statistical test of spatial autocorrelation. As an alternative approach, RF is a machine learning method designed to produce accurate predictions that do not overfit the data. In RF analysis, a group of regression trees is created using samples from the training data, which is called 'bagging' (Breiman, 1996). In bagging, each successive tree is independently constructed using a boot-strap sample of the data set (Liaw and Wiener, 2002) and random forests, as proposed by Breiman (2001) adds randomness to bagging. While each tree continues to be constructed using a different bootstrap sample of the data, random forests also changes the method by which classification or regression trees are constructed. Unlike a standard regression tree, a random forest tree splits each node by using the best of a randomly chosen subset at that node. For the regression, the average prediction for

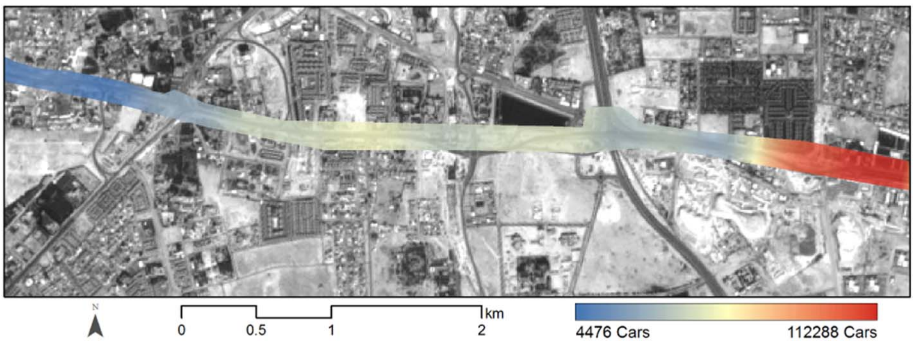

Fig. 5. Traffic on a subset of Al Rayyan wherein predicted number of cars is a continuous surface, interpolated from on-ground counts.

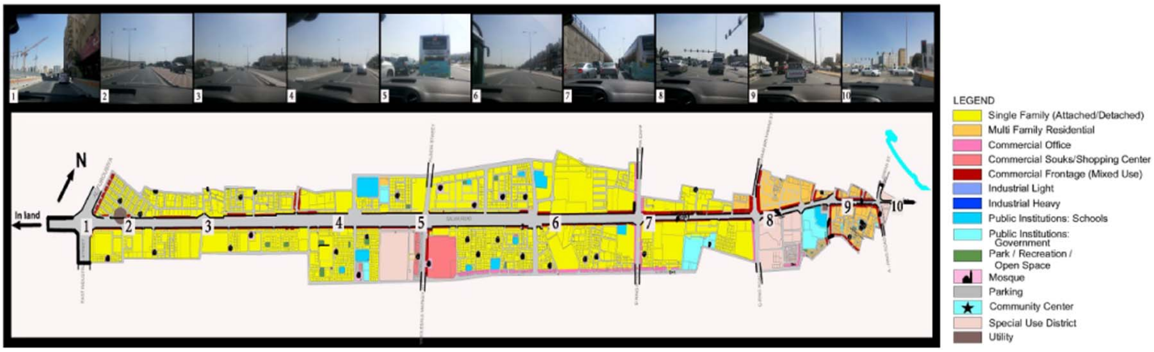

Fig. 6. Description of the land uses and photos along Al Salwa Road.

all trees are considered; for classification, predictions are considered the 'vote' for the most popular class among all trees (Breiman, 2001; Hastie et al., 2009; Liaw and Wiener, 2002; Prasad et al., 2006).

The R statistical software (R Core Team, 2016) with an extension called "randomForest" was utilised for the analysis (Liaw and Wiener, 2002). To compare the accuracy of each statistical model, a 'holdout method,' is applied which partitions the data into two mutually exclusive subsets - a training set and a test (or 'out of bag' OOB (Breiman, 2001)) set. Typically this method suggests selecting 2/3 of the data as the training set and the remaining 1/3 as the test set (Kohavi, 1995). For this study, we used 70% of the traverse data, randomly selected, as the training set and the remaining 30% of the data as the test set.

The following variables were generated for each point of the traverse: Distance to the Coast, Total Traffic Volume, Building Volume Density (BVD) and Vegetation Mean Amount. Air temperature along each of the 24 separate traverses was compared to the land characteristic data sets described in 3.3 (with both BVD and Vegetation being converted into 8 new multi-distance datasets using 50 m intervals from 50 m to 400 m) (Charabi and Bakhit, 2011; Ho et al., 2016; Krüger and Givoni, 2007; Makido et al., 2016). This comparison built out a table, wherein each land/environment descriptor populated a new column in the traverse data that could be tested for ability to predict the measured air temperature using RF modeling.

4. Results

We report our results in relation to the specific research objectives. First, we report on the vehicle-based traverses, which provide an orientation to the path from the coastal to inland areas. The land uses vary throughout both corridors, Al Rayyan and Al Salwa (Fig. 6). Beginning with multifamily and commercial developments adjacent to the coast and becoming predominately single family residential towards the inland areas, the photos additionally illustrate that the building density decreases as one travels inland along the corridor. In addition, the air temperature data from each traverse was charted, using the raw data and then again with corrected data after applying the background temperature correction discussed in Section 3.2 (Fig. 7).

Second, we describe, for each traverse, a series of outputs generated to assist in analysing and interpreting the results of the Random Forest analysis. These included a test of linear fit, which used the 30% of data that was held in reserve for testing the Random Forest model. The R^2 value and the RMSE (Root Mean Square Error) offers a direct measure of the goodness of fit for each of the models. Another set of metrics determined the relative importance of each variable tested (Table 2, Al Rayyan Road and Table 3, Al Salwa Road).

For both corridors, we observe that our random forest model generally provides highly predictive values for all time periods studied. Overall, the observed temperatures vary along the corridor with different trends at different times of the day. Distance to the

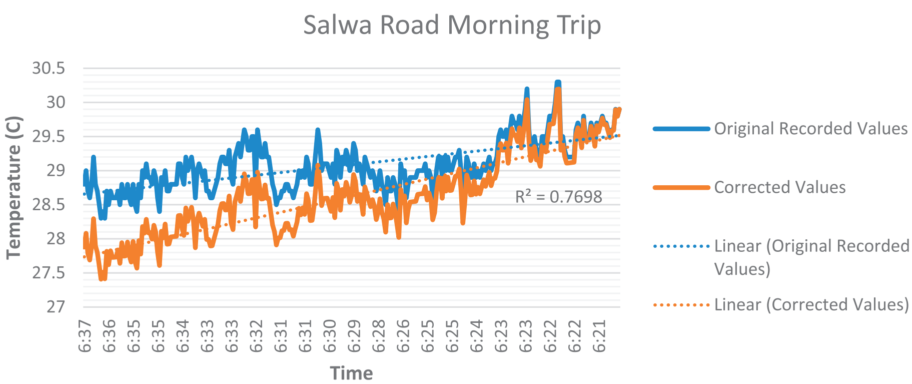

Fig. 7. Graph of thermocouple temperature measurements and corrected measurements for morning of Friday April 29th, 2016.

Table 2
Summary of the five most important variables and overall R^2 and RMSE values for all traverses of Al Rayyan Road.

Al Rayyan Road												
	26-Apr (Tues)			29-Apr (Fri)			29-Jul (Fri)			2-Aug (Tues)		
Variables	Morning	Midday	Evening	Morning	Midday	Evening	Morning	Midday	Evening	Morning	Midday	Evening
Distance to coast	1	1	1	1	1	4	1	1	1	1	1	1
Traffic	4	3	2	2	2	2	4		2	2		2
Building variables												
Building density 400 m	2	5		3	3	3	2		4	4		
Building density 350 m	3			4	5	1	3		5	3		3
Building density 300 m										5		
Building density 250 m		4										
Building density 200 m		2				5		3				
Building density 150 m								2				
Building density 50 m				5					3		5	
Vegetation variables												
Vegetation 400 m					4			5				4
Vegetation 350 m			5								2	5
Vegetation 300 m			4					4			3	
Vegetation 250 m			3								4	
Vegetation 150 m	5											
Vegetation 50 m							5					
Statistical results												
R^2	0.71	0.63	0.60	0.95	0.92	0.61	0.49	0.32	0.43	0.86	0.47	0.83
RMSE (°C)	0.44	0.68	0.37	0.16	0.60	0.43	0.20	0.76	0.37	0.38	0.85	0.44

Table 3
Summary of the five most important variables and overall R^2 and RMSE values for all traverses of Al Salwa Road.

Al Salwa Road												
	26-Apr (Tues)			29-Apr (Fri)			29-Jul (Fri)			2-Aug (Tues)		
Variables	Morning	Midday	Evening	Morning	Midday	Evening	Morning	Midday	Evening	Morning	Midday	Evening
Distance to coast	1	2	1	1	1	1	1	1	1	1	1	1
Traffic	5	1		3	3	2	4	3	4			2
Building density variables												
400 m	3		2	2	2	3	2			4		3
350 m	2			4		4	3					5
300 m						5		5				
250 m	4		3	5			5			2	4	
200 m			5							3		
150 m										5	3	
100 m			4								2	
50 m								4			5	
Vegetation variables												
400 m		3							2			4
350 m		5			5							
300 m												
250 m					4				3			
200 m									5			
150 m		4						2				
50 m												
Statistical results												
R^2	0.90	0.30	0.86	0.87	0.80	0.78	0.64	0.30	0.68	0.74	0.45	0.61
RMSE (°C)	0.28	0.83	0.38	0.20	0.85	0.28	0.30	0.79	0.41	0.27	0.82	0.51

coast clearly stands out as the most influential variable across all traverses and is 2–3 times more important than any other variable on the April Friday midday and August Tuesday evening traverses in both corridors. We note that others have also observed similar patterns in terms of distance to coast, although from a city-wide perspective (Makido et al., 2016). The morning data is quite similar across days and seasons, with a warming trend in temperature measurements from inland to coast, typically in the range of 1–2 °C, even after accounting for the natural background warming that occurs at this time of day. This trend is reversed for 1 PM traverses in both April and July, with coastal measurements typically being cooler, and substantially cooler, by approximately 7.5 °C, on Friday April 29th. For evenings, no clear trend is observed, with slight cooling trends towards the coast for Tuesdays, and slight warming trends on Fridays for both seasons.

Traffic was frequently the second or third most influential variable in most traverses on Al Rayyan Rd., while BVD measured at a distance of 350 m or 400 m was the second or third most influential variable for Salwa Rd. BVD also is found to be third or fourth most important in eight out of twelve of the Al Rayyan traverses. Surprisingly, given the overall sparseness of vegetation in Doha, Mean Vegetation does appear as one of the top five most important variables in roughly half of the Al Rayyan traverses and one-third of the Salwa Road traverses, most often at larger distances of 250 m–400 m. However, it should also be noted that the traverses which have vegetation as one of the top five variables also show some of the lowest R^2 and highest RMSE values (R^2 values as low as 0.30 and RMSE as high as 0.85). Although in other studies vegetation is strongly correlated with ambient temperature (Voelkel et al., 2016), we speculate that vegetation is not a particularly strong predictor of the air temperature in our study area because the corridors lack large amounts, and hence it does not register with a high RMSE value.

Considering days of the week, strong peaks in the air temperature data were found at major intersections for Tuesdays with troughs along several sparsely-built segments of roadway, while Fridays (the first day of the weekend and a day of rest for the majority of the population) show very few peaks and troughs during the morning traverses. Strongest correlations for any single day were on Friday April 29th; incidentally this is also the day generally recording the lowest windspeeds during traverse times, ranging from 1.1–3.2 km/h for the three stations noted in Fig. 3. This compares to Friday July 29th, the day with the strongest wind speeds during traverse times, ranging from 3.2–6.7 km/h. Except for July 29th, all traverses recorded windspeeds in the range of 0–3.5 km/h. Stronger correlations were usually found for evenings than midday, with the exception again of Friday April 29th, when midday correlations were stronger, especially for the Al Rayyan Rd.

Mornings show the strongest correlations typically for both corridors, with R^2 values of 0.74–0.90 for Salwa Rd. and values of 0.71–0.95 for Rayyan Rd. (excluding the traverse for this corridor on 29th July, which showed relatively low correlation across the whole day).

Comparing results for April with July, stronger correlations are found in April, with the exception for Al Rayyan road where the Tuesday August 2nd traverse shows stronger correlations for morning and evening. RMSE values do not show a consistent trend when comparing between seasons. We are uncertain why specific days or specific time periods have lower predictive power or RMSE values, although we note that overall these patterns are consistent with the existing literature.

5. Discussion

We investigated several important variables related to the influence of the built and natural environment on urban near-surface air temperature for two major urban transport corridors in the city of Doha, Qatar. We found that the two most critical variables that predict temperature patterns are the distance to the coast and the traffic volume. Confidence in the results of the study is supported by the fact that the primary method of data analysis, the Random Forest method, has been tested previously (Breiman, 2001; Hastie et al., 2009; Liaw and Wiener, 2002; Makido et al., 2016; Voelkel et al., 2016). The results are consistent with the larger scale city-wide results obtained in the earlier study of Doha by Makido et al. (2016), which also found that the proximity to coastal areas influences UHI and that the location and pattern of the UHI differs throughout the day. As in the previous study, the UHI is typically higher near the coast in the early morning, moves inland during the midday, and then is quite variable during the evening. Traffic, however, is not as strong of a predictor of air temperature on the Al Salwa Rd. corridor, which is a much wider road where traffic volumes are typically evenly spread out and freely flowing at all times of day, whereas Al Ryann Rd. experiences traffic congestion in morning and evenings at key intersections. Amount of vegetation, primarily within distances of 250 m–350 m, was sometimes an important variable, but with lower correlation and no consistent pattern for time of day or season.

This coastal influence has implications for UHI interventions for hot, arid coastal cities such as Doha. Whereas coastal areas may experience UHI in the morning and evenings, these are the times of day when temperatures are relatively lower in comparison to midday. The areas that are most critically in need of intervention are those that are inland with a high midday UHI. Particularly in Doha, which frequently experiences extremely high summer temperatures (40 °C), the midday is a critical time as people are frequently moving throughout the city at this time for work, school, and social activities. Therefore, interventions must also consider the influence of coastal breezes and the potential channeling of wind from sea to inland through major corridors (Yoshida et al., 2014). For this reason, the configuration of coastal development requires further scrutiny with regard to prevailing winds, perhaps designing ways that coastal breezes can channel winds to inland areas during the hottest times of the day. Nichol et al. (2009) note that this “wall-effect” due to reduced ventilation, high temperatures and the blocking of sea breezes by tall buildings on coastal reclaimed land as a contentious issue in Hong Kong, for example. This can also be compared to the case of Muscat, Oman, where the mountainous terrain tends to isolate the urban core from the cooling effect of the sea to land breeze circulation during the day (Charabi and Bakhit, 2011). These results have implications on the development of coastal areas, including the limiting of future high-rise developments in key areas along the coast, which can prove challenging given the competition of high real estate values along these areas.

Critically, for the inland areas of Doha, the density of development must be considered. From an overall sustainability stance, high-density cities and Neo-traditional planning approaches are often discussed (see Sharifi, 2016 for a critique of sustainable neighbourhood planning approaches) as being more sustainable due to efficiencies in transport (especially where public transport is available), proximity to goods and services, and efficient land use. However, in cities experiencing hot climatic extremes, such as Doha, it may be that lower density development allows for improved air circulation which, in turn, improves the overall thermal comfort of urban areas. While many studies cite the advantages of compact development in hot regions (Jamei et al., 2015) because of the advantages of building overshadowing, trade-offs are noted between lower daytime temperatures and lower rates of nighttime cooling (Ali-Toudert and Mayer, 2006). Further specific investigations are needed to determine the advantages and disadvantages and energetic balance of these two strategies.

Finally, given that traffic volume is also a key variable, one strategy could be to target specific sections of roadway that experience the highest volumes of traffic at specific times of day. Either looking at measures to reduce traffic in these key areas, or dissipating the heat produced by traffic by using urban greening interventions or changes in building and paving materials.

This study has benefitted from the ability to investigate air temperature in a corridor environment at fine spatial and temporal resolution, leading to improved understanding of the specific factors that can be changed in future planning design for Doha and cities facing similar climate regimes. The study's limitations include the relatively low number of traverses that could be performed under differing weather conditions and the unavailability of the highest quality terrain and building height data types, such as LIDAR. Future studies my benefit from the use of fixed sensors that monitor several variables at once and over a longer and continuous period, and from improved datasets on building height and volumes that can be determined through high resolution remote sensing.

6. Conclusions

This study presented the existence and extent of air temperature variation for twelve traverses over four days in April and late July/early August within an urban corridor of different land uses in Doha, Qatar. We are not aware of any other studies that have used multiple traverses across multiple days to assess the impact of the built environment at such high resolutions. We found that the significant contributors to the corridor temperature variation were: distance to the coast, and traffic volume. The typical UHI pattern of warming in the city centre, which is densely urbanized, is also influenced by its coastal location and sea breezes. The study also found that significant spikes in temperature occur at several key intersections during morning and evening weekdays, indicating further that traffic data is a key factor in the temperature patterns observed. Analysing microclimate data for locations, such as Doha, that experience extreme temperatures is necessary in the context of both developing cities and UHI effects.

In terms of the implications of our findings on the practice of climate action planning, we interpret our findings to suggest that future development in Doha and cities that face similar hot, arid climate regimes and rapid urbanization include: restricting the development along the coast to prevent blocking of coastal winds by high rise buildings; restricting building density and built volume (plot ratios) to allow for wind movement and open/vegetated areas between densely built areas; and increasing shading measures, such as tree cover, vegetated archways, or other shade structures at key intersections, where traffic volume is highest, or preferably, improve access to public transport to reduce traffic volumes; and develop improved shading measures for pedestrian pathways and outdoor recreational areas, especially for inland areas as these experience the strongest UHI at midday when both air temperatures and mean radiant temperature are highest.

Acknowledgements

This paper was made possible by NPRP grant # NPRP 5-074-5-015 from the Qatar National Research Fund (a member of Qatar Foundation).

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