Spatial distribution and microscale characteristics of the urban heat island in Tel-Aviv, Israel

Hadas Saaroni*, Eyal Ben-Dor, Arieh Bitan, Oded Potchter

Department of Geography and Human Environment, Tel-Aviv University, P.O. Box 39040, 69978 Ramat Aviv Tel Aviv, Israel

Received 9 December 1998; received in revised form 6 September 1999; accepted 22 October 1999

Abstract

A significant urban heat island (UHI) was identified in Tel-Aviv on a stable winter day. The UHI detection was performed using air temperatures at both the roof and the street levels (using fixed-station and car-traverse measurements) and at the surface level (using an airborne thermal video radiometer [TVR]). Whereas the complex microscale characteristics of the UHI studied by the TVR at the surface level showed variations of up to 10°C, at the street level, air temperature variations of 3–5°C were identified between the city center and the surrounding areas. It was found that during the nighttime, the warm Mediterranean Sea has a moderating effect on the roof-level temperatures, whereas, at the street level, the urban heat island is more pronounced. The combined method of monitoring the UHI from different levels and on different scales for the first time enabled a spatial assessment of the city’s UHI and its diverse thermal coverage characteristics. The thermal differences of neighborhoods, urban activity and urban components were compared. It was demonstrated that the city cover plays an important role in the thermal activity of Tel-Aviv. A similar UHI spatial pattern was obtained using isotherm maps, generated from the air temperatures at street level, and thermal images, generated by the TVR at the surface level. It was concluded that there are differences in the magnitude of the UHI at different levels of the canopy layer and at different times, but the UHI pattern has similar trends. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: Urban heat island; Thermal video radiometer (TVR); Coastal city

1. Introduction

1.1. General background

The urban heat island (UHI) is one of the most studied phenomena of a city’s climate. Almost universally the modified thermal climate in cities is warmer and leads to a set of distinct micro- and mesoscale climates (Roth et al., 1989). Comprehensive reviews of typical UHIs have been provided by many UHI workers (Landsberg, 1981; Atkinson, 1985; Oke, 1987). Oke (1995) described the different types of heat islands, identifying the differences between surface and air distribution of UHIs as well as the differences between the urban canopy and boundary layers. The magnitude of the UHI has been studied mostly in terms of the temperature differences between rural and urban stations. Its spatial distribu-
tion pattern, although showing a large thermal variability at the canopy layer, has been interpolated into isotherm maps showing a high correlation between land use and temperature distribution. For example, park areas appear to be relatively cold and maximum temperatures appear at the city center (e.g. Oke, 1987; Moreno-Garcia, 1994). Several studies have pointed out a phenomenon called ‘negative UHI’ or ‘urban heat sink’, which develops in cities, especially in city centers, during the daytime. A ‘negative UHI’ has been recognized both in surface temperature measurements (e.g. Wanner and Hertig, 1984; Carnahan and Larson, 1990) and in air temperature measurements (e.g. Myrup, 1969). The canyon geometry, which characterizes cities, and especially city centers, can be a major contributor to the negative UHI during the daytime. This is because the insolation absorption decreases at the street level with the relatively high heat capacity of the buildings. The influence of the urban geometry on surface and air temperatures has been widely studied by Oke (1981), Barring et al. (1985) and Eliasson, 1990/1991; 1996).

Pease et al. (1976) described the complex thermal behavior of an urban area, referring both to air and surface levels. Whereas air temperature measurements provide spot data of a selected point or route, thermal remote sensing methods give a spatially continuous view of the surface UHI. Although the genesis and temporal dynamics of surface and air UHIs have dissimilarities, they are, nevertheless, related (Oke, 1995; Voogt and Oke, 1997), and several studies have shown good correlation between them. Stoll and Brazel (1992) obtained good correlation between surface radiometric temperature (measured from a distance of 3 m by a thermal radiometer) and air temperature (measured at a level of 1.5 m) over Phoenix, Arizona. Yang et al. (1994) obtained positive agreement between the surface radiometric temperature (acquired from an airborne sensor) and air temperature over Wuhan, China. Thermal remote sensing from satellites is a common useful technique for studying the surface UHI and its spatial complexity (Carlson et al., 1977; Balling and Brazel, 1988; Roth et al., 1989; Reutter et al., 1994). However, such data can be deficient in spatial and spectral resolution and can be attenuated by a thick atmosphere. On the other hand, there are some excellent airborne IR scanners with relatively high spectral and spatial resolution capabilities that can be used for UHI studies (e.g. Eliasson, 1992; Quattrochi and Ridd, 1994; Yang et al., 1994). The ability to cover large areas simultaneously on a repeated basis and the ability to measure almost every element on the ground are additional significant advantages of this method over conventional climatic methods.

Accordingly, because the UHI is a reflection of the totality of microclimatic changes brought about by man-made alterations to the urban surface (Landsberg, 1981), it is important to combine both air and surface measurements in order to understand the complexity of the UHI and its inner differences.

This study investigates the UHI of Tel-Aviv City, Israel, as expressed at different levels of the canopy layer (roof, street and surface levels) and examines the relationships among them. This investigation used both conventional air and remote sensing measurements. The spatial distribution, magnitude and characteristics of the UHI are of great interest to the climatic and environmental planning missions of cities in general and of Tel-Aviv in particular. The construction of high-rise buildings and the growth of the metropolitan area, reflected by a higher traffic load and higher air pollution levels, leads to a growth in energy consumption, heat stress (especially during the warm season) and other environmental problems (Bitan et al., 1992; EPU-NTUA and ICTAF, 1994; Rosenfeld et al., 1995).

1.2. Study area

The city of Tel-Aviv is located on the seashore at the eastern edge of the Mediterranean Sea (34°47’E 32°06’N) and has a subtropical dry-summer (Mediterranean) climate (Fig. 1). The city has an area of ca. 50 km² and extends along the sea coast for ca. 14 km with a width of 3–6 km. Tel-Aviv is the commercial, financial and cultural center of Israel with a population of 350 000 people in 1996 (Statistical Abstract of Israel, 1998). It is the center of the largest metropolitan area in Israel (Fig. 2), with a combined population of 1 950 000 (together with Tel-Aviv itself). The research area is defined as the municipality of Tel-Aviv, which is considered to be the heart of the metropolitan area. Most of the buildings in Tel-Aviv are 3–4 floors (10–15 m) high. Several high-rise buildings up to 30 floors (up to 100 m), mostly offices and hotels,
are scattered throughout the city. The dominant anthropogenic heat sources in the city are transportation (57%) and use within buildings (34%). Industry energy consumption is small, 9% (EPU-NTUA and ICTAF, 1994).

1.3. Study time and weather conditions

Generally, the UHI has the greatest magnitude at nighttime and under stable weather conditions — calm air and cloudless skies — defined by Oke (1982) as
‘ideal’ conditions for the development of UHI (Oke, 1981; Landsberg, 1981; Oke, 1987; Eliasson, 1996). These conditions were selected for this study (27 and 28 February 1995).

The synoptic conditions were as follows: the lower levels were influenced by an anticyclone over the eastern Mediterranean, with light northeasterly winds. An upper barometric ridge caused air subsidence and thus high stability. During the day there was a light sea breeze (3–6 m s\(^{-1}\)) at Tel-Aviv’s seashore; during the first half of the night until midnight, light easterly winds of 0–2 m s\(^{-1}\) blew, and calm conditions developed from midnight until morning. The radiosonde data for 27 February 1995, 01:00 hours local time from Bet Dagan (situated on the coastal plain of Israel, 7 km east of Tel-Aviv; see Fig. 2 for the exact location) indicated the stability by a strong ground inversion (up to 308 m) and a first upper inversion (from 354 to 578 m).

Generally, during the rainy season (October–May) ca. 50% of the days are under relatively stable conditions (Ronberg, 1984). However, easterly winds, which diminish the UHI effect, can be relatively strong under these stable conditions (Saaroni et al., 1996; Saaroni et al., 1998). At nighttime along the coastal strip, (October–May) calm conditions occur 17–40% of the time (Bitan and Rubin, 1994). During summer the persistent Persian Gulf trough causes Ethesian westerly winds combined with sea breeze of an average of 3–6 m s\(^{-1}\) during the daytime and a relatively weak land breeze (below 4 m s\(^{-1}\)) and with a frequency of calm conditions 37% of the time during the nighttime (Bitan and Rubin, 1994). Under an ‘enhanced’ Persian Gulf trough the winds are stronger, and the inversion layer is higher than under a ‘weak’ trough (Alpert et al., 1992; Bitan and Saaroni, 1992). These conditions are likely to have a dominant impact on the intensity of the UHI.

2. Methodology

Temperature measurements were acquired using various monitoring systems, airborne remote sensing and conventional ground meteorological measurements at fixed locations and mobile traverses. Air temperature was measured at the street level (2 m above the ground), using car traverses with thermocouples in ventilated screens, and at the roof level (2 m above the roof), using Stevenson screens. Radiant surface temperature was measured using a thermal video radiometer (TVR) mounted onboard a helicopter at an altitude of ca. 2000 m.

For spatial identification of the city, a 1:5000 map was digitized, using an Auto Cad package (Fig. 1). This map was further used for analyzing both the air and surface measurements.

2.1. Air temperature measurements

Air temperature measurements were taken at both the roof and the street levels as follows:

(a) Roof level: diurnal measurements of air temperature were taken at fixed (Stevenson) weather screens at six selected sites within the city (Fig. 4a; Fig. 1 shows their location). The roofs were approximately the same height, ca. 12 m. We used thermographs and minimum and maximum thermometers in the screens. All the instruments were calibrated, checked and com-

Fig. 2. The metropolitan area of Tel-Aviv and the location of the rural stations.
pared before and after the experiment under the same conditions. The stations represent the city’s diversity: The seashore (1), city center (2 and 3), southern margins (4) and northern margins (5 and 6). Note that the stations representing the city’s margins (4–6) are not purely rural areas, but are less dense than the city center (2 and 3). Air temperature was also measured at three rural stations (Fig. 4b): Bet Dagan (situated 7 km east of Tel-Aviv), Ben Gurion International Airport (situated 10 km east of Tel-Aviv) and Sde Dov Airport (situated in the northern suburbs of Tel-Aviv, 400 m from the seashore in an open area). Fig. 2 shows their exact locations. The measurements at these three stations were taken 2 m above the ground (not from roof level) in Stevenson screens.

(b) Street level: the data were taken along four main routes crossing the city from north to south by four mobile traverses (Fig. 1). The traverse measurements were conducted at four different times of the day, 14:00, 21:00, 01:00 and 03:00 hours local time. Each car was equipped with thermocouples (made of copper and constantan with a time response of <1 s), which were calibrated, checked and compared before and after the experiment under the same conditions. Thermocouple sensors were mounted on each car at a height of 2 m above the ground in ventilated screens, and the vehicles maintained a constant speed of 20–30 km/h. Temperature was measured every second, averaged every 20 s and stored in data loggers for further analysis. Data that were measured when the traverses had to stop (e.g. at intersections) were omitted from the database. Each car traverse took ≈20 min, therefore, no corrections in temperature had to be inserted because of time. The four main routes are highlighted in Fig. 1 as A, B, C and D. The A path represents the seashore route, B the city center, C the eastern part of the city and D the Ayalon Brook route. Path D (Ayalon Brook route) is a main road along an open area that is lower by ca. 10–20 m than the average city level and is surrounded by scattered urban areas. Fig. 3 illustrates a west–east schematic topographic cross section, with the above routes overlain. Each of the averaged measurements derived from the car-traverse database was georeferenced at 100-m intervals and overlain on the digitized city map.

2.2. Surface radiometric temperatures

The surface radiometric temperatures were acquired from an altitude of ca. 2000 m, by using a thermal video radiometer (TVR), INFaremtrics, model 760 (1994), mounted onboard a Bell 206 helicopter. Ben-Dor and Saaroni (1997) showed that using this instrument, it was possible to obtain highly sensitive results in terms of both radiometric temperature and spatial resolutions of urban areas ±0.05°C and ca. 2 m, respectively). For the current study, the sensor configuration was optimized to work across the 3–14 μm spectral region, and the optic configuration enabled a 20° field of view (FOV) along an instantaneous field of view (IFOV) of 1.8 msRad. Using an onboard internal calibration procedure, we recorded the calibration information for each scene of the raw data on an 8 mm NTSC magnetic tape. A temperature radiometric span of Δ10°C (varied between 0 and 15°C) was set according to ground radiometric temperatures. Under these conditions, the city area was covered by three north–south and three south–north trips (each consisted of a swath of ≈800 m in width) during a total flight time of 35 min. Selected images

Fig. 3. Schematic topographic west–east cross section of Tel-Aviv.
The flight took place at 03:00 hours local time, when traffic load was minimal and the weather conditions were calm and stable. We selected this time even though Roth et al. (1989) pointed out that at this time and under such conditions it is the air (and not the surface) heat island that is more pronounced. This is because during the nighttime the shadow effect is negligible (Lillesand and Kiefer, 1994) and detection of the surface thermal characteristics of the entire city is more reliable. We also wanted to compare the results with the air UHI, which is more pronounced at nighttime.

3. Results

3.1. Air temperature distribution at roof level

The diurnal air temperature measurements taken from the six roof-level stations are given in Fig. 4a. Fig. 4b presents the diurnal air temperature measurements taken at the three rural stations (Bet Dagan, Ben Gurion International Airport and Sde Dov Airport) compared with the seashore and the city center stations. Minimum and maximum temperatures and the diurnal temperature range ($\Delta T$) at these stations is presented in Table 1. It can clearly be seen in Fig. 4 that the maximum temperature differences between the stations occurred during the second half of the night (00:00–06:00 hours local time), just as has been observed in other research (e.g. Oke, 1982, 1987; Roth et al., 1989). The rapid cooling effect in the rural stations after sunset (17:40 hours local time) is significant when compared with the city center. Even in Sde Dov, which is located on the seashore, this effect is visible when compared with the city center. This phenomenon has also been described by Oke (1982) for other cities. It is known that the UHI causes a strong increase in the minimum temperatures, as compared with relatively small increases in the maximum temperatures. Thus, cities are characterized by a decrease in the diurnal temperature range ($\Delta T$) in comparison with rural areas (Landsberg, 1981). In Tel-Aviv City, the seashore station (No. 1 on Fig. 1) had the least diurnal variation ($\Delta T$ of 4.8°C), as compared with the city center stations ($\Delta T$ of 6.7–6.9°C), the margins of the city ($\Delta T$ of 7.9–8.4°C) and the rural stations ($\Delta T$ of 8.4–15.0°C). The smallest diurnal variation at the seashore station and the relatively small diurnal variation in Sde Dov Airport can be explained by the moderating effect of the warm Mediterranean Sea (17°C during the study time). The rural stations showed the greatest diurnal variations, whereas the relatively small variations at the city center stations (nos. 2 and 3 on Fig. 1) are related directly to the UHI’s effect.

The maximum temperature differences between the city center stations (nos. 2 and 3) and the city margin stations (Nos. 4, 5 and 6 on Fig. 1) were 1.2 and 2.5°C during the daytime and the nighttime, respectively. Since these stations are almost the same distance from the sea, the difference is attributed to the magnitude of the UHI at the roof level (during this case study). It should be pointed out that larger differences were expected between the city center and the surrounding rural areas during such calm and stable winter conditions. However, because the margin stations are in the suburbs, which are not purely rural areas, this expectation was not achieved.

Temperature differences between the two purely rural area stations (Bet Dagan and Ben Gurion Airport) and the city center stations were larger. During daytime, the rural stations were warmer than the city center (maximum $\Delta T=4.4°C$), and during nighttime they were colder (maximum $\Delta T=5.2°C$). These differences are attributed not only to the UHI effect but also to two more dominant factors: (a) the distance from the sea (the city center stations are ca. 1 km away, and Bet Dagan and Ben Gurion Airport are 7

<table>
<thead>
<tr>
<th>Station Type</th>
<th>$T_{\text{min}}$ (°C)</th>
<th>$T_{\text{max}}$ (°C)</th>
<th>$\Delta T$ (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seashore (1)</td>
<td>12.3</td>
<td>17.1</td>
<td>4.8</td>
</tr>
<tr>
<td>City center (2)</td>
<td>11.0</td>
<td>17.9</td>
<td>6.9</td>
</tr>
<tr>
<td>City center (3)</td>
<td>11.3</td>
<td>18.0</td>
<td>6.7</td>
</tr>
<tr>
<td>Northern margins (4)</td>
<td>9.7</td>
<td>17.9</td>
<td>8.2</td>
</tr>
<tr>
<td>Northern margins (5)</td>
<td>9.9</td>
<td>18.3</td>
<td>8.4</td>
</tr>
<tr>
<td>Southern margins (6)</td>
<td>9.8</td>
<td>17.7</td>
<td>7.9</td>
</tr>
<tr>
<td>Ben Gurion airport</td>
<td>7.2</td>
<td>19.8</td>
<td>12.6</td>
</tr>
<tr>
<td>Sde Dov airport</td>
<td>6.7</td>
<td>21.7</td>
<td>15.0</td>
</tr>
</tbody>
</table>

Table 1

Minimum and maximum temperatures and $\Delta T$ at fixed stations in Tel-Aviv City and at the rural stations.
and 10 km away, respectively); and (b) the measurements at the rural stations were taken 2 m above the ground, not from roof level.

The Sde Dov Airport station, although located near the seashore, was colder during nighttime than the seashore station in the city (station No. 1 [maximum $\Delta T$=3°C]) and the city center stations (station nos. 2 and 3 [maximum $\Delta T$=1.9°C]). The combined effect of the station’s height, the difference in the distance from the waterline and the UHI effect can explain these results.

3.2. Air temperature distribution at street level

The isotherm maps (Fig. 5a–d) present the mobile traverse measurements for each of the examined times. They show the existence of warm areas at the city center throughout the daytime and the nighttime, and great variability in temperatures can be seen along the north–south cross sections and especially within the city center. Careful examination of the isotherm pattern in Fig. 5 reveals the following chronological findings:

![Air temperature distribution at street level](image-url)
3.2.1. Noontime — 14:00 hours local time

The seashore area, in general, appears to be comparatively colder than the rest of the city because of the moderating effect of the sea, as discussed previously. Along the four routes (A, B, C and D in Fig. 1), steep temperature variations were observed, with a small tendency for increasing temperatures toward the city center. The highest temperatures (up to $\sim 21^\circ C$) were measured along the inner city routes (B and C). The Ayalon route (D), although generally situated at a relatively lower elevation than the majority of the city (ca. 10–20 m) and located relatively far from the sea (ca. 2–3 km), was found to be cooler by ca. 1–2.5$^\circ C$ than the inner city. Therefore, it is postulated that the dominant urban heat effect is expressed along the inner city routes (B and C). The maximum air temperature difference across the city was found to be 4$^\circ C$, along a distance of ca. 5 km (between the northeastern open area (17.2$^\circ C$) and the city center (21.2$^\circ C$)). Maximum differences of 3.5$^\circ C$ were found between the colder seashore and the city center. However, several cold areas in the city center can be identified along route B, which are colder by ca. 1–2$^\circ C$ than their surrounding areas. The most noticeable

Fig. 5. An isotherm map of air temperatures ($^\circ C$) for different times: (a) 14:00 hours local time; (b) 21:00 hours local time; (c) 01:00 hours local time; and (d) 03:00 hours local time.
area is near the municipality plaza (annotated c.i. [Cold Island] in Fig. 5a). This area was found to be colder during daytime (Fig. 5a) and warmest during nighttime (Fig. 5d) and perhaps also describes a negative UHI. A colder area can be also seen at the northwestern part of the city, along the western part of the Yarkon River. Finally, the greatest temperature variation along the north–south cross sections was found to occur at noon.

3.2.2. Evening hours — 21:00 hours local time

At this time, the seashore area was still colder than the city center. Along the eastern route, Ayalon (D), the lowest temperature values were 13.2°C (at the northern and southern edges), and the maximum was 15.6°C (next to the warm areas of the city center). These differences are basically due to the physical characteristics of both areas, as discussed previously, which result in a rapid cooling process. The maximum temperature difference between the city center (17°C) and the northern and southern edges (13.2°C) was 3.8°C. A warm area along the city center can be clearly seen in Fig. 5b. In general, a more homogenous pattern is seen, compared with the isotherm map of 1400 h (Fig. 5a). This is because the intense thermal variation of the city center that appears during the daytime decreases at night.
3.2.3. Midnight — 01:00 hours local time

At this hour, the seashore area was observed to be as warm as the city center. The eastern part of the city, along the Ayalon route (D), was the coldest area. At this time of the day, and along the four routes, there was a more significant temperature increase toward the city center. A steep temperature decline was observed at both the north and the south edges of the city, which consequently became relatively cold. The maximum air temperature difference at this time was 5.6°C, as measured between the southern open area (9°C) and the warm city center areas (14.6°C).

3.2.4. Late nighttime — 03:00 hours local time

Results measured at 0300 were similar to those measured at 0100 h. The overall temperature values were colder than at 0100 by ca. 1–2°C because of the longer night cooling effect. Similar temperatures were observed along the seashore and the inner city routes. The maximum air temperature difference was 5°C between the southern open area (8.3°C) and the city center (13.3°C). It is notable that a difference of 2.2°C was found between Ayalon (D) and the east city route (C), which are 400 m apart.

3.3. Surface radiometric temperatures

Using the TVR, we were able to study the thermal behavior of each urban component and to identify the various heat sources throughout the city. The high resolution of the images enables a comparison of surface and air temperatures based on precise georeference points.

Fig. 6a–d shows four selected images throughout the city of Tel-Aviv. Their exact locations are shown on the city map on Fig. 1. The images show the thermal behavior of the selected areas on a microscale level and the thermal characteristics of selected neighborhoods and land uses inside these images. The areas selected are:

![Fig. 6. Four TVR images of selected sites within the city of Tel-Aviv: a, b, c and d (see Fig. 1 for exact location of each image).](image-url)
(a) The southeastern edge of Tel-Aviv, expressing the change from an open rural area to a residential area (a suburb of Tel-Aviv City), and one of the central junctions at the entrance of Tel-Aviv (Fig. 6a).

(b) The seashore area west of the city center, including the city’s marina (Fig. 6b).

(c) Two close neighborhoods at the center of the city (Fig. 6c).

(d) A residential neighborhood at the northeastern part of the city (Fig. 6d).

In order to get an idea of the thermal differences between various urban components, Fig. 7a–d provides a representative radiometric data histogram (average $T_{ave}$, minimum $T_{min}$, maximum $T_{max}$ temperatures) of selected targets within the above four images. The standard deviation (STD) is anno-
tated on the $T_{ave}$ column. The targets consist of different numbers of pixels (more than 24 pixels per target), based on their spatial size. The images (Fig. 6a–d) and the radiometric temperature results (Fig. 7a–d) clearly indicate the occurrence of thermal changes, resulting from cover surface variety, land use and anthropogenic activity. Below is a systematic discussion on each of the images.

3.3.1. Image a — the southeastern edge of Tel-Aviv (Fig. 6a)

The image illustrates the thermal changes between the rural open ($T_{avg}=4.0^\circ$C) and the built-up ($T_{avg}=7.8^\circ$C) areas. There is a noticeable change ($\Delta T$ of $3.8^\circ$C) between surface radiometric temperatures of the homogenous and cold rural area (A) and the warm built-up area (B). On the other hand, the residential neighborhood has the largest standard deviation ($0.5^\circ$C, as compared with $0.1^\circ$C in the rural area) because it consists of a wide variety of materials and complex structures. The roads appear to be the warmest element in the image ($T_{avg}=8.3–8.8^\circ$C), especially the road junctions (C), which are ca. $1^\circ$C warmer than the roads themselves ($T_{avg}=9.5–9.6^\circ$C). Note that the roads in the rural area are colder by ca. $0.5^\circ$C than the roads in the residential area.

3.3.2. Image b — the seashore area (Fig. 6b)

This image shows the seashore area and the western residential area at the center of Tel-Aviv City. Obviously, the sea and other water bodies in the image (such as the swimming pool that appears in the middle of the image) are the warmest targets during the nighttime, with radiometric temperatures of $>12.2^\circ$C (this was the upper detection limit of the current TVR measurement). In this image, a relatively warm spot appears at the piers in Tel-Aviv’s port ($T_{avg}=10.5^\circ$C), which was warm because of its asphalt coverage. Also, visible are the warmer edges of the piers which is caused by the relatively high water content at these areas. The sand strip along the seashore is relatively cold because of the low heat capacity, light color and absence of anthropogenic heat sources. Note that a thin warm strip associated with the sea’s waterline is visible, and its location moves with the motion of the sea waves. As in the previous image, the streets in the current image were found to be the warmest element throughout the land area, with the main streets (Ben-Yehuda St. [A] and Arlozorov St. ([B]) being the warmest. At Ben Gurion Boulevard (C), where relatively dense vegetation appears, the radiometric temperatures were relatively cold because of the canopy effect. The residential area presented in the image is characterized by minimum vegetation and a dense built-up neighborhood as well as a heavy traffic load along the main streets during the daytime. Note that within this residential area, a cold spot (D) was detected. This spot was found to be an uninhabited house (located beside the main street) which strongly suggests that anthropogenic activity can be monitored by the TVR at the house (microscale) level.

3.3.3. Image c — two close neighborhoods at the center of the City (Fig. 6c)

This image illustrates two neighborhoods that have noticeable thermal variations between them. These variations were found to be a function of the difference in the neighborhoods’ physical structures and urban activity. The cold neighborhood (A, known as the ‘Rakevet’ neighborhood) is a workshop area composed of low buildings such as garages, carpenter’s shops, small industries and storehouses. This area is empty during the nighttime and has no heating or urban activity sources to warm it at night. Additionally, the streets of this neighborhood are barely paved and appear bleached by a significant amount of dust coverage. During the daytime, such a configuration tends to reflect the solar energy, and, hence, diminishes the absorbed (and emitted) energy. Because the streets in neighborhood B are heavily paved with asphalt and have a relatively dense traffic load during the daytime, the differences that occur between the two neighborhoods are significant (the average temperature of the ‘cold’ and ‘warm’ neighborhoods are 8.0 and 9.3°C, respectively). Owing to the high spectral and spatial resolution of the TVR, radiometric temperature differences $\Delta T$ of ca. $10^\circ$C have been observed between two closely situated objects in the cold neighborhood (A), because of different emissivities, thermal conductivity and capacity. The ‘cold’ object is a storehouse with metal walls and roof that can be characterized by low emissivity and low thermal conductivity and capacity, which is visualized as cold. The ‘warm’ object is a gray brick workshop with a transparent asbestos roof acting as a greenhouse, which is visualized as hot. In the image a
warm neighborhood (B), which represents a residential area with a few cold public (uninhabited) houses (on its southern corner) and a commercial area (on its northeastern corner) is also visible. Note that a warm area is seen in the intersection located at the northern part of the image (C). This area contains a building where a newspaper is published, which is very active at night and, hence, is visualized as hot ($T_{avg}=10.7^\circ C$).

3.3.4. Image d — a residential neighborhood (Fig. 6d)

This image illustrates a heterogeneous residential area at the northeastern part of the city as well as an open area (east and southeast of this region). A noticeable temperature difference appears between the streets, and the northern street, Yehuda Hamaccabi (A), was found to be the warmest. Along this street and especially along its northern edge, several busy restaurants and night bars were operating during the time of the flight. These restaurants can be considered as a heat source for this street, which was easily detected by the TVR. The eastern street ([B]; Namir Drive) is one of the main roads in the city. A temperature difference appears between its northern part (B1), which is blocked between dense heat-emitting buildings, and its southern part (B2), which is situated in a cold open area. The image also shows several neighborhoods with different thermal characteristics. The western neighborhood (C) consists of 3- to 4-floor buildings (50 years old), with vegetated areas in their backyards and along the streets (as boulevards). The central neighborhood (D1-4) illustrates a heterogeneous area. Another old neighborhood (D1), similar to C, is visible. At the northwestern corner of the image some cold spots appear, resulting from a strip of small private houses (2 floors) that are heavily vegetated (D2). Also, a public area (museum) surrounded by a vegetated area (D3) shows relatively cold radiant temperatures. Next to the museum (D3), a relatively young area (10–20 years) with taller buildings (D4) appears to be comparatively warmer ($T_{avg}=9.1^\circ C$). The cold spot at the southeast corner of the central neighborhood is a bare soil area situated at relatively low topography (ca. 5 m lower than its surroundings; $T_{avg}=8.1^\circ C$). The eastern neighborhood (E) consists of younger (5–10 years) high-rise buildings (6–8 floors), which appear to be warmer than the older (10–20 years) western buildings. The southern part of the image consists of a cold, open area (F; $T_{avg}=7.2^\circ C$). Also, in this area are three tall buildings having 20 floors (G), which appear to be the warmest buildings in this image ($T_{avg}=9.8^\circ C$), and a small residential housing area (H) that appears to be relatively cold ($T_{avg}=8.3^\circ C$).

In summary, it can be concluded that the four selected images clearly show thermal variations on a microscale level, caused by coverage type, land use, building materials and activity patterns.

4. Discussion

Air temperature measurements from both roof and street levels indicated a noticeable UHI in Tel-Aviv City especially during the nighttime. At roof level, and during the daytime, the seashore was colder than the city center, based on the moderating effect of the sea. No significant differences were found between the city center stations and the margin stations, both located the same distance from the sea. The rural stations east of Tel-Aviv were warmer than the inner city by up to 4°C. During the nighttime the seashore station was warmer than the inner city, due to the moderating effect of the sea. Nevertheless, the city center was warmer than the margins, by ca. 1.5–2.5°C, which, in principle, indicates the UHI effect. These findings confirm the conclusion made by Bitan et al. (1992), who investigated the impact of the sea on the roof-level temperatures of Tel-Aviv City during a selected summer. They found that the impact of the sea is greater than the urban effect during both day and nighttime: “the seashore was found to be warmer than the city center during nighttime and colder during the daytime”. Our measurements also show that the Mediterranean Sea plays an important role in the roof-level temperatures during stable winter days, but the urban effect is more pronounced during nighttime. At roof level, the urban effect can be seen only on a north–south cross section (at the same distance from the sea), where the city center is warmer than its margins by ca. 2°C at night and by ca. 1°C during the daytime. The moderating effect of the Mediterranean Sea is also pronounced at the street level, especially in the daytime, where the seashore was found to be colder than the city center. During nighttime, whereas the seashore station (at the roof level) was found to be
warmer than the city center stations, the seashore route (at the street level) was not found to be warmer than the inner city routes. No land breeze was measured during nighttime, and, therefore, we speculated that there was no heat transfer from the city mass toward the seashore. This supports the assumption that at the street level there is a greater urban contribution to the creation of the UHI than at the roof level, where the sea’s effect is not blocked by the buildings and is therefore more pronounced. Thermal differences were also observed between the magnitude of the UHI at the roof and at the street levels. Whereas at roof level the UHI was obvious only during nighttime and the temperature differences between the city center and the margins were ca. 1–2°C, at street level the UHI was observed during both day and nighttime, and its magnitude was 4 and 5.6°C, respectively.

During the daytime, in addition to several warm areas observed from the air temperature measurements at the street level, several cold areas were found within the city center (Fig. 5a). The warm areas may be related to the heavy traffic loads, high urban densities, daytime heat sources and lower sea breeze ventilation. The colder areas do not appear to express a classic ‘negative UHI’ effect, but indicate that such a trend is possible. It should be noted that these cold areas are not characterized by a canyon geometry structure but by more open spaces, such as wide roads, junctions and a city plaza. Accordingly, it is assumed that the cold areas actually result from sea breeze penetration into these locations. It should be emphasized that there were no wind measurements taken on these streets to argue this assumption, but a westerly sea breeze (3–6 m s⁻¹) was measured at the seashore. Further study on temperature variations based on street geometry and wind pattern is needed for the city of Tel-Aviv.

The spatial and diurnal distribution of the UHI of Tel-Aviv, as can be seen from the isotherm maps (Fig. 5a–d), indicate that the UHI is more homogeneously pronounced during the nighttime, whereas during the daytime, there is a larger temperature variation, especially within the routes in the city center.

Although the TVR images present a bird’s-eye view (Voogt and Oke, 1997) of the city, they indicate the complex thermal behavior of an urban surface versus the homogeneity of open spaces. It clearly presents the thermal differences due to material composition, land uses, type of coverage, color and anthropogenic activities. Temperature differences between objects in the images were found to be higher than the differences found in the air temperatures (up to >10 and 5.6°C, respectively) for the early morning hours (0300). It is assumed that during the daytime the thermal differences between the same objects shown will be greater, because the surface UHI is more pronounced then (Roth et al., 1989; Voogt and Oke, 1997). The images show different heat sources throughout the city neighborhoods and present the thermal behavior of various urban elements in the city of Tel-Aviv.

The images indicated that the asphalt paved streets in Tel-Aviv are a significant heat source at night (images available) and probably during the daytime (images not available). An interesting finding was the fact that junctions were even warmer than the asphalt streets themselves, contrary to what Barring et al. (1985) found in Malmo, Sweden, and Eliasson (1990/1991) found in Goteborg, Sweden. They observed cold junctions relative to the street and explained this finding by the higher sky view factor (SVF) over the junctions. This interesting converse observation in Tel-Aviv may be explained by several factors:

(a) Differences in the material composition of the street: in Tel-Aviv the streets are paved with asphalt, and junctions were found to have more ragged asphalt, mostly covered with oil spots and the remains of tire friction. These alterations might cause changes in the target’s emissivity, which would result in higher temperatures.

(b) Differences in street geometry and climate conditions: Tel-Aviv is located in the Mediterranean climate at latitude 32°N. Therefore, even given similar street size and street geometry, the insolation conditions are different, differently affecting the warming and cooling mechanisms of the streets and junctions. Also, most streets shown in the images (Fig. 6) are quite wide (ca. 20–30 m).

(c) Our measurements were taken around 03:00 hours local time when the cooling effect is higher relative to 17:00–22:00 and 21:00 hours (local times), when Eliasson (1990/1991) and Barring et al. (1985) conducted their measurements, respectively. Therefore, the effect of the different SVFs is expected to be higher in
Goteborg and Malmo and lower in Tel-Aviv. As a result, it is assumed that the SVF is highly dependent on the local conditions of the area examined.

Despite the warm streets, air temperatures taken at street level indicated that along areas with vegetation, the temperature values were relatively colder than along non vegetated areas. The surface images show the spatial location of green areas, boulevards, gardens and parks, based on their thermal behavior. Vegetated areas are known to be comparatively colder during the daytime than most other urban elements (Wanner and Hertig, 1984) and bare soil areas (Sabins, 1987). During the nighttime, vegetated areas appear to be relatively warmer than bare soil areas (Sabin, 1987). Nevertheless, the thermal images obtained by the TVR (Fig. 6) show that the vegetated areas were colder at nighttime than most of the other urban components, and especially relative to the warm streets. This observation indicates that there is a noticeable nighttime contribution from both urban components and anthropogenic activity to the UHI. Accordingly, the daytime thermal differences between vegetated areas and urban components are expected to be even greater. Moreover, during the daytime, vegetation on the boulevards casts shadows on the surface of the streets, causing less absorption of insolation (in addition to its other environmental implications). Basically, vegetation has been reported to have a positive effect on reducing the heat stress and improving the climatic conditions of cities in warm regions (Givoni, 1991; Rosenfeld et al., 1995). In the current study, most roofs in Tel-Aviv were found to be relatively cold during the nighttime and were assumed to maintain this trend during the daytime as well. This characteristic is related to the light color of roofs, on the one hand, and to the extensive use of insulated material, on the other. The city of Tel-Aviv has been called the ‘white city’, because of the generally light color of the roofs. This is known to play an important role in reducing solar heating during the warm season and therefore reduces energy consumption and urban smog (Rosenfeld et al., 1995). From all of the thermal video data of the city (images not shown) it was observed that roofs covered with vegetation were warmer during the nighttime than were the light-colored roofs without vegetation coverage. A daytime monitoring is required to study the daytime thermal differences between exposed roofs and vegetated ones. Moreover, because the influence of humidity should also be considered during both day and nighttime, a future study should include an examination during the summertime, when the effect of humidity is at its greatest.

Several studies have revealed positive correlation between surface radiometric temperature and air temperature in urban areas (Stoll and Brazel, 1992; Yang et al., 1994; Ben-Dor and Saaroni, 1997; Voogt and Oke, 1997). In order to compare the patterns of the UHI (as measured by air temperature at street level and surface radiometric temperatures), we generated an isotherm map of the surface (TVR) radiometric temperatures (Fig. 8) by extracting the surface radiometric temperatures along the four routes (shown in Fig. 1) at the same ground locations where the air measurements were taken. A comparison between this map (Fig. 8) and the isotherm map of the air temperature for the same hour (Fig. 5d) results in the following conclusions:

(a) Both maps show a similarity in the magnification of the temperature variation as well as in the spatial thermal distribution.
(b) Both maps show a similarity in temperatures between the seashore and the city center routes (A and B, respectively), and the eastern part of the city was the coldest.

Although similar trends were observed between the two maps, there are some minor differences that can be explained by different atmospheric conditions over the four studied routes (see Ben-Dor and Saaroni, 1997).

In general, it can be concluded that the TVR, together with conventional air temperature measurements, provides a reliable spatial representation of the pattern, magnitude and microscale characteristics of the UHI.

5. Summary and conclusions

A significant UHI was identified in the city of Tel-Aviv using surface radiometric temperature as well as air temperatures measured from mobile traverses and at fixed stations, on a stable, calm winter day. The thermal images showed, for the first time, the thermal
pattern and complexity of the city’s coverage in Tel-Aviv, which impact its UHI. The UHI was found to be most pronounced during the nighttime. During the daytime, several isolated warm areas were observed next to colder ones, indicating, perhaps, a negative UHI. The influence of the warm Mediterranean Sea is obvious at the roof level and is diminished at the street level, where the urban effects are more pronounced. Air temperature differences of up to 6°C at the street level and of ca. 2°C at the roof level were identified between the city center areas and the southeastern margins of the city (ca. 5 km distance) during nighttime. The isotherm maps of the mobile traverses at different times indicate the pattern of the UHI in Tel-Aviv, which is a function of the physical conditions, the effect of the Mediterranean Sea, the local topography and the urban characteristics such as land uses, building density, traffic load, construction materials and anthropogenic heat sources. These isotherm maps, generated from the air measurements, are an interpolation that gives an inclusive picture of the pattern of the UHI in Tel-Aviv. A comparison between the isotherm maps of the air and surface radiometric temperatures indicates a similar pattern and suggests that the TVR can rapidly depict the overall pattern of the UHI. The TVR also enables imaging of the microscale pattern and shows the influence of the different urban components, indicating the great complexity of UHI sources. It shows the noticeable contribution of asphalt streets and their junctions as well as the influence of diverse anthropogenic activities and significant effect of both open and vegetated areas. The thermal images, acquired by the TVR sensor, emphasized the major role of vegetation in cooling the city. The parks and open areas were the coldest elements within the city during both day and nighttime. Furthermore, the advanced TVR sensor enables thermal recognition of the city’s different areas. Noticeable differences between neighborhoods in the city (resulting from the type of urban activity, building patterns, structural materials, street color, vegetation and open area characteristics) could be depicted by this tool. The presented study integrates several methods and techniques that can be used to characterize the UHI in both micro- and mesoscales. Identification of the different heat sources in Tel-Aviv, their spatial distribution, intensity and spatial influence may lead to better understanding the UHI of the city. The results have further relevance for environmental implications in a time of global warming, especially in a warm region such as the Mediterranean basin.

Acknowledgements

The authors wish to thank the heads of the Geography Department, Tel-Aviv University, Professors J. Portugali and A. Bitan, for supporting the flight expenses; Mr. E. Cohen from Elbit Israel LTD, for providing the radiometer; Dr. A. Manes, Mr. A. Israeli

Fig. 8. An isotherm map of surface radiometric temperatures (°C) for 03:00 hours local time.
and Dr. A. Dozortsef from the Israel Meteorological Service, Dr. J. Dorfman and Dr. O. Tsafir from the Geography Department and Mr. A. Tal from ICTAF for their technical assistance.

References


Hadas Saaroni (Ph.D., Tel-Aviv University, 1994) is a lecturer at the Department of Geography and Human Environment, Tel-Aviv University, Israel. She is an expert in urban climatology and synoptic climatology. Her studies focus on two fields: (1) Climatological aspects of urban areas in Israel; (2) Synoptic climatology of the Levant region and Israel and its correlation with polar outbreaks, severe storms, forest fires and other climatological aspects of the region. Her current studies focus on analyzing the UHI characteristics of cities along the eastern Mediterranean and the effect of various green areas in the city, combining theoretical and field study, using climatological and remote sensing techniques. Mailing address: Department of Geography and Human Environment, Tel-Aviv University, P.O. Box 39040, Ramat Aviv, Tel Aviv, Israel 69978.

Eyal Ben-Dor (Ph.D., Hebrew University of Jerusalem, 1992) is a senior lecturer at the Department of Geography and Human Environment, Tel-Aviv University Israel. He is an expert in soil and remote sensing sciences and is interested in broad environmental aspects using state-of-the-art remote sensing technology. His studies deal with high spatial and spectral resolution analysis of the lithosphere, hydrosphere and atmosphere from the visible, near infrared and far infrared spectral regions. He was a visiting scientist at the Center for Study of the Earth from Space (CSES), at the University of Colorado from 1992 to 1994 under special grants of the NOAA. His current studies focus on quantitative mapping of soils and water from hyperspectral data and developing of low cost remote sensing capabilities. Mailing address: Department of Geography and Human Environment, Tel-Aviv University, P.O. Box 39040, Ramat Aviv, Tel Aviv, Israel 69978. http://www.outasites.com/tauinv

Arieh Bitan (Ph.D., Hebrew University of Jerusalem, 1970) is a full Professor and head of the Unit for Applied Climatology and Environmental Aspects, Department of Geography and the Human Environment, Tel-Aviv University. Twice head of the Department of Geography, Tel-Aviv University. Previous positions: Department of Geography, Hebrew University, Jerusalem, Lecturer. Department of Geography, Haifa University, guest lecturer. Professional specialization: Urban climatology, applied climatology and planning and climate of Israel. Professional activities: Research on the urban climate of Tel Aviv. Consultant in applied climatology to different ministries, public agencies and private companies in integrating climatic considerations in national, regional and urban planning.

Oded Potchter (M.A., Tel-Aviv University, 1984) is a teacher and researcher at the Department of Geography and Human Environment, Tel-Aviv University, Israel. His main expertise are applied climatology, urban climatology, regional climatology and climate and human habitation. His current studies focus on the climatic aspects of urban parks and green area, climatic aspects of human settlement in ancient time, human settlement in arid zones and climatic aspects of vernacular architecture. Mailing address: Department of Geography and Human Environment, Tel-Aviv University, P.O. Box 39040, Ramat Aviv, Tel Aviv, Israel 69978. E-mail: Potchter@post.tau.ac.il