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The urban heat island of a city in an arid zone: the case of Eilat, Israel

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With 4 Figures

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Summary

This study presents the results of a preliminary research that was conducted in the city of Eilat, located in an extreme hot and arid zone on the northern coast of the Red Sea. The purpose was to analyse the characteristics of the local urban heat island (UHI). Diurnal pre-dawn and early-afternoon measurements were taken in winter and summer weather conditions on three separate occasions for two consecutive years. The results show the development of a moderate UHI located around the most intensive area of human activity; the city business centre and dense hotel belt. The UHI is more significant at midday during the summer period, while early morning inversions in winter have a weakening effect on the UHI intensity. It was found that the topography and wind regime have a dominant effect on the location and intensity of the UHI, while the sea has a very marginal effect. Due to the UHI influences on the spatial distribution of the heat stress in the city, it is suggested that further applied UHI research should be focused on the summer period.

1. Introduction

Our major aim is to present preliminary results of the case study of an ''urban heat island'' (UHI) in an arid area, the city of Eilat, Israel, and thus to contribute to the discussion of UHI in arid areas. The UHI, a phenomenon characterizing the urban climate, is defined as the difference between temperatures measured in the urban space and those in the non-urban space surrounding it (Oke, 1987). Most of our knowledge is derived from research conducted in northwest Europe and North America and, to some extent, in tropical and subtropical areas (Arnfield, 2003).

The magnitude and structure of UHI are determined by two main groups of factors (Goldreich, 1970; Oke, 1987; Arnfield, 2003). The first is comprised of climatological factors, such as climatic region, season, time of the day, synoptic conditions, and wind regime. The second includes factors related to the physical and human nature of the built environment, such as geographical location and site selection, character of the relief, shape of the urban landscape, type of building materials, and intensity of human activities, as well as others.

There are few published studies of heat island studies in arid environments: Phoenix and Tucson, Arizona (Hsu, 1984; Balling and Brazel, 1986, 1987; Tarleton and Katz, 1995), Kuwait City (Nasrallah et al., 1990) and, less fully Beer-Sheva, Israel (Ganor, 1965; Skibin, 1979). The Arizona studies show that UHI intensity is higher during summer nights, and that it increases in time, due to rapid urbanization growth. Unlike the case of Phoenix, the UHI for Kuwait City is poorly developed (Nasrallah et al., 1990).

Explanations suggested include the proximity of the city to the coast and the effect of the Arabian Gulf sea breeze; low average building height in both the commercial and residential areas; and the extensive use of local building materials that have thermal characteristics similar to those of the surrounding uninhabited area.

The main findings suggest, among others, that the expansion of the urban area and the resultant changes in land use, followed by an increase in temperature, may have a downward effect – sometimes quite strong – on the level of atmospheric humidity (Brazel and Balling, 1986; Balling and Nasrallah, 1991). Usually, for the same air mass, the effect of the temperature increase on the heat stress value is stronger than that of the humidity decrease. The latter may have a detrimental effect on urban areas in arid environments, especially at noon in summertime, when the temperature is higher and the radiation intensity much stronger (Balling and Brazel, 1987).

Table 1. Main climatic characteristics of Eilat

Climatic characteristic	Period	February	August
Daytime mean temperature (°C)*	1981–2000	15.7	33.0
Diurnal temperature range (°C)*	1981–2000	10.6–20.8	26.2–39.8
Relative humidity value for 08 h (%)*	1981–2000	54	39
Relative humidity value for 14 h (%)*	1981–2000	28	18
Daytime mean wind velocity ($m\,s^{-1}$)[a,**]	1964–1983	5.0	6.1
Nighttime mean wind velocity ($m\,s^{-1}$)[a,**]	1964–1983	2.1	3.1

[a] Wind velocity for January and July
Sources: * Central Bureau of Statistics (2005); ** Bitan and Rubin (1994)

2. Study area and methodology

2.1 Study area

Eilat is located at the southern edge of the Arava Valley, on the northern coast of the Red Sea (latitude 29′33″N; longitude 34′57″E). The 175 km long valley, running from north to south, reaches a width of 6 km at Eilat. The mountain range to the west peaks at 900 meters and in the east – on the Jordanian side – the peak is as high as 1,300 meters. The city is situated in complex and varying topography, on the lower eastern mountain slopes of the western ridge, ranging from a height of 180 meters above sea level down to the Red Sea shore. The area of Eilat suffers from an extremely hot and dry climate (Table 1), the average annual precipitation is 32 mm, and on average there are about five rainy days. Due to the arid conditions, there is a significant difference between day and night and summer and winter temperatures.

The combination of the orographic relief with the local pressure systems affects the wind direction such that during the year the most frequent wind (about 80%) blows from the north. This frequency declines towards noontime, while the frequency of the north-easterly wind increases, with a peak around noon. The north-easterly winds are replaced at night by north-westerly winds, with a frequency of about 40%. The average wind velocity in summer is higher in daytime compared with night-time, and twice as high as in winter (Table 1); calm conditions are rare. In summary the high frequency and relatively high velocity of northerly winds limit the effect of the sea breezes (Bitan and Rubin, 1994; Saaroni et al., 2003).

The resort city of Eilat has grown rapidly in recent years, tripling its population since 1972, and by the end of 2002 there were 42,800 residents (Central Bureau of Statistics, 2005). The actual population is larger, it undulates according to the tourist season, and when the hotels are at full capacity, they provide accommodation for more than 25,000 tourists. Including staff and tourists in other types of accommodation, the total population can reach at least 80,000.

The land use pattern (Fig. 1) shows that the densely built hotel belt is concentrated along the northern and western coasts. Industrial areas stretch between the main highway and the old, low-density residential areas in the northern part of the city. The central business district (CBD), including the central bus station, is located on the lowest mountain slope, adjacent to the airport terminal. This CBD and the hotel belt experience the heaviest traffic flow. The new residential development area, especially in the southwest

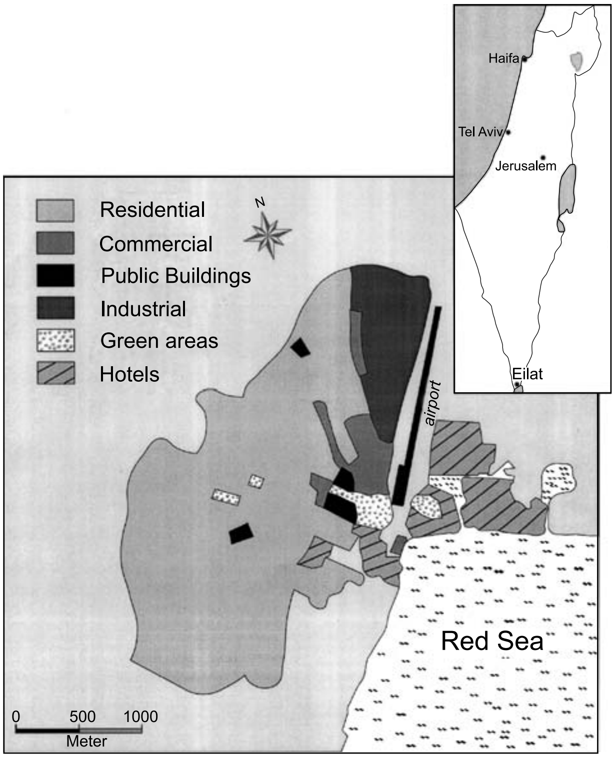

Fig. 1. Land use distribution in Eilat

part of the city, is located at an altitude between 80 and 180 meters above sea level and characterized by medium building density. The size of open green areas is limited.

The proportion of the total surface area that is built-up differs between neighbourhoods from 34% to 81%. Residential, commercial, and public buildings are most dense in the city centre, the neighbourhood near it, and the hotel belt. These neighbourhoods are also characterised by relatively dense road infrastructure, with about one-third of their area covered by roads and car parking lots. Obviously, open areas and parks account for a relatively small percentage of the space. Most of Eilat's built-up area is characterised by a high sky-view factor, even in the city centre, except for the hotel belt, where some of the buildings are over ten stories high.

2.2 Aims, tools and measurements

Operationally, three sets of questions were raised regarding the influence of the physical and anthropogenetic conditions on the UHI: (a) Where is the UHI located and what is the form of its spatial distribution? (b) What is its relative intensity according to time of day and season? and (c) What are the main factors that affect Eilat's UHI? We hypothesized that the UHI would be (a) located close to the main human intensive activities; (b) influenced by the topography and wind conditions; (c) stronger at night; and (d) more significant in summer than in winter.

The urban heat island discussed in this paper is a "canopy layer" heat island (Oke, 1987) measured at street level. Accurate measurements of temperatures for different hours of the day could not be obtained from either of the two local meteorological stations in Eilat; however, they provided important data on wind direction at the time of the observations. Since there are no meteorological stations outside Eilat, no comparative data of the open desert environment is available. Therefore, data collection was based on mobile instruments installed on vehicles moving simultaneously along predetermined routes. In each mobile traverse, three climatic elements – air temperature, relative humidity, and air pressure – were measured at the height of two meters and at a rate of once per second. Measurements of temperature and relative humidity were taken using an NTC-DT029 temperature sensor (accuracy $\pm 0.1\,^{\circ}$C) and a DT014 relative humidity sensor (accuracy $\pm 2\%$), with a response time of 15 s (at 20 °C, 90% response). The sensors were installed inside a Gill Multi-Plate 41002 aspirated radiation shield. Air pressure was measured using a DT015 absolute gas pressure sensor that measures applied external pressure relative to zero pressure reference sealed inside the sensor (range between 150 to 1150 hPa), with total accuracy of ± 15 hPa, a response time of 1 ms, and an operating temperature 0–85 °C. The data were gathered using Fourier MultiLog electronic data loggers. Before each experiment, all instruments (sensors and data loggers) were calibrated and compared in order to avoid reading errors and inaccuracy of measurements. Each reading was taken standing for 60 seconds at each measurement point, allowing the sensor to stabilize to permit a reliable reading. An entire traverse measurement survey took about 45 min.

The data were compared with that collected by the two fixed meteorological stations situated along the route (the Israeli Meteorological Service station located in the city park centre and at Eilat's airport station). Corrections were made in cases where the temperature differences

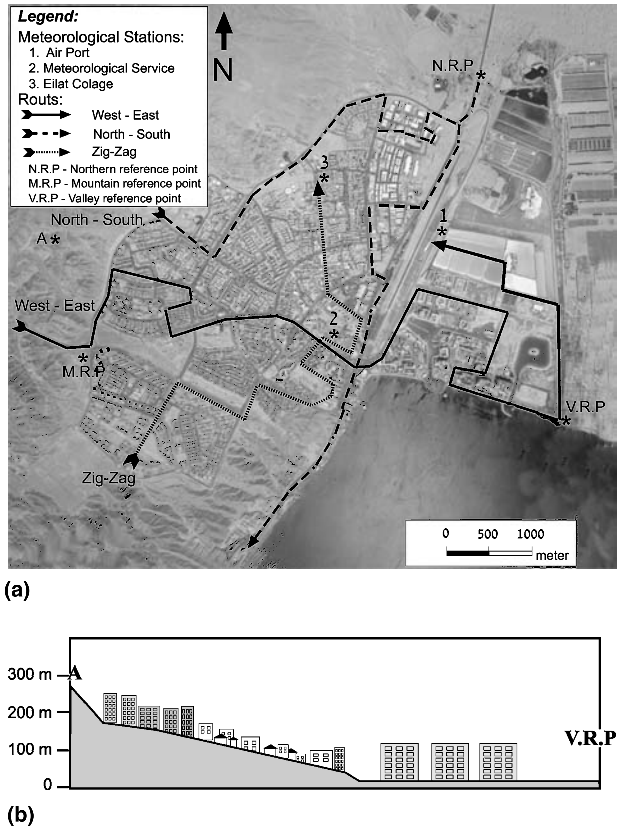

Fig. 2. (a) A map detailing the routes along which measurements were taken, fixed meteorological stations; (b) a schematic cross-section of the city along the line A–V.R.P

from starting point to final point were more than ±0.2 °C, according to temperature differences at the fixed station during the time of measurements.

Three routes covered the urban area, representing the varying topography, the disparity in the built-up density, and the distribution of land uses (Fig. 2).

1. West–east traverse: from the open area on the western slopes, at a height of 300 meters, through the built-up area, via the northern coast hotel belt, towards the open desert in the Arava valley, at an altitude of 5 meters above sea level. The two edge points are at similar distances from the edge of the built-up area, but the valley edge point is also close to the sea.
2. North–south traverse: from the western city boundary towards a point one kilometre north of the city, through the city centre, and along the coastline, to the open area south of the city boundary.
3. Crisscross traverse: a cross-section inside the various sections of the urban area.

Each traverse consisted of 15 measurement points. The 45 recorded entries were then plotted on a map, isotherms were interpolated from the data points to express the thermal surface of the city, at a height of two meters, and the spatial differences at the time of the survey. On each occasion, the measurements were taken twice a day; before dawn (starting at 05:00) and in early afternoon (starting at 14:00), when the solar radiation and air temperature are at their peak.

The experiments were conducted on three different occasions:

1. During the winter of 2001, in the period 11–13 February, characterized by stable weather conditions.
2. During the summer of 2001, in the period 6–8 August. The synoptic conditions were typical for the summer.
3. During the summer of 2002, in the period 6–8 August. The synoptic stable conditions were brought about by the strengthening of the subtropical high, leading to high temperatures and reduction in the wind velocity.

3. Results

3.1 General

The presentation of the results is concerned with two lines of inspection, along which temperature

Table 2. Temperature differences, wind velocity, and wind direction, during the period of measurement

Date	Time	ΔT_{u-r} °C	ΔT_{v-m} °C	Wind speed $m\,s^{-1}$	Wind direction* (degrees)
11.2.2001	13:00–14:00	1.0	1.2	2.0	360
12.2.2001	05:30–06:00	0.7	−0.2	2.5	12
12.2.2001	13:00–14:00	1.3	1.2	1.5	104
13.2.2001	05:30–06:00	0.3	−1.0	2.5	15
6.8.2001	05:00–05:30	0.6	1.1	1.5	360
6.8.2001	14:00–14:40	1.6	1.7	4.0	30
6.8.2001	21:00–21:40	1.2	0.6	3.0	330
7.8.2001	04:30–05:00	1.5	1.6	2.5	330
7.8.2001	14:00–14:40	1.4	1.4	4.5	30
7.8.2002	05:00–05:30	1.5	0.3	3.5	360
7.8.2002	14:00–14:40	1.4	1.4	3.5	20
8.8.2002	05:00–05:30	0.2	−2.2	1.0	50
8.8.2002	14:00–14:40	1.2	0.9	3.5	40

* Wind data from the local meteorological stations of the Israeli Meteorological Service

differences between two extreme points express the effect of the urban space or the topography on the temperature.

- ΔT_{v-m} expresses the effect of the topography, measured by the air temperature difference between the western boundary of the city, at an altitude of 200 meters, and the eastern boundary, in the Arava Valley, at an altitude of 5 meters above sea level.
- ΔT_{u-r} expresses the difference in air temperatures between the city centre and a point in the open desert environment located 700 meters north of the built-up area, at similar altitudes of 30 meters above sea level. This difference between urban and rural areas presents the effect of the urban area.

Table 2 presents all the recorded temperature differences, thus revealing the intensity of the urban heat island, recorded along both inspection lines, according to date, hour, and wind velocity and direction at the time of the measurement. Four of the thirteen events recorded, representing both winter and summer, are shown in Figs. 3 and 4. These figures display air temperatures,

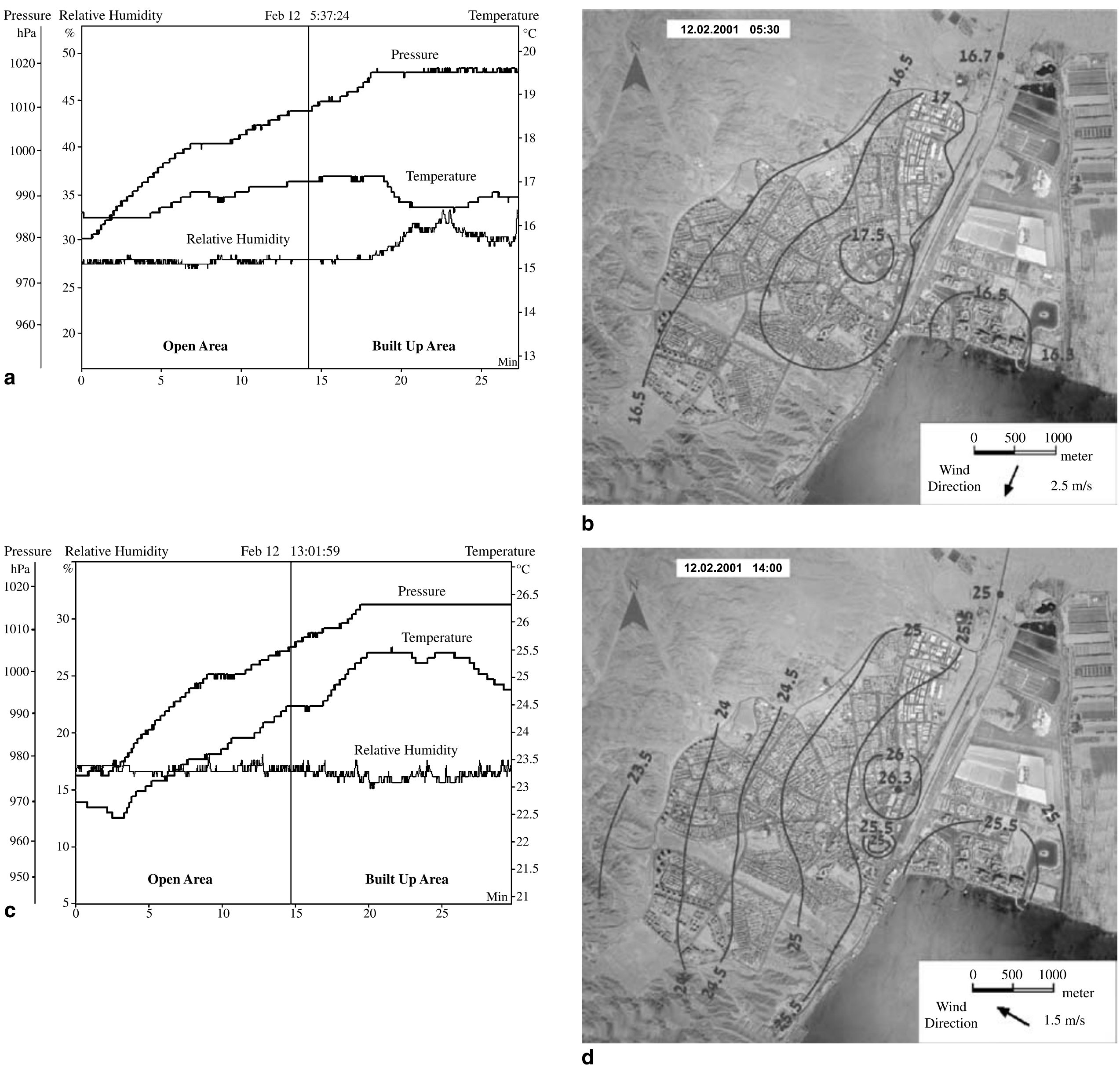

Fig. 3. The spatial distribution of air temperature, pressure, and humidity during winter days

relative humidity, and pressure values (which express the changes in the relief) recorded along the routes, thus allowing measurement of the edge values for each line of inspection. The initial assumption is that these figures present the typical state of weather for both seasons.

3.2 Winter season (Fig. 3)

- A heat island with an intensity of 0.3–0.7 °C was developed around and in the vicinity of the CBD in the early hours of the morning, peaking at a level of 1.0–1.3 °C by early afternoon. A secondary UHI was located in the hotel zone.
- In the early morning, along the west–east topo-climatic cross-section, a decrease in temperature was recorded (up to 1 °C) with the decline in altitude. In contrary, in the afternoon, the temperature increased (by 1.2 °C) with the decline in altitude.
- Temperatures in the urban park in the afternoon were 1 °C degree lower compared with the recorded temperature for the built environment.

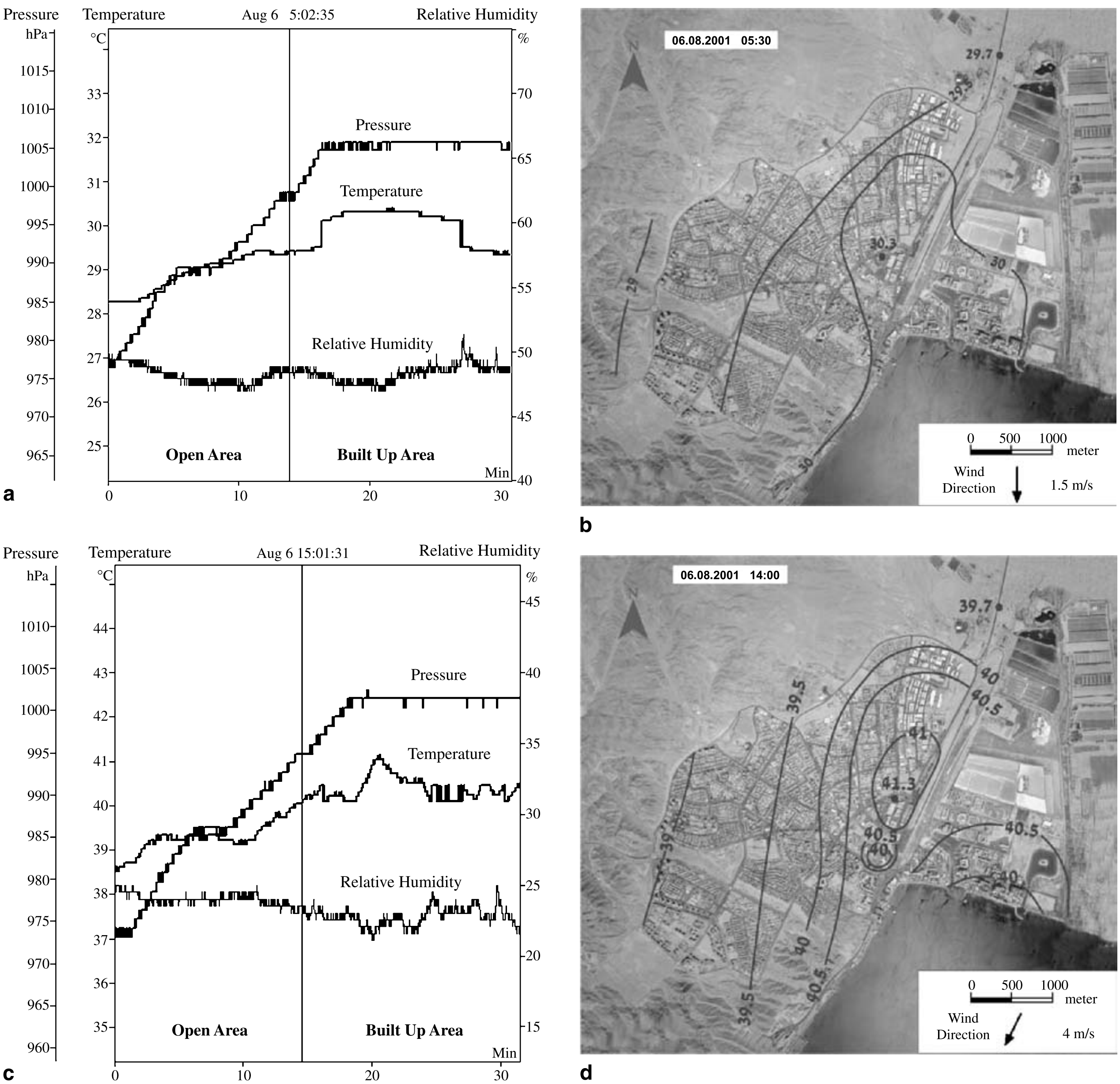

Fig. 4. The spatial distribution of air temperature, pressure, and humidity during summer days

- Although measurements of relative humidity show small spatial differences, ranging between 2% and 5%, there was an increase of $1\,g\,kg^{-1}$ in the absolute humidity with proximity to the sea.

3.3 Summer season (Fig. 4)

- A heat island with an intensity of 0.5–1.5 °C was developed around the vicinity of the CBD in the early hours of the morning. This UHI reached a level of 1.2–1.6 °C by early afternoon, with a minor spatial shift towards the industrial zone.
- In general in the early morning, along the east–west topo-climatic cross-section, an apparent increase in temperature was recorded (0.3–1.1 °C) with the decline in altitude. In contrast, in the afternoon, the temperature increased (by 0.9–1.7 °C) with the decline in altitude.
- On the northern shore, along the hotel belt, the recorded temperature was 1 °C lower compared with the open shoreline.
- In the afternoon, the temperature in the urban park was lower by up to 1.5 °C compared with the temperature in the built environment.
- Although measurements of relative humidity show small spatial differences, ranging between 2% and 5%, an increase in absolute humidity, by up to $2\,g\,kg^{-1}$, was recorded near the sea.

A summary of the main results, suggests that:

- Generally, for the same hours, the UHI intensity in the summer is higher than in the winter, and the UHI intensity is higher in the afternoon than before dawn.
- In the afternoon, there is a decrease in temperature with decline in altitude. This phenomenon is stronger in the summer compared with the winter period. The trend is opposite in the morning, under stable conditions, mainly in the winter period.
- The focal point of the UHI shifts with season and time of day.
- The effect of the sea on the intensity and location of the UHI is largely negligible.
- Times of stable conditions and cold air accumulation in the valley are characterized by slight temperature differences between the city centre and the non-urban space surrounding it, i.e. low intensity of the UHI.

4. Discussion and conclusions

The data demonstrate some important issues that are universal; however, there are others that are specific to the UHI of arid areas.

An important point is the link between the existence of stable conditions, relief, and UHI intensity. Both winter measurements indicate that the valley temperatures were lower than those for the mountains and the UHI intensity was below 0.7 °C. An extreme inversion was also recorded on one occasion in the summer, which led to a UHI value of 0.2 °C. It is therefore possible to argue, as others have before (Goldreich, 1984; Kuttler et al., 1996), that in cities located in valleys, the UHI intensity decreases as stability increases; this arises as a result of the accumulation of cold air in the valley, especially in the early morning hours. Nevertheless, and although the UHI intensity in Eilat is comparatively low contrary to the findings of former research, the intensity is higher in the daytime. This finding suggests that compared with earlier studies, which suggest the UHI is more significant under stable conditions on winter nights and in early mornings, in the case of Eilat, the UHI is more significant on summer afternoons.

These findings explain the linkage between wind velocity and UHI intensity, because it is known that with stronger winds, the UHI is weaker. The data for Eilat apparently show the opposite. Under stable conditions characterized by low wind velocity, the UHI intensity does not necessarily increase. Nevertheless, one may argue that the low UHI intensity is derived from the scarcity of "calm events" and influenced by the wind velocity (of 1.5–4.5 $m\,s^{-1}$) during the experiments. The relatively limited number of experiments, however, precludes a definitive conclusion.

Examination of the distribution of the relative humidity in the city shows that closer to the beach, the values increased or decreased by 2% to 5%. Since temperature differences for the similar cross-section increased in the range of 0.5 °C up to 1.7 °C, the calculations show that with proximity to the sea, absolute humidity values increased by up to $2\,g\,kg^{-1}$.

The data show that a small arid city such as Eilat can develop a relatively small UHI. Yet, this UHI is not insignificant in comparison with the UHI recorded for Kuwait City, a coastal

Middle East desert city much larger than Eilat. In this context, as shown for Eilat, research on urban climate in hot and arid zones should consider focussing special attention on the daytime in the summer season, particularly with respect to the influence of the UHI on heat stress. Moreover, the tendency in some studies, especially in temperate latitudes, to investigate the UHI during wintertime is not necessarily applicable in lower latitudes.

The number of observations used in this research is relatively small. This limits the possibility of proposing decisive conclusions. Our aim is to accumulate further data for a number of consecutive years, thus building a more complete body of knowledge on the UHI and its characteristics in Eilat. Nonetheless, the findings contribute to the present knowledge on UHI in arid zones and its implications for human discomfort. Such data may assist planning by identifying the climatically disadvantaged city zones.

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