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Assessment of the canopy urban heat island of a coastal arid tropical city: The case of Muscat, Oman

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ABSTRACT

The spatio-temporal variability of the canopy-level urban heat island (UHI) of Muscat is examined on the basis of meteorological observations and mobile measurements during a span of 1 year. The results indicate that the peak UHI magnitude occurs from 6 to 7 hours after sunset and it is well developed in the summer season. The warm core of the UHI is located in the Highland zone of Muscat, along a narrow valley characterized by low ventilation, high business activities, multi-storied buildings and heavy road traffic. Topographically, this valley is surrounded by mountains formed of dark-colored rocks such Ophiolites that can absorb short wave radiation and contribute, herewith, to the emergence of this warm urban core. In addition, this mountainous terrain tends to isolate this location from the cooling effect of the land–sea breeze circulation during the day time. In this warm valley the hottest temperature is encountered in the compact districts of old Muscat. In comparison, the urban thermal pattern in Lowland zone of Muscat is fragmented and the urban–rural thermal difference is reduced because of the lower urban density of the residential quarters. In addition, the flat alluvial terrain on which these residential quarters are located is consistently exposed to the land breeze circulation. Also, the study illuminates and emphasizes the importance giving due consideration to the nature of the rural baseline when assessing the urban effect on an area's climate. For Muscat City, irrespective of the rural baseline used, a significant difference in the value of the urban heat island is registered.

1. Introduction

The Arab Gulf countries lying on the West Coast of the Arabian Gulf share several geographical characteristics and have many traits in common. The emergence of oil-wealth in the Arab Gulf countries in the last three decades has transformed the region into one of the world's primary centers of business. Oil has become, in nearly two decades, the main contributor to the region's seemingly overnight transformation from desert and simple fishing communities to modern, industrialized nation states (Babikir, 1986). Oil wealth has been accompanied by a huge influx of foreign workers and new ways of life (El-Arifi, 1986). During the last decade, liberal economic policies have encouraged fierce competition among Gulf States and fueled efforts to attract human and financial capital. This has resulted in an urgent need for infrastructure and rapid expansion of the urban landscape.

This unprecedented form of urbanization which has taken place in tropical desert regions hastens the need for detailed studies of their effects on local climate change. Sustaining an acceptable quality of life for this growing population in arid cities may depend, to a critical extent, on our understanding of the climatic modifications induced by urbanization (Pearlmutter et al., 2007). The desert urban areas of the Arab Gulf states constitute an ideal living laboratory to examine the double risk of urban population to urban heat island and global climate change factors that are increasing and intensifying as they interact (Guyot, 2008). They are heavily populated, hot and arid—like many places around the world experiencing rapid urbanization and limited water

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supplies. No doubt, that the environmental consequences of the actual urban sprawl are not restricted to the physical limit of the city, but may indeed arise at regional and global levels. Cities create their own micro- and local climate but are connected to regional and global climates through the chemistry of the atmospheric effects on radiation balance and greenhouse gas emissions (Roth, 2007).

The urban heat island (UHI) is the most intensively studied climatic feature of cities (Montávez et al., 2000; Souch and Grimmond., 2006). Universally the modified thermal climate in cities is usually warmer than the surrounding areas and, hence, leads to a set of distinct micro-and mesoscale climates (Roth et al., 1989; Gluch et al., 2006). Comprehensive assessment of distinctive UHIs has been provided by many UHI researchers (Jauregui, 1973; Landsberg, 1981; Oke, 1973, 1981, 1982, 1986, 1987; Atkinson, 2003). Several factors have been postulated to explain the extra warmth of cities. They are (1) increased absorption of short-wave radiation, (2) increased storage of sensible heat, (3) anthropogenic heat production, (4) reduced long-wave radiation losses, (5) lower evapotranspiration rates, and (6) lower sensible heat loss due to reduced turbulence in urban canyons (Oke, 1987). Other factors, such as synoptic weather conditions (e.g., wind speed, cloud amount and height) (Oke, 1998), topography (Goldreich, 1984), city morphology, and size (Oke, 1973) modify the magnitude of UHI intensity, which is defined as the temperature difference between the urban area (Tu) and its rural (Tr) surroundings (ΔTu $-$ $r = T$u $- T$r) (Chow and Roth, 2006).

Over the past 50 years, most of our knowledge about urban climate is derived from research conducted in Northwest Europe and North America and, to some extent, from tropical and subtropical areas (Arnfield, 2003). Roth (2007) has reviewed from available literature the nature and the intensity of the UHI in tropical and subtropical cities. The reviewed studies cover a large portion of subtropical climate types and encompass a wide range of cities ranging from the extreme dry areas (e.g., Lima in Peru) to the continuously wet areas (e.g., Kuala Lumpur in Malaysia). These reviews have paved the way for comparisons with data from temperate latitudes. The preliminary conclusion reached from these comparisons points to a seasonal variation of monthly nocturnal UHI with lower intensities during the wet season and higher intensities during the dry season. The registered lower nocturnal maximum UHI intensities are comparable to those of temperate cities with comparable population. Besides, the review study shows the existence of a relationship between population in subtropical cities and nocturnal maximum UHI intensities. However, the available data are insufficient to confirm logarithmic relationship or systematic differences between different climate types. Moreover, differences in urban morphology, variations in the nature of the rural reference and differences in methods and time of observation prevent from reaching robust conclusions.

Literature and scientific knowledge pertaining to heat island in arid environments are very restricted and limited to few cities; Phoenix and Tucson, Arizona (Hsu, 1984; Balling and Brazel, 1986, 1987; Tarleton and Katz, 1995), Kuwait city (Nasrallah et al., 1990); Pune (Deosthali, 2000); Cairo (Rooba, 2003), Ouagadougou (Linden, 2004); Eilat city (Sofer and Potchter, 2006) and Negev Desert, (Pearlmutter et al., 2007). The Arizona investigations demonstrate that UHI intensity is higher during summer nights, and that it increases in time, due to rapid urbanization growth. The UHI of Kuwait City is poorly developed (Nasrallah et al., 1990). In Eilat City, the results prove the development of a moderate UHI located around the most intensive area of human activity. The UHI is more pronounced at midday during the summer season, while early morning inversions in winter have a weakening effect on the UHI intensity (Sofer and Potchter, 2006).

Arid urban environments offer to climatologists a specific domain of investigation with circumstances that can be qualitatively and quantitatively different from those encountered in temperate areas. These distinctions are most clearly pronounced in the following points; the daytime levels of relative humidity in an arid region may be considerably lower than what is experienced in surrounding non-arid areas. Atmospheric conditions in arid areas are characterized by clear skies and intense radiative exchanges. The high amounts of solar energy gained during daytime are balanced by nocturnal long-wave losses, resulting in a pattern of thermal extremes over the daily and seasonal cycles. A scarcity of moisture is most often reflected in sparse vegetation, which significantly changes the characteristics of the natural terrain surrounding desert cities. High albedo, strong winds, unstable or encrusted soils, and frequent sand or dust storms typify arid-region landscapes. But, while such places are distinguished by harsh thermal extremes, they also present unique opportunities for microclimatic enhancement (Pearlmutter et al., 2007).

A multidisciplinary research project examining accurately the urban climate and air pollution in Muscat city was initiated in Sultan Qaboos University (Oman). This project seeks to observe, measure, model and analyze how the rapid growth of Muscat city since 1970s has impacted the region climate and air quality. This paper presents the results of the preliminary research that was conducted in Muscat city, located in an extreme hot and tropical arid area and in a complex topography on the coast of the Sea of Oman. The primary aim of this paper is to explore the combined effects of topography, mesoscale circulation, urban form and landscape variability on air temperature at 2 m above the ground. To capture the expected spatio-temporal variability of air temperature at meso- and micro-scale various meteorological parameters were recorded using mobile traverses during 1 year. Data were also obtained for the same period from temporary meteorological station installed in rural area and from suburb and urban weather stations of the Directorate General of Meteorology and Air Navigation (DGMAN). This paper focuses on the analysis of differences in air temperature among the sites, and discusses them in the context of an assessment of the canopy UHI.

2. The study area

Muscat, the capital of the Sultanate of Oman (23°25′N and 57°00 E), extends from Seeb in the North to the Quariyat in the South along a coastline that runs around 200 km along the Sea of Oman (Fig. 1). By virtue of its location astride the Tropic of Cancer, Muscat city exhibits a typically arid environmental setup: day time temperatures are high, rainfall is scanty and highly variable and evaporation rate is high. The average yearly precipitation over a 30-year period is approximately 100 mm and occurs mainly between November and March

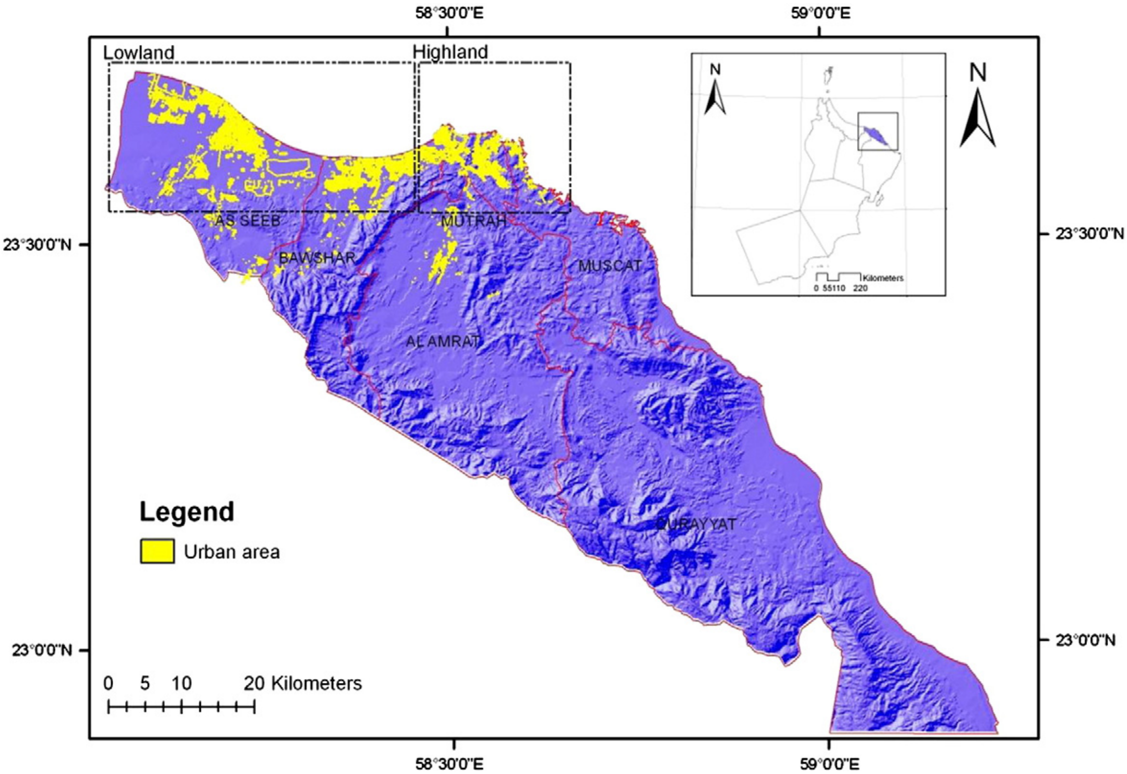

Fig. 1. Localization and hills shade of Muscat.

(Charabi and Al-Hatrushi, 2010). Having a coastal location, the city is exposed daily to sea breeze circulation during day time and weak land breeze turning sometimes to calm conditions at night. Only during the winter season (November–February), the Northeast winter monsoon prevails most of the time. The duration of daily bright sunshine varies between about 11 hours in December [altitude of sun at noon 43.3°] and 14 hours in June [altitude of sun at noon 89.9°].

Muscat is situated in a very complex topographical setting (Fig. 1) that can be divided in general in two contrasted zones: Highland Muscat and Lowland Muscat. Highland Muscat extends eastward and southwards from Ras Al-Hamra. Eastwards from Ras Al-Hamra extends an irregular coast with numerous rock heads that protrude into the sea leading, hereby, to the formation of very rugged and steep sea cliffs which are separated with small and narrow coastal bays. This mountainous terrain is composed of the outcrops of different rocks. The most prominent of all is Ophiolite which distinguishes itself through its dark color (Fig. 2). This mountainous terrain is the dominant feature in, for example, Matrah, Mina Al-Fahal, Sidab, Al-Bustan, Gantab and Quariyat. A number of big and small wadis have carved, on their way to the sea, distinct V shaped valleys which divide the area into numerous peaks and steep ridges. These wadis, in addition to few other basin-shaped pockets, formed in fact the most suitable locations of residential settlement and economic activities. The most important of these locations in this difficult terrain is Ruwi basin and its extension Al-Wadi Al-Kabir which currently form the most crowded area in Muscat (Fig. 3).

Westwards from Ras Al-Hamra, this mountainous train starts to retreat away from the sea in a broad curve giving way to the development of a narrow accumulation plain, of 6–20 km width in average, which is built mainly by the numerous wadis that drain the surrounding slopes in a predominantly SW–NE direction. For a long time before the growth of Muscat to an expanding metropolis this alluvial plain has been extensively used for agricultural purposes. Under the effect of urban sprawl, the agricultural plots have been gradually transformed into urban functions and arrangements. Evidence of this is Medinat Qaboos, Bawshar, Al-Resail and Al-Khoudh which form now basic quarters in the settlement mosaic in Muscat.

Muscat city witnessed a spectacular socioeconomic development since 1970, stimulated by oil exploration and production. The primacy given to the capital triggered an unprecedented demographic pull. The population size rose from 56,000 to 236,000 in one decade (1970–1980) with an enormous annual growth rate of 12.3%. This sustained growth raised the population of Muscat to more than 549,000 in 1993 and to 796,000 in 2007 constituting, thus, 27% of the total population in Oman. Currently, the population of Muscat grows at an annual rate of 7.6% as compared to a national demographic growth rate of 4%.

An analysis of the history of land use showed that Muscat experienced three phases of urban expansion (Fig. 4): (i) in the period 1960–1970 the expansion was very limited and took place only between the two old towns of Matrah and Muscat, (ii) between 1970 and 1980 the expansion extended from the coast line towards the west suburbs and (iii) between 1980 and

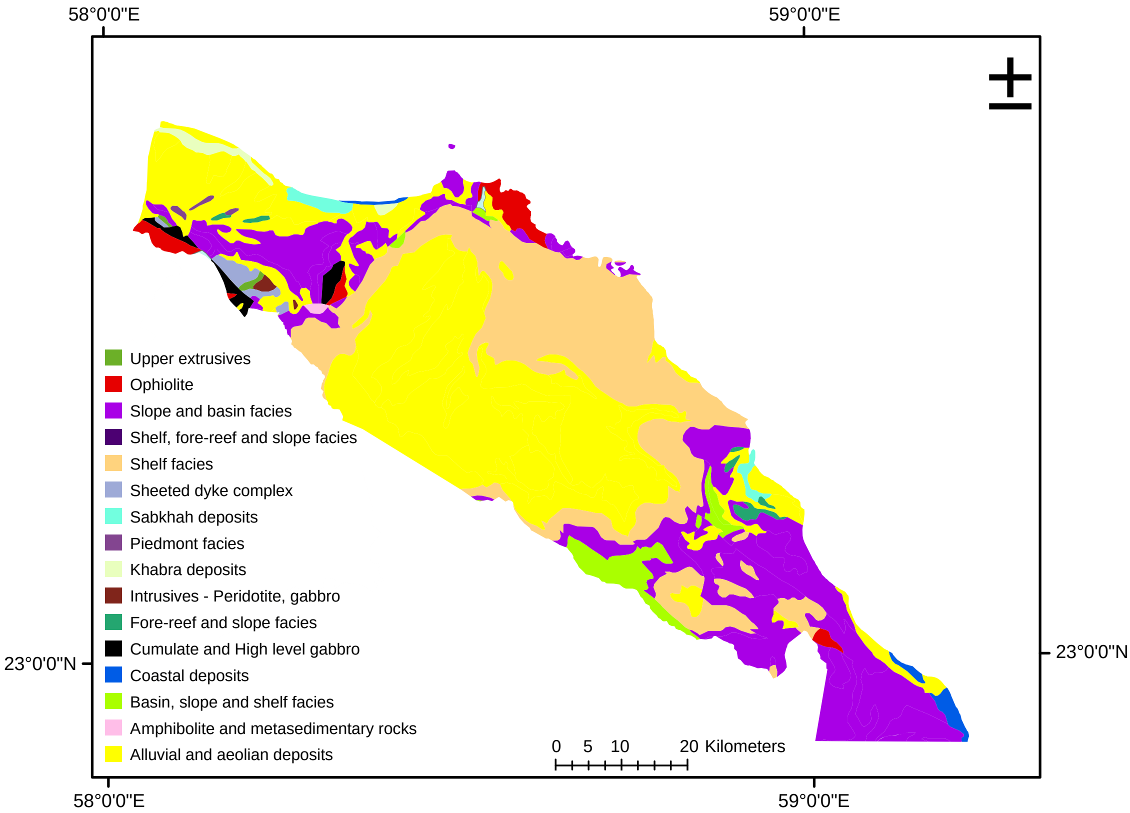

Fig. 2. Simplified geological map of Muscat.

2003 the urban expansion started filling the spaces and gaps between the previously built-up areas. In addition, this urban sprawl has been associated with significant changes in the land use categories. A summary of these changes is given in Fig. 5 which shows the total areas under each class for each year. Fig. 4 and Fig. 5 clearly reflect that the major increase in urban growth has taken place in the decade 1970 to 1980. This growth amounts to more than 3.5 times the increase in the previous decade. It can also be inferred that during this decade a significant increase in residential land has taken place. It is worth to note that public building category has the largest share of the built up area especially in 1980 period and late. It formed about 29.8% in 1980 and rose to 30.2% in 2003. This is attributed mainly to the large portion of land allocated to schools, hospitals, government buildings, mosques, public companies, military and security uses (Al-Awadhi, 2008).

The physical aspects of the site of Muscat have logically influenced the direction of the urban expansion giving the city its linear plan of 60 km length and of 1 to 12 km wide. Throughout, this topographically varied coastal band, the urban space seems paradoxically to have the profile of a continuous area and the structure of a fragmented body. This leapfrog pattern of urban development leads to a very low density of buildings. In the low land of Muscat city, the residential batches are likewise dispersed and individual housing plots show a patchy urban landscape. In 2007, the building permits issued in Muscat city point out that the standard size of the plots is about 649 m^2 and it represent 74.3% of issued permission. These facts mean that the number of buildings per hectare is less than 13 units which is one of the lowest among the worldwide urbanized areas. Actually, the city continued to extend towards the south-west and north-west directions (low land). The built-up area of about 200 km^2 looks currently as a ribbon meandering throughout the narrow coastal prone areas as well as across hill slopes and wadis (Mokhtar, 2010).

In terms of microclimate, most of Muscat built-up area is characterized by a high sky-view factor (SVF), except for the CDB area of Ruwi, where some of the buildings are over ten floors high. Street structure in the old cities of Muscat and Matrah is extremely compact with very low SVF (Fig. 6). The buildings are usually not more than three stories high. The streets are narrow and form deep canyons throughout the old city. No transport by car is possible except on few distributor roads. Because of this narrow and irregular street network, mutual shading by buildings is very pronounced. The shading at street level is further enhanced by the protruding upper floors which in some places bridge the alleyways.

3. Observations and methodology

The aforementioned physical and human characteristics combined have influenced to a large extent the overall thermal behavior in the city. The interactions between different natural and artificial elements in the lower urban boundary layer produce patterns of varying local climate conditions very sensitive to structural changes. The heterogeneity of the local surface temperatures over the urban area,

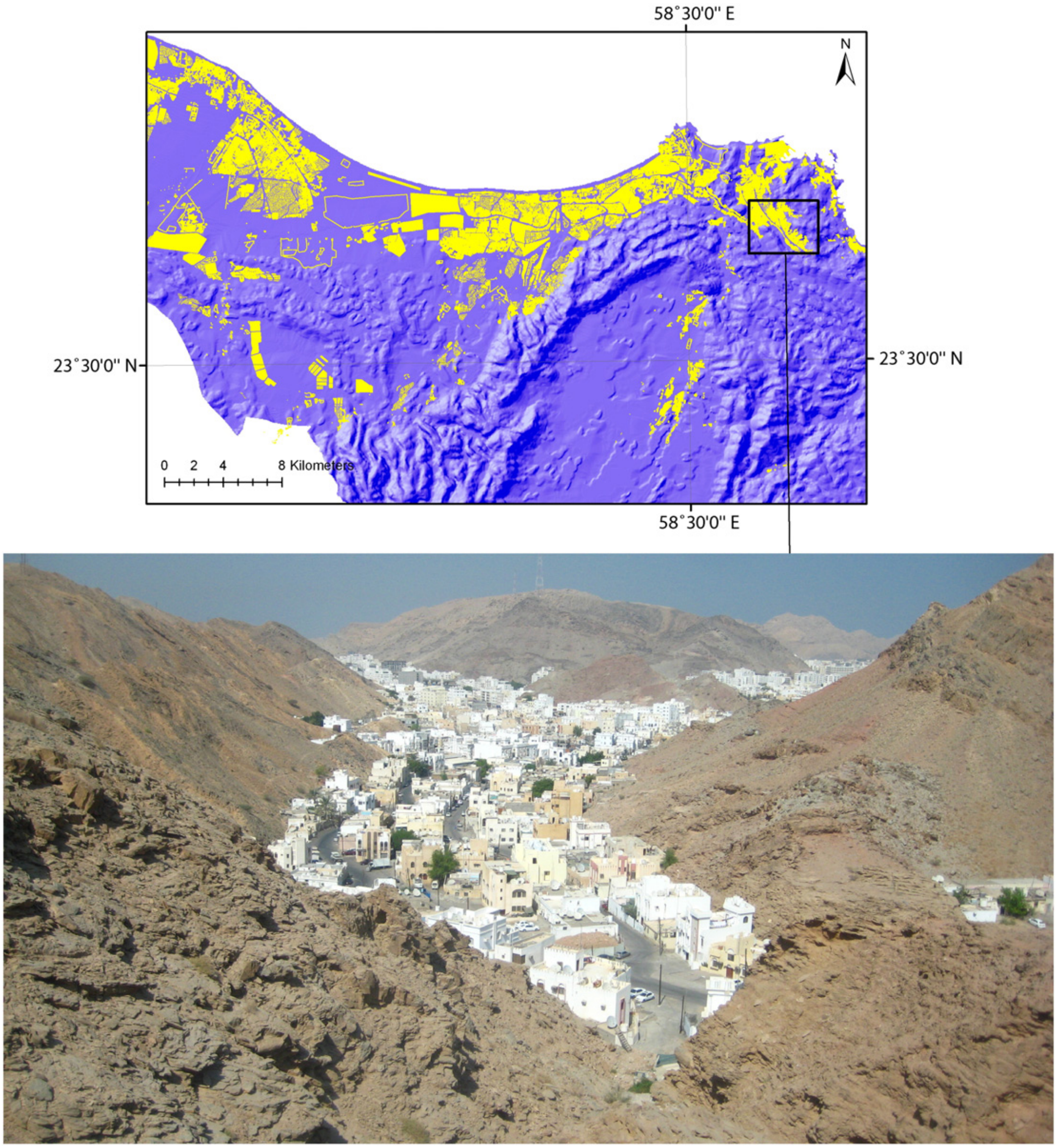

Fig. 3. Urban area of the valley of Wadi Al-Kabir.

due to the geometrical complexity of the canopy and to the diversity of the thermal properties of the different materials, generates strong thermal anisotropy effects at the district scale. The complex topography of the study area raises sets of initial questions regarding the influence of the physical and anthropogenic conditions of the UHI: (i) the form, the location and the spatial distribution of the UHI; (ii) the intensity or the magnitude of UHI and its temporal variability at different temporal scales; (iii) the main factors that shape Muscat's UHI.

Understanding the urban signal and, hence, the urban impact, of a city situated in a complex topographical setting like Muscat is a demanding theme which needs a very cautious approach. This is because the presentation of the possible ranges of this impact and the scales of changes in the climatic components pertaining to that impact are larger than what might be expected over flat terrain. In this case and depending on the stratification of the atmosphere, the UHI may be either enhanced or suppressed. Therefore, it may not always be possible to perform the ideal experiment that would capture the urban impact, i.e., measurements without the city and then measurements with the city at any stage of its growth (Lowry, 1977). Thus, several common approaches are used to characterize the magnitude of the urban effect. To evade these difficulties, a number of approaches have been adopted. These include employing mobile traverses across the city with automobile-mounted sensors (Sun et al., 2009), accessing remotely sensed thermal images (Voogt and Oke, 2003), developing weather-network spatial interpolations (Knight et al., 2010), conducting time-trend analyses of key

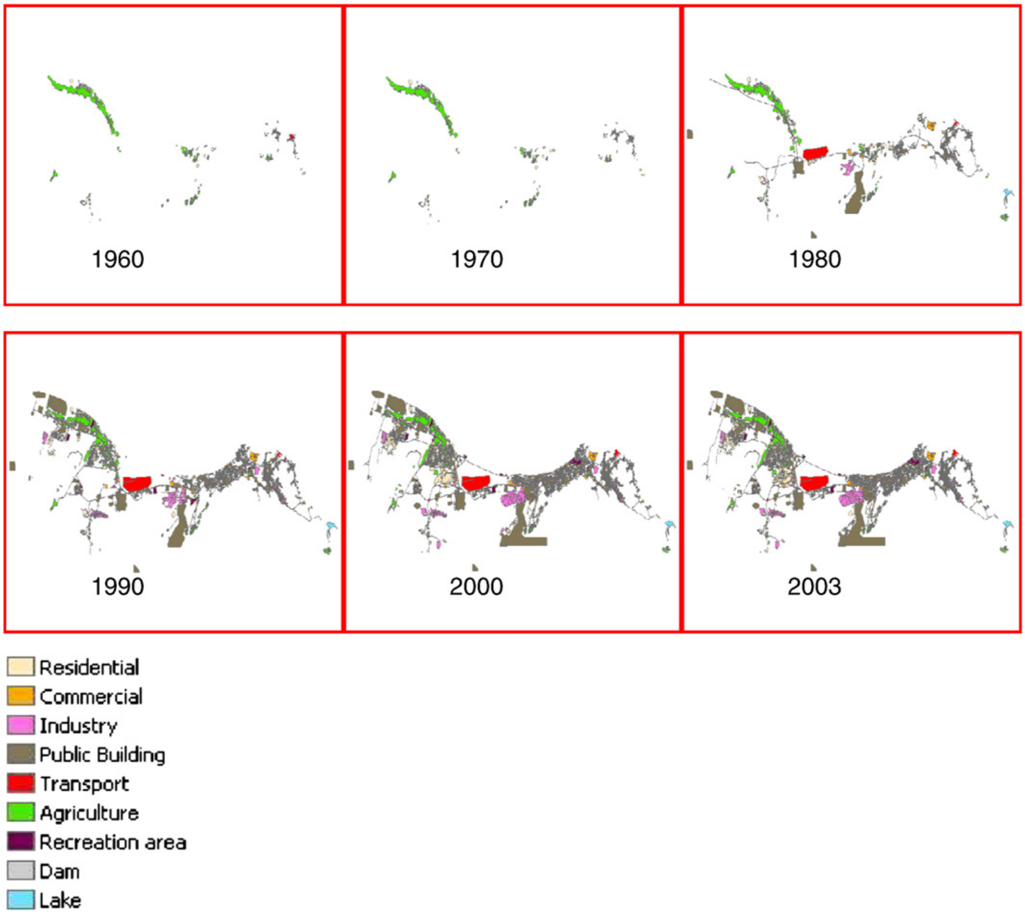

Fig. 4. Evolution of land use cover in Muscat city between 1960 and 2003 (Al-Awadhi, 2008).

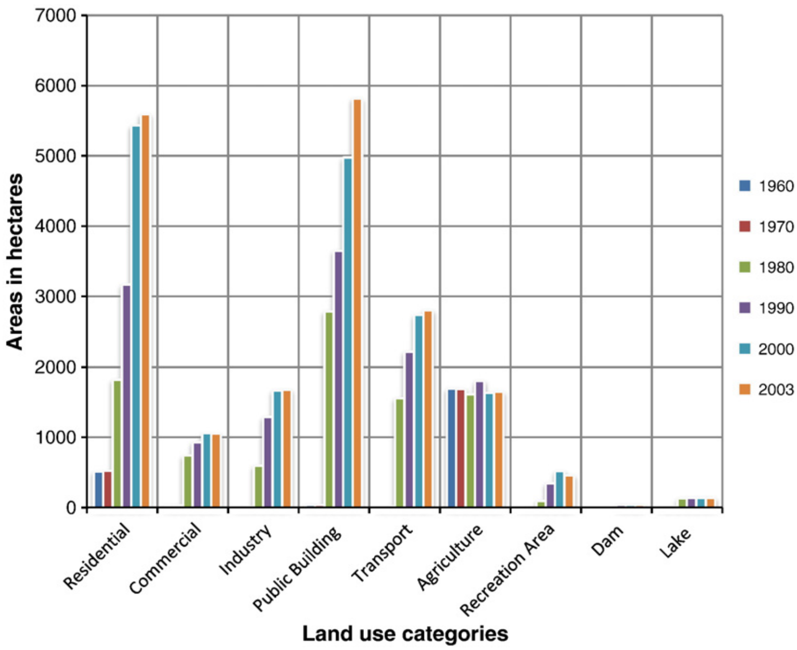

Fig. 5. Dynamic of Land use categories between 1960 and 2003 (Al-Awadhi, 2008).

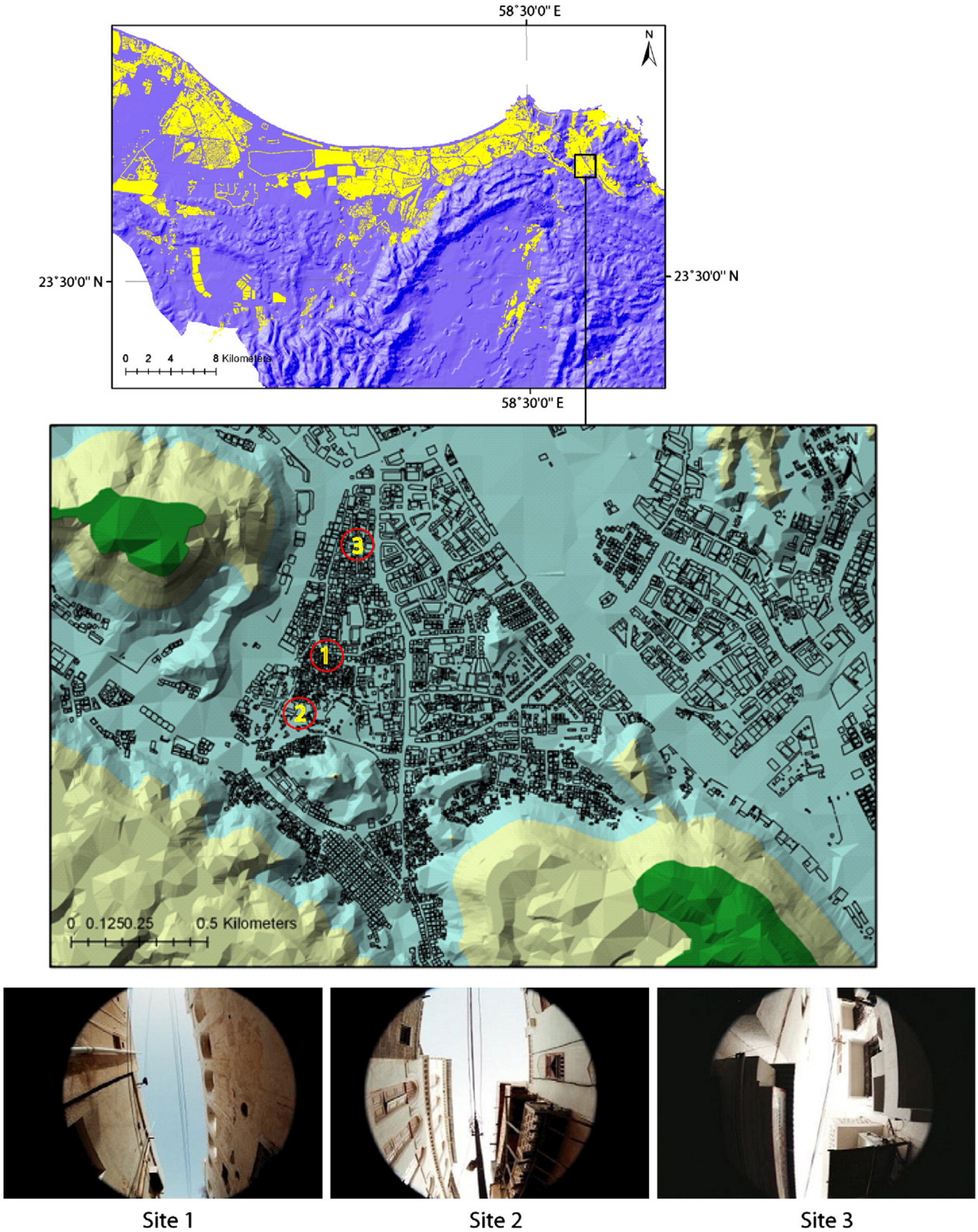

Fig. 6. Sky view in the old districts of Muscat.

sites (Fujibe, 2009), calculating energy balances (Masson, 2006) and calculating urban and rural site differences (Hawkins et al., 2004).

The urban heat island discussed in this paper is a canopy layer heat island (Oke, 1987) measured at street level. Despite the limitations of budget and manpower, several attempts were undertaken to collect data of high spatial and temporal resolution about the urban impact. The conventional meteorological network of the DGMAN in Muscat city is composed of two coastal stations situated in two different urban environments: the first in Muscat International Airport (elevation 8.40 m, sea distance 3000 m) which is situated in the suburban area of Al-Seeb in the West and the second is Mina Sultan Qaboos Station (elevation 4.08 m, sea distance 100 m) located in the core of the urban area. In order to compensate for the absence of meteorological stations in the environs, which might otherwise have facilitated comparison, an automatic meteorological station was installed and left working for 2 years (2007 to 2008) in the rural suburb of Al-Amerat (Fig. 7).

In order to enhance the spatio-temporal density of the meteorological data in the study area, the technique of mobile measurements was largely used. As a start, this technique was used to measure two meteorological parameters, namely air temperature and relative humidity. The mobile instruments were installed on vehicles moving simultaneously along predetermined routes. In each mobile traverse, air temperature and relative humidity were measured at a height of 2 m and at a frequency of once per second. All measurements were captured using a TG-502 coupled with GPS for georeferencing and estimation of altitude. The TG-502 probe is designed for indoor air quality with accurate sensors for air pollutants, air temperature and relative humidity. These first operations of mobile measurements revealed the problems inherent in the scale of data analysis. One of these is the complex topography of the study area in which usually poses short distance abrupt changes in the urban landscape. For example, at a speed of 40 km/hour the vehicle can run a distance of 333.33 m in 30 seconds and reveals a problem in the spatial attribution of the recorded measurements.

In order to optimize the accuracy of mobile measurements and allow the sensors the necessary time to restore stability, a series of itinerant measurements based on a predetermined network of points were carried out in advance. In addition, meteorological and air pollution sensors were used to measure the principal parameters which include air temperature, relative humidity, wind direction, wind speed, CO, NO, O_3 and VOC concentrations. Also, itinerant measurements were taken from several transects that cover the urban area in order to capture impacts of the varying topography, the disparities in the built-up density, and the distribution of land use categories. For comparison purposes, the measurements were extended to outside Muscat. The sites of measurements were selected according to the ability of each site to represent the local climate and, especially, the geometry of space around the points of measurements. This information was extracted from a GIS data base obtained from National Authority of Survey in the Sultanate of Oman. Nine parameters were extracted from this data base: two parameters to describe the geometry of buildings around measurements points (i.e., distance to the nearest wall and width of the street) and six parameters obtained from the fraction of different urban surfaces (i.e., built-up, green areas, wooded areas, water surfaces, roads and open areas) based on the four values of 50, 100, 200 and 500 m.

The two parameters extracted from the GIS data base to describe the building geometry around the site of measurement were restricted to the horizontal plan. In urban environments, narrow streets and high buildings generate horizontal and vertical roughness in the surface which ultimately leads to the creation of deep microclimatic canyons. This 3D geometrical configuration plays a crucial role in regulating long-wave radiative heat losses restricting to a large extent, hereby, the

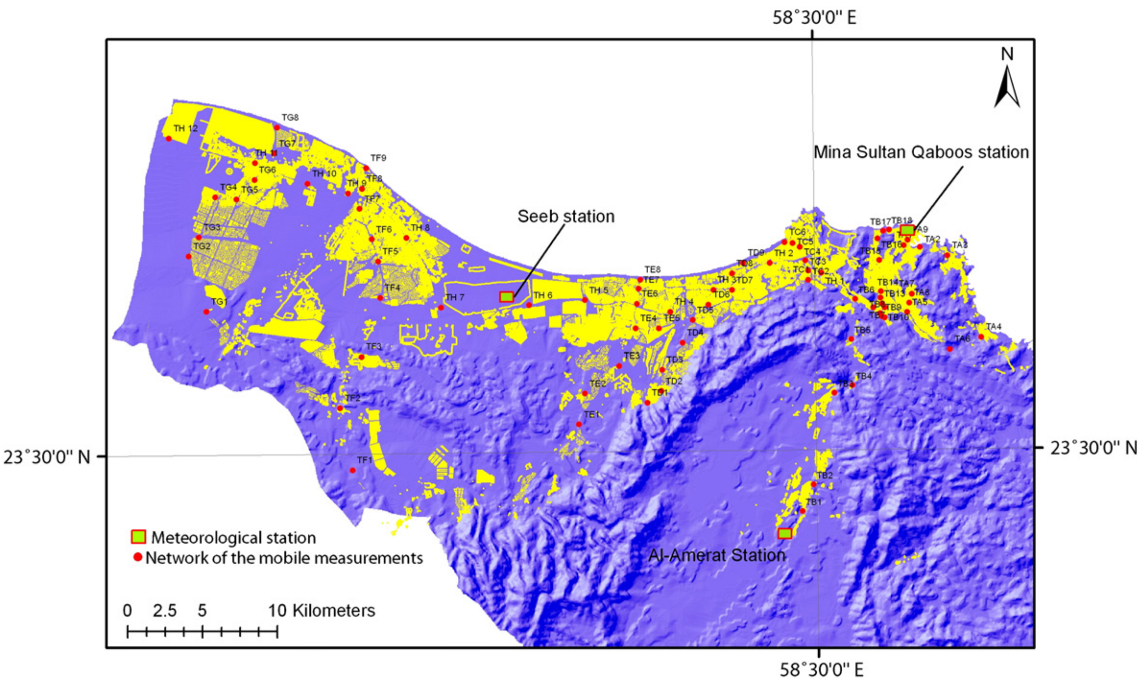

Fig. 7. Localization of the fixed meteorological stations and the mobile measurements network.

outgoing long-wave radiation losses. Thus, urban geometry is a crucial contributing factor in intra-urban temperature variations below roof level (e.g., Oke, 1981; Eliasson, 1996). Added to all that, measurements of SVF were carried out. A digital camera with fish-eye lens coupled with Rayman software was used to determine the SVF ratio.

In total, 10 transects were run through Muscat city covering a network of 83 points of measurements, whereby along each transect 14–20 points were located (Fig. 7). The measurements were carried out by three teams, each moving simultaneously over one transect, covering, hereby, an average of 45 points. Measurements were taken at four local time intervals: 19–20 hours, 04–05 hours, 07–08 hours and 15–16 hours. The maximum measurement duration of each transects is 45 min. In order to cater for the significant natural fluctuation of air temperature during sunset and sunrise, corrections were introduced in cases where the temperature difference from starting point to final point was more than ± 0.3 °C measured according to the readings at the official meteorological station.

The measurement operations were carried out on two different seasons. Measurements during the winters of 2007 and 2008 were run in December to mid-January, which is a period characterized by stable synoptic conditions with a clear skies. This was augmented by further measurements during February and March where the synoptic conditions are largely influenced by the winter monsoon and the incursion sometimes of the east mobile trough that brings rainfall to the Northern parts of Oman. In the summers of 2008 and 2009, measurements were carried out during the period June to July wherein the synoptic condition are usually favorable for the enhancement of the local wind circulation, especially sea breeze, in the study area. For plotting the thermal surface of the Muscat city at a height of 2 m, the difference between the core of the urban heat island and the other points of the network is calculated.

4. Results and discussion

4.1. Structure of the urban heat island

An idealized spatial pattern of an urban heat island features usually outward temperature decreases from a city center in nearly concentric isotherms. A typical example of this prototype was encountered in previous studies in Lille Metropolitan area in northern France and Sfax city in southern Tunisia (Charabi et al., 2002; Charabi and Melki, 2006). However, because the two areas are characterized by different regional climates, it is most probable that this similarity of their urban heat island pattern may be attributed to the location of both in flat topography. The urban heat island in Muscat city deviates considerably from this prototype; in comparison, its portrays distinct multiple forms. This is mainly because of the varied topography of the city in addition to the maritime influences it entertains and the location of the main commercial quarters in it. Temporal and spatial mapping of the identified temperature distribution displays the following general traits:

Fig. 8 shows that by night time, the relatively warm regions are located mainly in the Highland zone in the East, while the relatively cold regions are located in the Low Land zone in the West. However, within this general picture the coastal fringe entertains a special setting where temperature is, as would be expected, relatively warm due mainly to the influence of the thermal transfer of the air coming from the sea and the urbanized coastal shore. Besides, along the urbanized coastal line the velocity of the nocturnal land breeze is significantly reduced, which contribute to the warming of the shore line of the study area. In addition, several warmest quarters are observed in the Highland zone. Particularly, warmest temperature occurs along the narrow valley of Wadi Al-Kabir and in Ruwi, Matrah, Bait Al-Falaj and Darsit (marked by the red and black points in Fig. 8). Being the most favored business center in Muscat is one reason why these warm air temperatures are generated in these locations in particular. High-story buildings have combined to keep free air ventilation to the minimum. The heating effect is further accentuated by the presence of the dark-colored rocks such as Ophiolite which crop at the immediate vicinity and contribute to the emergence of this warm urban core (Fig. 8). So, in reality, the mountainous terrain which surrounds this part of Muscat tends to isolate it from the effects of the land–sea breeze circulation and, hence, contributes, herewith, to the emergence of these warm urban cores and to their maintenance all day long.

Within this warm urban valley the highest temperature values are encountered in the old parts (called *Hila*) of Ruwi and Matrah which are particularly distinguished by compact urban forms and narrow streets that lead to the development of deep canyons with a raise of temperature of about 0.7 °C (marked by the black points in Fig. 8). The lower SVF generated by this densely built-up urban fabric prohibits the emission of long-wave radiation and, hence, leads to the trapping of heat which eventually results into higher temperatures especially at late night hours. The same scenario is repeated in an isolated warm quarter in old Muscat north-east of this warm valley in which high urban density is confined within a narrow valley with surrounded by steep slopes.

However, westwards from this warm valley, especially in the residential areas of Al-Qurum, Medinat As Sultan Qaboos and Al-Khuwair A-Janubiyah (Khuwair South), the temperature anomaly decreases mainly because of higher elevation and less urban density. The sites of these residential areas benefit from the natural ventilation caused by the enhanced land–sea breeze circulation which contributes effectively to the cooling of air temperature.

In comparison, the behavior of the heat island in the urban area situated in Lowland of Muscat is devoid of the complications inherent in Highland Muscat. As mentioned before, in this area open flat terrain dominates the landscape and the built-up area is fragmented. Accordingly, the effect of the anthropogenic heat release on air temperature is highly reduced and the rural–urban thermal heterogeneity is abridged. So, Lowland of Muscat is strongly affected by land breeze that contributes significantly to the homogenization of air temperature.

The mobile traverses of the winter season (not shown) reveal that the spatial configuration of the UHI is static and exactly comparable to the summer pattern. The noticeable changes are observed in the intensity of the UHI. The winter season in the study area is mainly characterized by the decrease of the duration and the intensity of solar radiation, which reduce considerably the absorption and retention of the solar energy by urban surfaces. The emitted radiation is reduced and affects the development of the UHI.

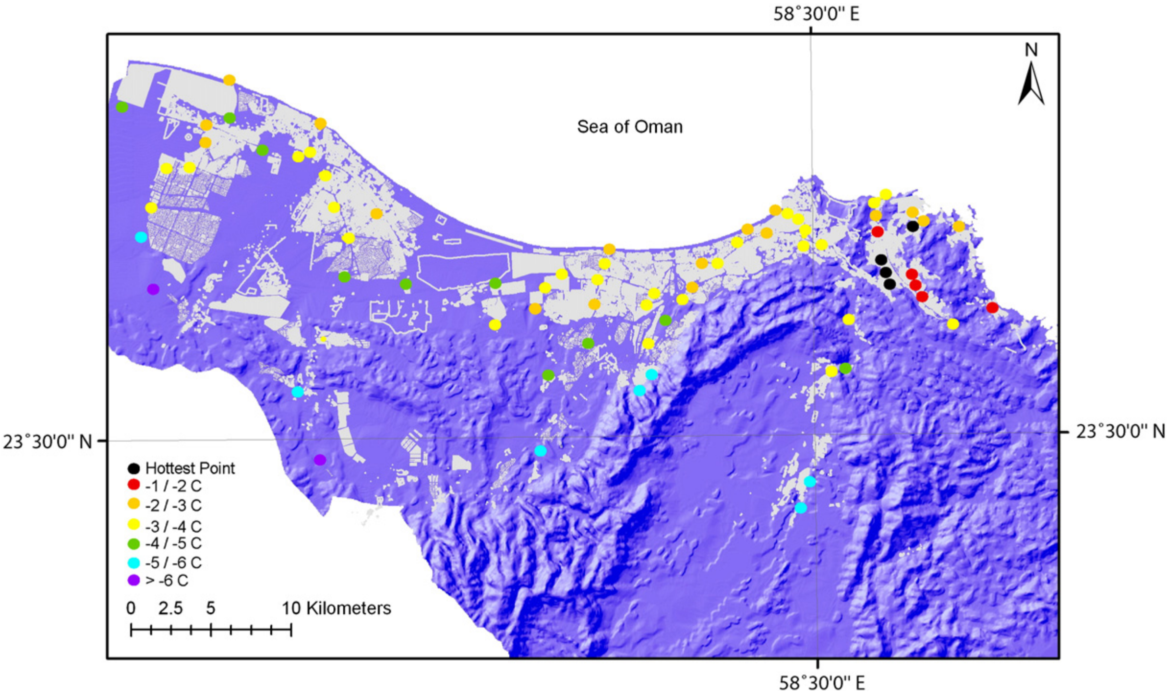

Fig. 8. Thermal difference between the core of the UHI (black points) and the other points of the network. Strong UHI between 02h30 and 3h30, on 6 June 2008.

4.2. Urban heat island intensity

For the purpose of investigating the temporal characteristics of the urban heat island intensity in Muscat, two meteorological stations are selected: (1) Mina Sultan Qaboos meteorological station, to represent the Highland zone. Despite its isolation from the direct influence of the heat flux generated by the traffic road, it is the only fixed station near the urban core. (2) As Seeb meteorological station located in Muscat International Airport, to represent Lowland of Muscat and suburban conditions. In addition, a temporary meteorological station was installed in Al-Amerat to represent the rural site. It is envisaged that comparisons of the readings of these stations during a period of 1 year (February 2008 to January 2009) can yield reliable indicators of the daily development of thermal differences between rural and urban areas and the disturbances that affect wind velocity under the combined impact of urbanization and topography.

The difference between the temperature at Mina Sultan Qaboos (urban) and Al-Amerat can be regarded as the maximum intensity of the urban heat island in Muscat (Fig. 9). The average maximum urban heat island intensity over the 1-year

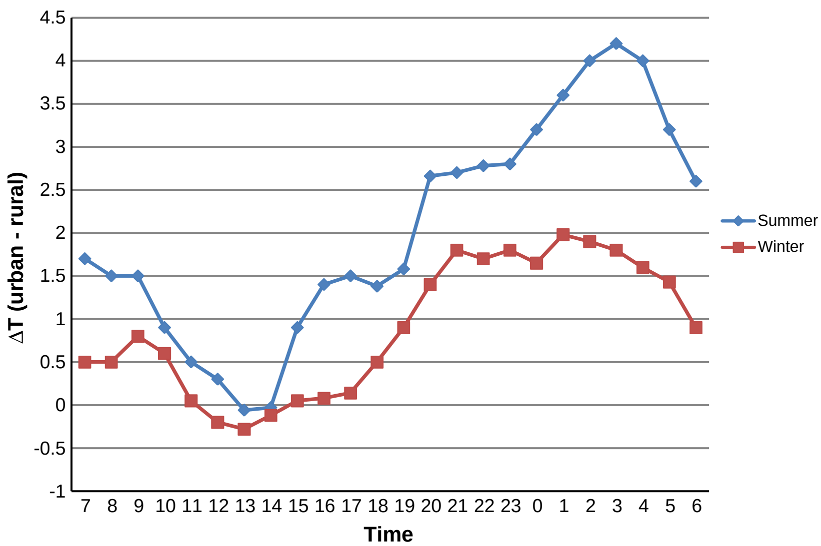

Fig. 9. ΔT between the urban station of Mina Sultan Qaboos and the rural station of Al-Amerat during one year.

period is 2.4 °C. However, evaluation of readings of urban heat island intensity discloses clear cycles. Diurnally, it is strong during nighttime (2100–0400 hours) than during daytime (800–1700 hours). In average, maximum urban heat island intensity is the strongest at 0300 hours (3.2 °C) and is the weakest at 1300 hours (0 °C). Seasonally, the analysis indicates that urban heat intensity tends to be strong in summer and weak in winter (Fig. 9). During the summer season, the UHI intensity can reach a maximum of 4.3 °C in nighttime and 2.3 °C in daytime. In the short winter season, especially during ideal synoptic conditions of clear and calm weather, the nocturnal UHI intensity decreases to 2.4 °C. However, during the winter NE monsoon this nocturnal UHI intensity can reach its minimum values. The seasonal variation of the urban heat island seems to be related to the seasonal variations in the incoming solar radiation. The monthly mean of the total solar radiation in Muscat exceeded 8000 Wh/m^2/day in June and 4407 Wh/m^2/day in January. These large values of the total solar radiation and its seasonal variations directly affect the amount and seasonal variations of the heat trapped by urban surfaces.

For the estimation of the urban heat island over the whole city, the data collected during field campaigns of mobile measurements were used. Identification of the urban heat island intensity is based on the calculation of the difference between the average of temperatures registered over the urban areas that exhibit the highest values and the lowest temperature registered on the selected rural site. An ensemble of hot quarters forming the core of the urban heat island emerges in the old central part of urban area, in the immediate proximity of the dense traffic roads. Among these warm quarters, four have developed along the canyon street of old Muscat. For the rural signal, two rural sites were selected; Al-Amerat, situated in a small alluvial enclave south-west of the Highland zone of Muscat city to represent the Highland zone, and Al-Mabela (point TG 1 in Fig. 7), situated in large alluvial flat, to represent the Lowland zone.

The results derived from comparison between the fixed meteorological stations confirm the diurnal and seasonal cycles of the urban heat intensity. However, the $\Delta T_{(\text{u-r})}$ values derived from mobile measurements are much more pronounced. The evaluation of the intensity of urban heat island was calculated for each rural site. Depending on which rural site was used to calculate the heat island, the average heat island over the study period ranged from to 3.7 C° to 5.2 C°. The maximum heat island ranged from 4.3 C° to 6.2 C°. For both the average and maximum heat island, the smallest heat island value using rural location of the Highland and the larger heat island occurred using rural site of the Lowland. The maximum heat island for each rural site occurred in summer season, after sunset and when urban heat island evolution is expected to peak during the cooling phase (Oke, 1987).

On the basis of the results obtained, several factors can be postulated to explain variability in the magnitude of the urban heat island of Muscat city. Given that the urban and the rural signals are influenced mainly by the conditions surrounding the site of measurements, intra urban variability in the computed values reflects to a large extent the impact of topography, urban density and the anthropogenic heat produced by road traffic as well as that from air conditioning. The selected sites of the mobile measurements of the warm city center are situated in a topographically narrow valley. Given that it is the major business district in Muscat, this valley possesses a high urban density and is exposed to intensive road traffic. Hence, it can be ascertained that the low ventilation triggered by the topography of the site, the anthropogenic heat flux generated by the combustion of fossils fuel and heat emissions from air conditioning are most probably the agents responsible for this extra warmth. However, there is a need for a more thorough effort for the provision of a more accurate estimation of the anthropogenic heat flux in Muscat and to quantitatively relate the spatial and temporal distributions of anthropogenic heat flux to the urban heat island.

However, for the sake of comparing the magnitude of heat island in rural areas with that in urban areas, it should be borne in mind that, in addition to topography, morphology and anthropogenic heat changes, land cover specifics should be taken into account. Rural arid sites are usually scattered, buildings are not so dense and exhibit bare surfaces on which only sparse herbage biomass can be found. Furthermore, the surfaces of the surveyed sites are composed of different materials; in some, it is a mixture of sedimentary coarse grey gravel with sizes ranging from boulders to silt and in others it is mainly lava rocks such as Ophiolite and dark Gabbro. The response of this surface cover to heat absorption and radiation is very variable and, hence, plays a significant influence on the budget regime of surface energy. This may explain why the assessment of the magnitude of UHI in these rural areas is variable. Assessment of the rural sites around Muscat has revealed the existence of a thermal contrast between sedimentary alluvial soil cover and dark Gabbro and Ophiolite cover that reaches a value of 2–3 °C. Further, the source of this variability may be partly related to local topography of each site: the rural site of the Lowland Zone is situated in a large flat alluvial fan and, hence, is much more exposed to the cooling effect of land breeze.

5. Summary and conclusions

The main features of the spatio-temporal evolution of the UHI in Muscat have been analyzed using hourly data from two urban stations and one rural station. The data recorded over a period of 1 year and complemented with mobile measurements along selected transects reveal that the warmest core of the UHI is located in the Highland zone of Muscat, along the narrow valley of Wadi Al-Kabir, Ruwi, Matrah, Bait Al-Falaj and Darsit. In this valley, the hottest air temperature is encountered in the old compactly built districts. The main factors responsible for the retention the released thermal energy in the lower atmosphere in this location are the local topography (low ventilation), the land cover (black lava rocks), urban geometry (high urban density) and the anthropogenic heat from road traffic and air conditioning. In Lowland of Muscat, the urban thermal pattern is fragmented and the urban–rural thermal difference is reduced. Reasons for this are the flat alluvial terrain, the low urban density of the subsequently established residential quarters and the recurrent exposition of this Lowland zone to land breeze circulation.

The UHI exhibits a diurnal and seasonal cycle. The UHI reaches a maximum approximately 7 hours after sunset. In addition, the UHI is well developed in the warm months of the year, i.e., mainly in summer. This seasonal variability can be attributed to the variability of sun radiation. It is noticed that during the rare winter rainfall spells and the occasional winter monsoon the UHI intensity usually decreases. These findings correlate well with the empirical generalizations identified by Oke (1982).

The assessment of the UHI intensity in the probed rural locations reveals strong variability among them. The variations arise mainly from differences in the configuration of their local topography which influences the local airflow. In addition, land breeze, which usually moves fast, exercises a tangible cooling of air in the rural sites of the Lowland. The study point out that a cautious approach should be adopted when assessing the effect of the built environment, to take into account the characteristics of the rural area. The UHI of Muscat depends on the specificity of the rural site used to determine the magnitude. This result corroborate with the finding of Hawkins et al. (2004) about Phoenix, Arizona, in which they demonstrate that the variations in land covers characteristics in the rural area exert significant control on the magnitude of UHI.

The preliminary investigation shows the complex nature of assessing the impact of urbanization in arid tropical coastal environment. The results illustrate the meso- and micro-level variability of temperature due to several competing factors in this region—topography, mesoscale circulation, urban form and landscape variability. However, attempts to isolate the effect of those parameters or to give a quantitative assessment for each factor and its respective contribution in the genesis of the UHI are well beyond the scope of this study. The number of observations used in this investigation is small and limits the possibility of proposing decisive conclusions. Therefore, in order to adequately address the potential degree of variability introduced by topography, recourse to the regional and local air flow and temperature simulation models using digital topographic and remotely sensed biogeophysical data can throw more light on this issue. However, the findings of this study contribute to the corpus of knowledge about UHI in arid zones.

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