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Human-biometeorological conditions and thermal perception in a Mediterranean coastal park

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Abstract This study looks at the interrelation of human-biometeorological conditions, physiological thermal stress and subjective thermal perception in the design and use of a new waterfront park in Tel-Aviv, Israel. Our initial assumption was that the park's design would embody a comprehensive response to the area's ever-increasing heat stress and water shortage. However, almost half of it is covered by grass lawns, irrigated with fresh water, while the remaining area is mainly covered with concrete paving, with minimal shading and sparse trees. We hypothesized that stressful thermal conditions would prevail in the park in the summer season and would be expressed in a high discomfort perception of its users. Thermo-physiological stress conditions in a typical summer month were compared with the subjective comfort perceptions of pedestrians surveyed in the park. It was found that even during mid-day hours, the level of thermal stress tends to be relatively mild, owing largely to the strong sea breeze and despite the high intensity of solar radiation. Moreover, it appears that the largely favorable perception of comfort among individuals may also result from socio-cultural aspects related to their satisfaction with the park's aesthetic attractiveness and in fact its very existence. Adaptive planning is proposed for such vulnerable regions, which are expected to experience further aggravation in thermal comfort due to global as well as localized warming trends.

Keywords Thermal comfort · Comfort perception · Heat stress · Index of Thermal Stress (ITS) · Sea breeze · Coastal park · Tel Aviv-Jaffa

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Introduction

Thermal comfort is a major issue in urban meteorology, combining physical aspects of environmental stress with subjective aspects of human sensation. The sensation of thermal comfort, and the extent to which it is determined by the energy balance of the body (Höppe 1993), is especially important in the inhabited open spaces of cities located in regions with stressful meteorological conditions. Jendritzky et al. (2012) suggest that the term "thermal environment" links the atmospheric heat exchanges with the body (stress) and the body's physiological response (strain). According to the standard of ASHRAE (2004), thermal comfort is defined as "the state of mind which expresses satisfaction with the thermal environment."

In order to assess human thermal comfort, various indices combining meteorological parameters with thermo-physiological parameters have been developed. Epstein and Moran (2006) listed about 40 such indices, ranging from simple measures based on the dry and wet bulb air temperature, such as the Heat Stress Index of Thom (1959), to complex energy balance models which account for the various mechanisms of heat exchange between the body and the environment, such as the Physiologically Equivalent Temperature Index (Mayer and Höppe 1987). A central determinant of the PET and similar indices is the mean radiant temperature (T_{mrt}), which is intended to encapsulate the

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thermal effects of radiation emitted by the sun and the surrounding environment.

In outdoor, as opposed to indoor, environments, radiation fluxes often dominate the energy balance of the body—especially solar radiation under clear daytime conditions (Mayer et al. 2008; Lee et al. 2013). Rather than expressing these radiant energy fluxes as an "equivalent" temperature, they may be calculated directly as flux density values, in watts per square meter. In this way, they may be quantified in the same units as heat exchange by convection, which is a function of the speed at which air flows across the body and the temperature difference between the two. One thermal index that is based on a direct energy balance of this sort is the Index of Thermal Stress (ITS), which expresses the equivalent latent heat of sweat evaporation required for the body to maintain thermal equilibrium under warm environmental conditions. This index incorporates a direct calculation of all components of the energy balance, including short- and long-wave radiation, convection and metabolic heat production (in watts for the whole body surface). An important physiological aspect of the model is the recognition that not all sweat evaporates, and thus a sweat efficiency factor is included to express the limitation imposed on evaporative cooling of the body due to humidity. The ITS model has been found to reliably predict subjective thermal sensation in open spaces with rapidly changing and substantially stressful conditions (Pearlmutter et al. 2014) and is adopted as a central metric in this study. The computational methodology, as developed for outdoor spaces, is described in further detail in "Database and analysis".

The subjective perception of human thermal comfort has typically been gauged through questionnaires (Thorsson et al. 2007; Lin 2009; Krüger and Rossi 2011; Cheng et al. 2012; Yin et al. 2012; Pantavou et al. 2013), which are often used in conjunction with measurements of local micro-meteorological conditions. Pearlmutter et al. (2014) showed the validity of this correlation for ITS under outdoor conditions (R^2=0.57) in a hot and dry region, but the slope of the regression line was found to be shallower than for previously evaluated indoor conditions, indicating that pedestrians in open spaces may have greater tolerance for thermal variations.

Andrade et al. (2011) studied the relationship between thermal comfort perception and weather conditions in two open leisure areas of Lisbon, Portugal, and found that the preference for a different air temperature is strongly associated with wind speed and that most people preferred lower wind speeds in all seasons. They also indicated a higher tolerance for warmer conditions than for cooler ones.

Lin et al. (2011) argue that thermal perception of individuals in outdoor conditions is strongly affected by psychological and behavioral factors and thus cannot be entirely explained by the human energy balance. They examined the effect of these factors, defined as thermal adaptation, on thermal comfort in central Taiwan through interviews and concurrent micrometeorological measurements. Their results indicated that thermal perceptions were strongly related to variations in air temperature and mean radiant temperature (T_{mrt}), but not significantly to wind speed or humidity, although the climate of Taiwan during summer is consistently humid. Different results were obtained by Yin et al. (2012) for the subtropical monsoon climate city of Nanjing (China) during summer. Using a survey of 205 students, they found solar radiation to be the most important determinant, followed by atmospheric pressure, maximum air temperature, wind speed and RH. Knez and Thorsson (2006, 2008) and Knez et al. (2009) found that different populations may vary in their psychological evaluation of a given thermal environment even when physical conditions are similar. These factors are subjective variables which people bring to the space (Nikolopoulou et al. 2001).

Nevertheless, the use of urban parks in regions suffering from heat stress conditions is highly dependent on the thermal comfort. Studies have shown that parks are "cool islands" within the urban environment (e.g. Chang et al. 2007; Bowler et al. 2010) including under summer sultry conditions in coastal Mediterranean climates (e.g. Saaroni et al. 2000; Potchter et al. 2006; Zoulia et al. 2009). The importance of land use for thermal comfort is further indicated, for example, by Potchter et al. (2006) and Cohen et al. (2012, 2013), who showed for Tel Aviv that lawn areas have a minimal cooling effect compared to trees or other vegetation. The wind and especially sea breeze also have a dominant effect on thermal comfort, especially during daytime, as exemplified by Papanastasiou et al. (2010) for the coast of a Greek city, by Lopes et al. (2011) for Madeira, by Johansson and Emmanuel (2006) for Colombo, Sri Lanka, and by Saaroni et al. (2004) for the hyper-arid city of Eilat, Israel.

As indicated by Chiesura (2004), urban nature and parks make an important contribution to the broader well-being of urban inhabitants and to the sustainability of the city, not least because of their potential for microclimatic stabilization and reduction of stress. In cities of the Eastern Mediterranean (EM) region, this focus on outdoor human comfort takes on special significance. This is firstly due to the persistency of discomfort conditions for much of the year, with high levels of heat stress prevalent along the coastal plain of Israel for at least 3 months in the summer season. It is additionally significant in light of the intensive trend toward warming and aggravation of heat stress which the region has been undergoing over the last several decades, which is forecast to continue in the future. The persistence of thermal stress in summer is well expressed by the minimal inter-diurnal variation of only 2.8 °C at the 850-hPa level (Ziv et al. 2004; Saaroni et al. 2010) and intra-diurnal variation of only 5.6 °C at the coastal station of Tel Aviv (Israel Meteorological Service 2013). Typical summer midday hours in Tel Aviv-Jaffa are characterized by air temperatures of 30 °C and 70 % RH (water vapor pressure of

29.7 hPa), whereas the minimum (nighttime) average is 24.6 °C with ~80 % RH (water vapor pressure of 24.8 hPa)—such that conditions defined as heat stress may prevail over the entire daily cycle, including night time (Ziv and Saaroni 2011; Israel Meteorological Service 2013).

The persistency of heat stress in summer over the EM results from the permanent upper-level subsidence of the subtropical high that is combined with relatively cool and moist advection in the lower levels due to the onshore seasonal Etesian winds associated with the sea breeze circulation (Ziv et al. 2004; Harpaz et al. 2014). The discomfort conditions are further aggravated due to the significant regional warming over the last several decades, being larger than the global rate (Ziv et al. 2005; Shohami et al. 2011). Climate models for the twenty-first century forecast further intense warming over the EM (Meehl and Tebaldi 2004; Intergovernmental Panel on Climate Change IPCC (2013) together with a significant decrease in precipitation, which is predicted for the entire MB including the EM and Israel (Krichak et al. 2011; Intergovernmental Panel on Climate Change IPCC (2013). These trends, including prolonging dry spells within the rainy season, have severe implications for human comfort, energy consumption and water availability (e.g. Ziv et al. 2014; Saaroni et al. 2014).

Beyond the global and regional warming trends, urban areas are subjected to higher temperatures due to the Urban Heat Island (UHI) effect. Although most pronounced during nighttime, elevated temperatures have been observed in urban areas during daytime hours as well. McCarthy et al. (2010), based on global climate models, indicate future aggravation of the daily maximum temperature imparted by the UHI, although by a smaller magnitude then for minimum temperatures. The UHI has been well documented in Tel Aviv during both daytime and nighttime hours, indicating higher temperatures within the city (Ben-Dor and Saaroni 1997; Saaroni et al. 2000). Saaroni and Ziv (2010) developed a method to estimate the long-term contribution of the net UHI beyond that of the regional or global warming. They showed, for an arid city in Israel, that the net UHI contribution varied between + 0.8 and +3.1 °C (for the period 1967–2004), with the highest values during the night hours.

Summer heat stress at a particular location in the city may also be influenced by the immediate surroundings due to micro-scale urban effects on air flow and radiation balance as well as air temperature and humidity (Pearlmutter et al. 2007)—and these effects highlight the significance of parks and other heavily vegetated open spaces. In this study, a recently constructed coastal park at the edge of a dense neighbourhood serves as a laboratory for investigating the human-biometeorological effects and for comparing the physical conditions prevailing in this unique park with the perception of these conditions by its users. The aims of the study are as follows:

- To analyze the meteorological and human-biometeorological conditions of a coastal Mediterranean park under typical summer conditions and to assess the severity of thermal stress within the park compared to those within the adjacent built-up area
- To quantitatively estimate the micro-scale effects of vegetated and paved areas of the park on ground surface temperatures and overall thermal stress
- To examine the correlation between human-biometeorological conditions and human thermal perception, within the context of a landscaped urban area that provides a range of amenities in addition to potential modification of the sultry conditions along the Mediterranean coast

Methodology

Study area

Jaffa Slope Park, which served until 2004 as a construction debris waste site, was transformed into a park in 2010. The park is bounded by Jaffa port in the north, the Aliya Hill beach in the south, and the residential neighbourhood of Ajami in the east (Figs. 1 and 2). The park's design (Fig. 2) consists of three major man-made hills covered with grass lawns and a light-colored concrete paved plaza along the seafront. The grass lawns cover about 20 acres of the total 50-acre area of the park. This expanse has only a small number of scattered trees with minimal canopy and is mostly exposed to direct solar radiation and the sea breeze. The trees (see Fig. 2) planted on the hills of the park include *Tamarix* (maximum radius of 2 m and height of 2–12 m), *Morus* (maximum radius of 3 m and height of ~6 m) and *Albizia* (maximum radius of 2 m and height of ~6 m). Along the main entrances to the park, *Washingtonia* trees (maximum radius of 1.5 m and height of 12–15 m) are planted. None of these trees provide substantial shade or play a major role in the landscape of the park. The remaining area includes bike/walking paths, a playground with exercise facilities and a small amphitheater. Three main paved pedestrian axes traverse the grassy area, from the neighbourhood down to the plaza (see Figs. 1b, d and 2).

The park's development represents a progressive approach in terms of public involvement as the planners led a comprehensive public participation process facilitating exposure to and discussion with a variety of stakeholder groups, including local residents from different cultural backgrounds, over the design of the park. The process included ten meetings with a total of 300 participants (in all meetings) who were informed regarding the park's plan and intended uses, and the feedback was used in the development of the design and its implementation.

Fig. 1 The location (**a**) and the landscape of the Jaffa Slope Park: the concrete plaza (**b**), the lawn from a viewpoint to the west (**c**), and the lawn from a viewpoint to the southeast (**d**)

The major features of the park are the exposed grass lawns and paved surfaces. The rationale for this approach was explained by the planners in terms of the desires of local residents who asked for large lawn and open areas that would be an inviting hub of activity for the neighbourhood and its surroundings. The minimal shrubs and trees in the park ostensibly result from the meteorological and ecological conditions near the sea, as well as from security considerations. (The latter was brought up mainly by local Arab women, who asked that the park landscape remain rather exposed without any hiding places or heavy shrubbery, which could form hidden spots where misconduct is more likely to take place.)

Construction of the park included the recycling of 1.275 tons of waste, with 200,000 m^3 re-used on site. Most of the activities in the park take place in two main areas: the grass lawns, especially at the foot of the hills, and the paved concrete plaza and paths along the waterfront. It should be noted that the nearest buildings are several tens of meters downwind of the park, and in this sense it is atypical of an urban park.

Database and analysis

Data from meteorological measurements and occupant questionnaires were collected between June 30, 2011 and July 22, 2011, a period that can be defined as typical of the summer season. Meteorological data (10-min averages of air temperature, RH, wind speed and upper wind gusts) were taken from the coastal station of the Israel Meteorological Service located on the southern coast of Tel Aviv, about 2 km north of the park (location designated in Fig. 1a), with instruments mounted on a roof mast at a height of 20 m above sea level, which is approximately equal to the hilltop location in the park. Wind speed at head height (2 m) was estimated using an attenuation factor (Pearlmutter et al. 2007) based on the logarithmic vertical wind profile over open ground.

Both the station and the park are open to the sea and have similar elevation and surrounding characteristics. Measurements taken at the park over a typical daily summer cycle were compared with simultaneous measurements at the meteorological station used for the main analysis. This comparison confirmed the high similarity between the meteorological station and the park (average of grassy hill, flat lawn and concrete plaza locations) in terms of ambient air temperature, with an average deviation of 0.2 °C, a maximum deviation of 0.7 °C in late afternoon and R^2 of 0.91. Relative humidity values at the meteorological station were within 5 % of all park locations at all hours, and wind speed and direction were highly comparable as well.

Hourly global radiation data were taken from the Bet Dagan meteorological station located approximately 8 km eastward. Due to the absence of clouds in the summer season, this station closely represents the radiation conditions at the park. Ground surface temperature, both for the grass area and the paved concrete plaza within the park, was estimated from

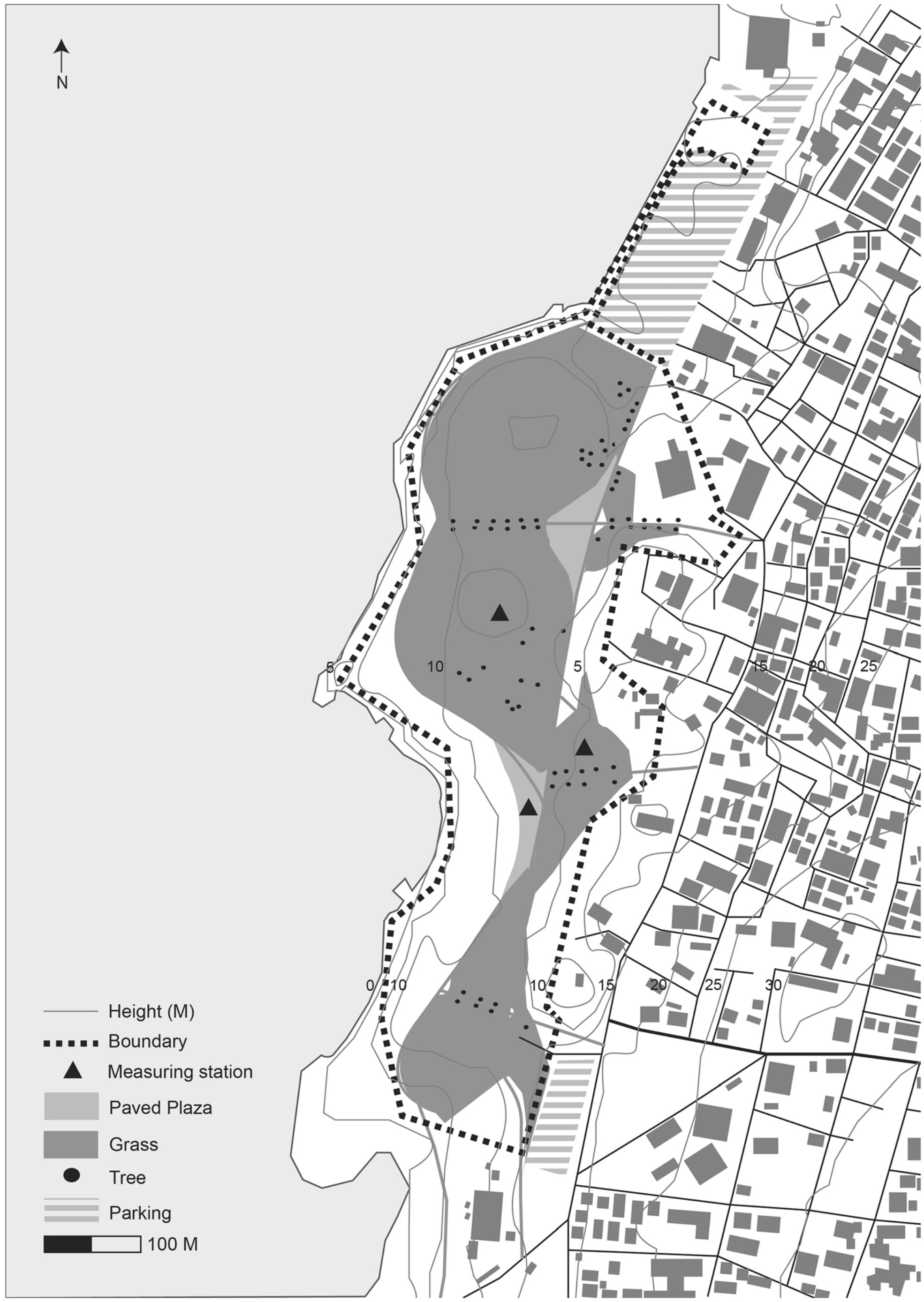


Fig. 2 Map of the Jaffa Slope Park and neighbouring buildings

ambient air temperature and absorbed solar radiation using empirical functions derived from intensive on-site measurements taken in the park over the course of a typical summer day (see "Estimation of ground surface temperature").

Based on measured meteorological data, the Index of Thermal Stress (ITS) was computed according to the method of Pearlmutter et al. (2007):

$$\mathrm{ITS} = [R_\mathrm{n} + C + (M - W)]/f \tag{1}$$

in which R_n and C are the energy exchanges due to net radiation and convection, respectively, between the human body and the environment, $M-W$ is the net heat production due to internal metabolism and f is the sweat efficiency factor (expressing the extent to which cooling of the body by sweat evaporation is limited by the water vapor content of the air). As seen in Fig. 3, the exchange of energy through radiation and convection is calculated in W m^{-2} of body surface for a rotationally symmetrical person standing upright in the given space (Pearlmutter et al. 1999, 2006).

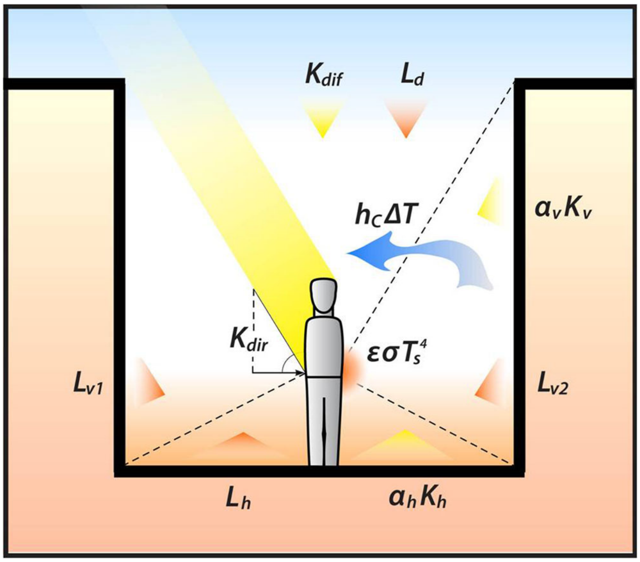


Fig. 3 Schematic depiction of pedestrian-environment energy exchanges for calculation of the Index of Thermal Stress. Radiation includes short-wave components which are direct (K_{dir}), diffuse (K_{dif}) and reflected from vertical (a_vK_v) and horizontal (a_hK_h) surfaces and long-wave components which are emitted by the sky (L_d), vertical walls (L_v), and horizontal (L_h) surfaces. Convective exchange is a function of a wind-dependent heat transfer coefficient (h_C) and the body-air temperature difference (ΔT)

The net radiation R_n consists of short-wave components which are received as direct radiation from the sun (K_{dir}), diffuse from the sky (K_{dif}) and reflected from horizontal ground (K_h) and, if present, vertical surfaces (K_v) as well as long-wave radiation which is absorbed from the sky and other downward-radiating elements (L_d) and from horizontal ground surfaces (L_h) and vertical wall surfaces (L_v) and emitted by the body to the environment (L_s):

$$R_n = (K_{dir} + K_{dif} + K_h + K_v)(1-\alpha_s) + L_d + L_h + L_v - L_s \quad (2)$$

The absorption of short-wave radiation is based on the measured intensity of incoming global radiation, incidence angles for direct radiation, angular view factors for indirect (diffuse from the sky and reflected from the ground) radiation and the measured albedo of surrounding surfaces and of the body itself (α_s). Long-wave absorption from these surrounding surfaces is calculated on the basis of view factors, empirically estimated surface temperatures and emissivity values for the relevant materials, while emission from the body is based on a constant skin-clothing temperature of 35 °C. The emission of downward long-wave emission from the sky dome is calculated from clear-sky emissivity (as estimated from air temperature and water vapor content) and sky view factors. Each long-wave flux L (W m^{-2}) is computed as $L=\sigma\varepsilon T^4$ where σ is the Stefan–Boltzmann constant, ε is the emissivity of the emitting body and T is its temperature in Kelvin. A detailed description of the calculation of individual radiation components is given by Pearlmutter et al. (2006).

Energy exchange by convection C is calculated by:

$$C = h_c(T_s - T_a) \quad (3)$$

where T_s-T_a is the difference in temperature between the skin and the surrounding air, and the heat transfer coefficient h_c is a function of measured wind speed V_a:

$$h_c = 8.3{V_a}^{0.6} \quad (4)$$

To calculate the overall energy balance, radiative and convective flux densities in W m^{-2} are multiplied by the DuBois body surface area to yield fluxes in watts, to which is added the body's net metabolic heat production. The sweat efficiency f is calculated from an empirical relation based on the vapor pressure of the surrounding air (as well as wind speed and a clothing coefficient), as detailed by Pearlmutter et al. (2007).

The value of ITS was calculated for each point in time and space that a comfort vote was cast by a person at the site. For this purpose, a total of 300 questionnaires were administered among the users of the park (as described below). Due to the high sensitivity of the residents and users in this area to personal questions, the survey query had to be concise and was therefore limited to four questions. Two of these questions concerned the comfort perceptions of the users, the first gauging their *personal feeling* on a 7-point scale (very cold = 1, cold = 2, cool = 3, comfortable = 4, warm = 5, hot = 6, and very hot = 7). The second question inquired as to their comfort *preference* at that moment, asking whether they would prefer cooler conditions, no change (i.e. they feel satisfied) or warmer conditions. Another question referred to the users' aesthetic evaluation of the park (grading its attractiveness on a 5-point scale from most to least beautiful), and finally respondents were asked to name and grade the most attractive sections of the park (e.g. the grassy hills, the lower lawn areas, the paved plaza, the sea, the playground, etc.). No additional information about the individuals, such as age, ethnicity, gender, and occupation, was solicited. All respondents were stationary while answering the query and standing in areas fully exposed to the sky, thereby controlling for activity and location. Although the park is located adjacent to a predominantly Arab neighbourhood, women wearing traditional long-sleeved clothing represented a small portion of the users (<10 % of the questionnaire responses). Visitors in the park, including local men and children, were generally wearing light summer clothes with short sleeves at the time of the interview.

The questioning was done during three time periods of the day, with 100 questionnaires administered in each period: mid-day (13:00-15:00 LST; the warmest hours), late afternoon before sunset (17:00-19:00 LST) and evening, after dark (20:00-22:00 LST). These periods represent the main times of activity in the park, and each was expected to exhibit different comfort conditions. For each time period, the 100 questionnaires were evenly divided between the two main areas characterizing the park and where most activities take place: 50 questionnaires were administrated at the paved concrete plaza and path near the waterfront and the other 50 in the exposed lawns next to the paved concrete plaza.

A least-squares regression analysis (using Pearson's correlation coefficient for evaluating the statistical significance) was performed to test the correlation between the ITS and the simultaneous thermal sensation responses.

Results

Estimation of ground surface temperature

An important component in the calculation of ITS is long-wave radiation emitted from solid surfaces surrounding a pedestrian as a function of their radiant surface temperature T_s (°C). The thermal comfort survey was conducted in open areas of the park, with respondents standing either in the paved concrete plaza or in the grass lawn areas, such that the temperature of these surfaces must be provided as input for the calculation of ITS. In lieu of direct measurements at the time of the interviews, T_s was estimated from ambient conditions, using an adaptation of the "sol-air" temperature model (Ulgen 2002) as:

$$T_s = T_a + \left(\frac{I \times \alpha}{h_c}\right) - E \quad (5)$$

where T_a is ambient air temperature (°C), I is the flux density of incident short-wave radiation (W m^{-2}), α is the material's solar absorbtivity (i.e. the compliment of its surface albedo) and h_c is a convective heat transfer coefficient (W m^{-2} K^{-1}). In the case of grass, an evapotranspiration component E is included to account for evaporative cooling (quantified as a temperature depression, in °C) of the vegetated surface.

While air temperature and global radiation could be obtained for the survey period from a nearby meteorological station, the albedo of the two types of ground cover could only be roughly approximated from on-site observation. Further, while the value of h_c has been quantified in a number of empirical studies (often as a function of wind speed), it is highly sensitive to local conditions—and the value of E is essentially an unknown. Therefore, an intensive on-site measurement campaign was performed in order to provide data which could be used to estimate these unknown parameters.

Over the course of a representative summer day (26.6.2013), on-site measurements were made of air temperature and wind speed at screen height (2–2.5 m), and for the quantification of surface albedo, identical upward- and downward-facing pyranometers (Kipp & Zonnen) were used to measure global and reflected radiation above both the concrete paving and grassy areas. The surface temperature of each of these ground cover types was measured hourly using a FLIR B350 thermal imager and a handheld radiometer, with results from two locations in the park compared and averaged to derive representative values.

The average albedo obtained for the concrete paving was 0.42, and the value for grass was 0.26, with both values found to be fairly constant over the mid-day hours. This contrast in measured albedo reflects the visually apparent difference between the relatively smooth, bright concrete and the rough, dark green lawn (which was irrigated in the early morning and essentially dry by the time of measurements). Using Eq. (5) and measured data, a value of 25.5 W m^{-2} K^{-1} was derived for the heat transfer coefficient h_c over the paved area, and for the grass area, a coefficient of h_c=50.5 W m^{-2} K^{-1} was derived together with an evaporative cooling factor of E=3.4 °C.

These values of h_c reflect the high aerodynamic roughness of the grass as compared to the smooth concrete, and they are given as constants rather than as a function of simultaneously measured wind speed because the optimal statistical fit was achieved with a wind speed of zero.

Comparisons between measured and modeled surface temperature using these values indicate that while the model provides a close correspondence, it does not capture the time lag between net short-wave radiation and the surface-air temperature differential which results from the thermal inertia of the surface. These time lags can be seen in both the time series and scatter plots shown in Fig. 4, with the latter taking the characteristic form of a "hysteresis loop" (Camuffo and Bernardi 1982; Grimmond et al. 1991; Pearlmutter et al. 2005). For the concrete surface, whose heat capacity is especially high, a time lag of 1.5 h was found when deriving the best fit for these data, and for the grass, a similar but smaller time lag of 0.5 h was found. Correcting the data for this time lag results in an extremely high correlation between measured and modeled values (as seen in Figs. 5 and 6 for concrete and grass, respectively)—and this corrected function was used to estimate surface temperature for the calculation of ITS.

A further comparison between the concrete and grass surfaces may be given in terms of the mean radiant temperature (T_{mrt}) as calculated from the point of view of a standing pedestrian surrounded by either of the two types of terrain. T_{mrt} is computed (in °C) as:

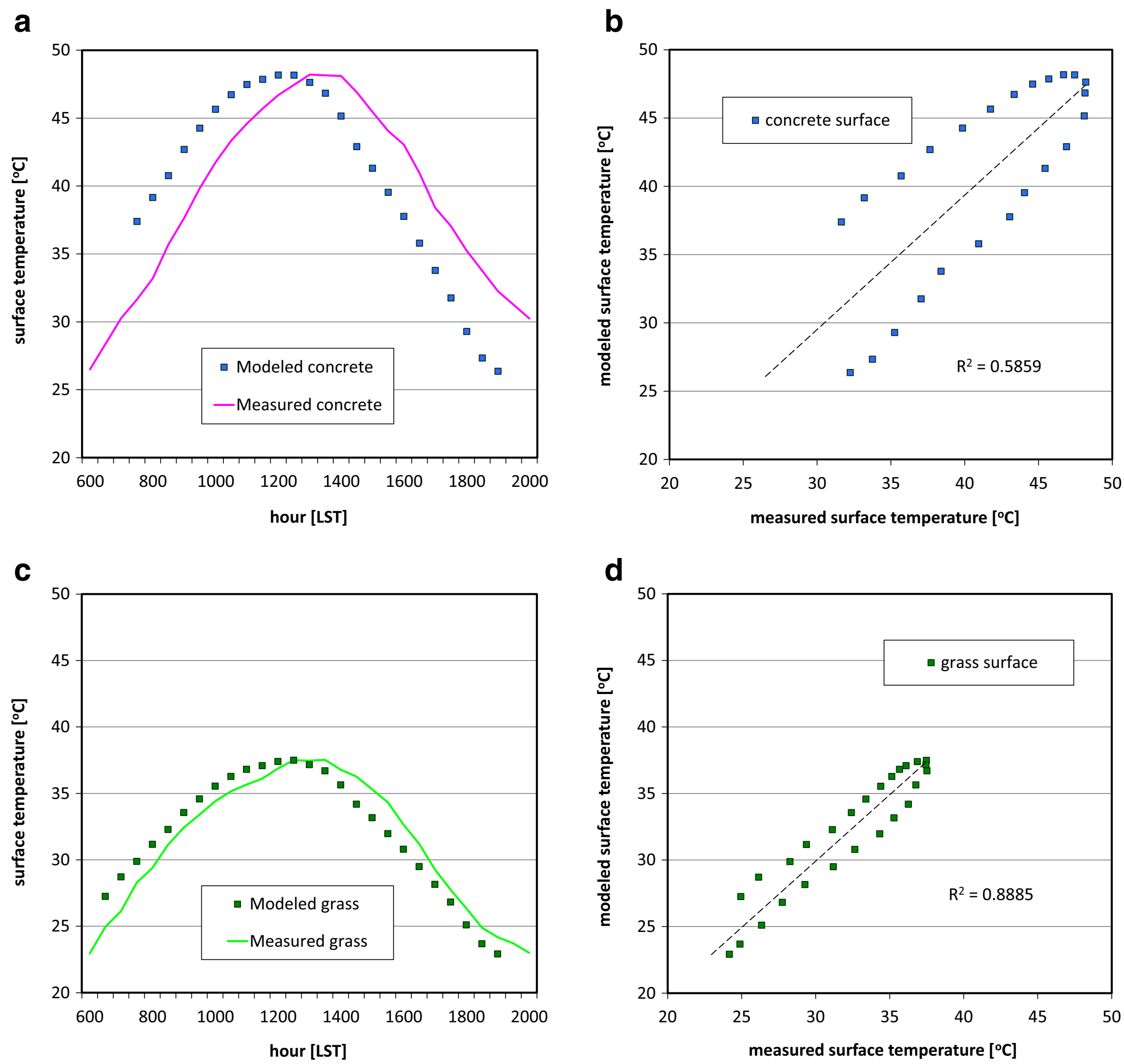


Fig. 4 Comparison of measured and modeled surface temperature over daytime hours without correction for time lag for the grass-covered area and concrete paving as hourly time series (**a** and **c**, respectively) and as scatter plots showing regressions between the two variables (**b** and **d**, respectively). Note the hysteresis *loop* in the uncorrected scatter plots

$$T_{mrt} = \sqrt[4]{\frac{R_{abs}}{\sigma\varepsilon}} - 273 \quad (6)$$

where R_{abs} is the total flux density of radiation absorbed by the body (in W m^{-2} of body surface), with short- and long-wave component fluxes calculated as described in “Database and analysis” above, for the calculation of ITS (see Eq. 2).

It can be seen in Fig. 7 that T_{mrt} is higher for concrete than for grass during all summer daytime hours, with the difference between them reaching a mid-day peak of about 10 °C. Values for concrete during these hours range from 56 °C to nearly 70 °C, and for grass they are in the range of 50–60 °C. It should be emphasized that compared to air temperature, T_{mrt} tends to vary sharply over short spans of time and space—as its value is highly sensitive to small fluctuations in environmental conditions, such as the proportions of direct and diffuse solar radiation at low sun angles in the early morning or late afternoon (Lindberg et al. 2014). Absolute values of T_{mrt} are especially sensitive to minor variations in the estimated values of thermal properties such as environmental emissivity—with an incremental change of 0.1 in ε resulting in a difference of approximately 10 °C in calculated T_{mrt}.

Weather and thermal comfort conditions

Weather conditions during the study period (July 2011) were typical for the summer season in Tel Aviv. The average noontime global radiation (at the Israel Meteorological Service station) was 957 (±24) W m^{-2}, with generally clear skies attributed to the persistent upper-level subsidence of the subtropical high (Ziv et al. 2004). Figure 8a shows that a daily air temperature range of 24–28 °C, together with relative

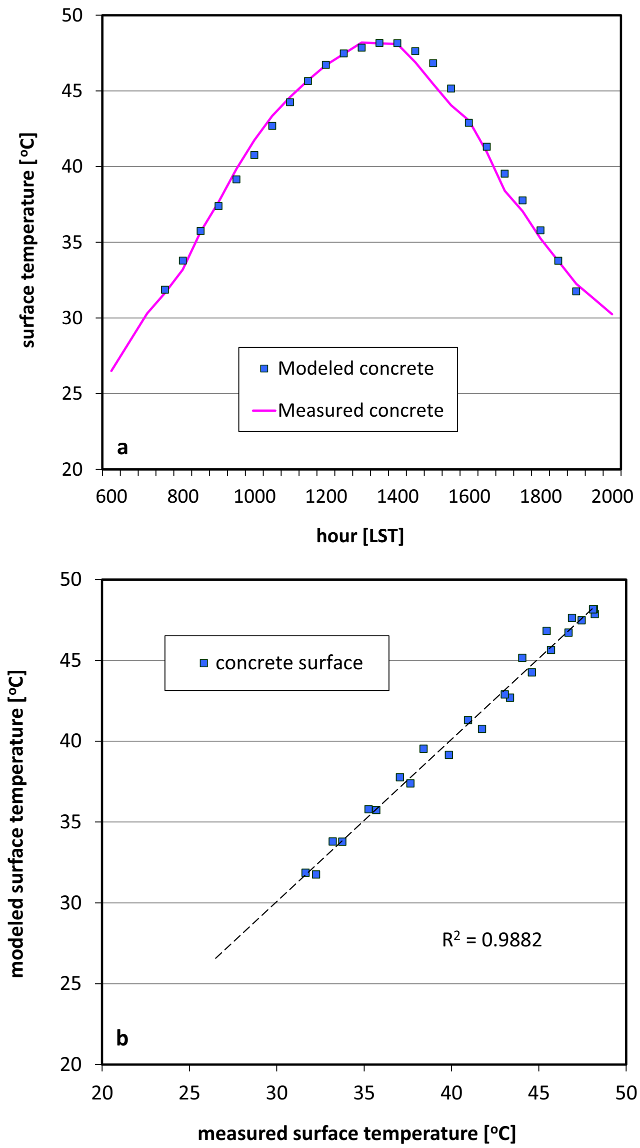


Fig. 5 Comparison of measured and modeled surface temperature over daytime hours for concrete paving as an hourly time series (**a**) and as a scatter plot showing the linear regression between the two variables (**b**). Modeled values are corrected for time lag

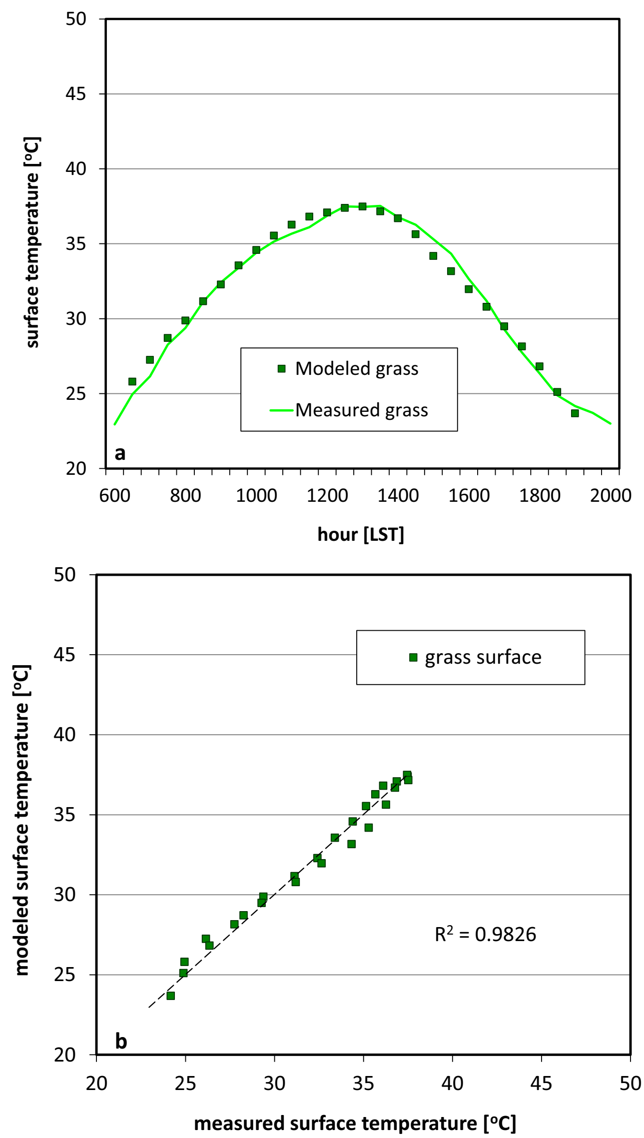


Fig. 6 Comparison of measured and modeled surface temperature over daytime hours for the grass-covered area as an hourly time series (**a**) and as a scatter plot showing the linear regression between the two variables (**b**). Modeled values are corrected for time lag

humidity of 72–79 % and water vapor pressure of 23.5–27.5 hPa persisted throughout the average daily cycle during the study period. It should be noted that the minimum air temperature was above 23 °C on all nights. This is above the threshold defined for heat waves by Meehl and Tebaldi (2004), who pointed out the importance of referring to the minimum temperature and not only to the maximum temperature when considering heat waves and discomfort conditions, which make a significant contribution to the increase in energy consumption in cities. The breeze circulation is stable, with a dominant sea breeze during daytime hours producing an average speed of 2.5–5 m/s and a consistent flow direction from the west (Fig. 8b).

In order to highlight the localized influence of micrometeorological factors such as the sea breeze near the coast, we compared the weather and comfort conditions in the park area with street-level measurements taken within the city of Tel Aviv during the study period. The city station is placed in a street-oriented west–east, at a height of 12 m above sea level, perpendicular to the sea which is 1.8 km to the west. The height of the air temperature and RH sensors is 4 m above the ground. This is a typical urban street with a width of 14 m between the facades of adjacent buildings, whose average height is approximately 15 m (i.e. an aspect ratio near unity). Figure 9a presents air temperature at 14:00 and 20:00 LST in these two locations, indicating the higher air temperature in the midst of the city than at the seashore both in the daytime

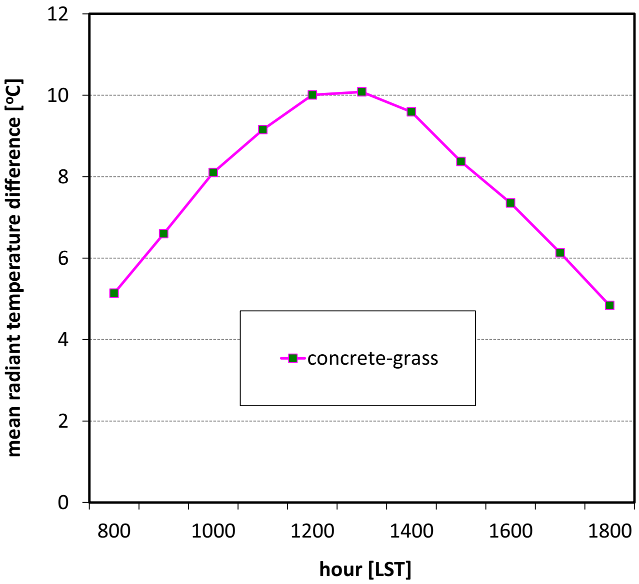
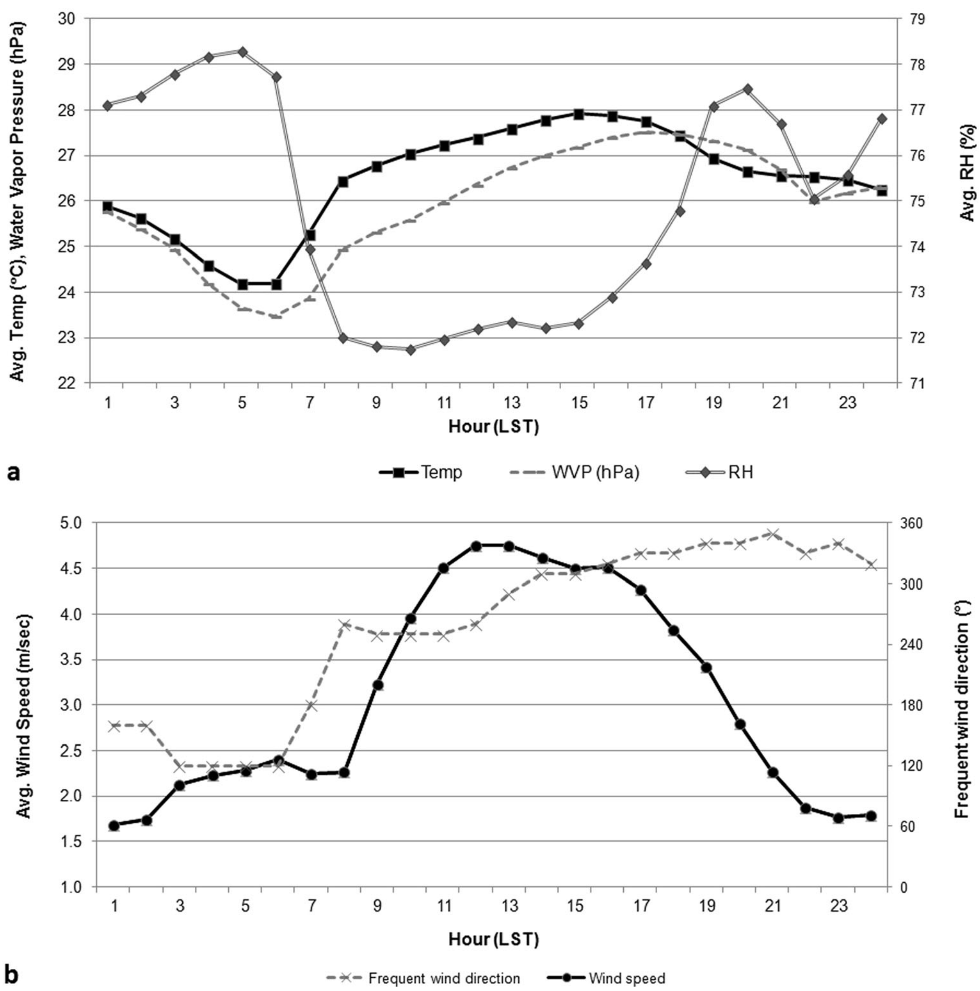


Fig. 7 Hourly daytime differences in mean radiant temperature between the concrete plaza and the grass lawn as computed from the point of view of a pedestrian standing above each surface on the basis of measured summer data

and evening hours. These results express the combined effects of the mid-city location's greater distance from the sea and other factors supporting the UHI—which, as mentioned previously, has been shown to exist in Tel Aviv not only as a nocturnal phenomenon, but also during daytime (e.g. Saaroni et al. 2000). Note that even in the evening hours, when inland regions are cooling faster than the coast (which is located beside the warm sea, with its average sea surface water temperature of 30 °C), the city still experiences a higher air temperature than the coast, which can be attributed to UHI effects. The weather and thermal comfort conditions during the specific times that the questionnaires were administered are summarized in Table 1. The results of thermal stress calculations using the ITS model (see Tables 1 and 2) show significantly large differences between the mid-day, late afternoon and evening hours, attributed to the dominant effect of solar radiation and wind speed. The effect of the wind speed on reducing heat stress is further pronounced when using the upper wind gust rather than the 10-min average (Table 1).

Figure 9b presents the ITS results for the park area in comparison to the city (street level) at 14:00, 17:00 and 20:00 LST. The wind speed at street level was estimated from

Fig. 8 Hourly average air temperature (°C), relative humidity (%), and water vapor pressure (WVP, hPa) (**a**) and wind speed and frequent wind direction (**b**) over the study period at the meteorological station representing the Jaffa Slope Park



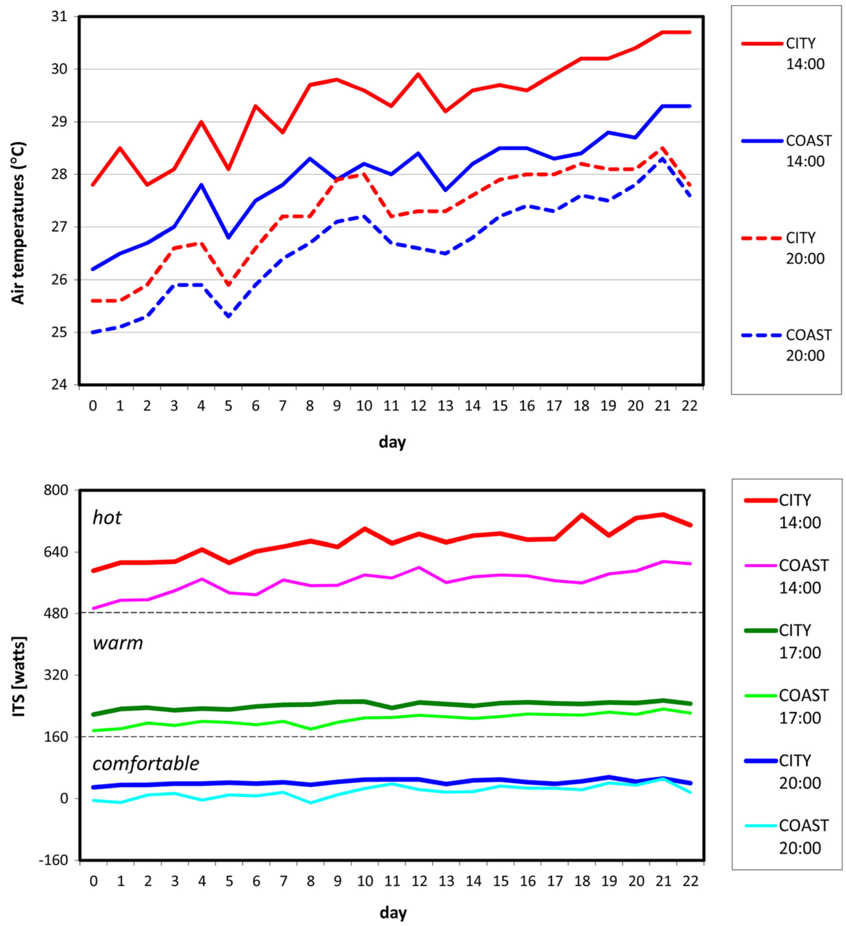


Fig. 9 **a** Comparison of the air temperature (°C) for Tel-Aviv city center (*red*) and the coastal station (near the park, *blue*) in the study period, 1–22 of July 2011, for the noontime (14:00 LST, *solid*) and evening (20:00 LST, *dashed*) time of the questionnaires. **b** Comparison of the Index of Thermal Stress calculated for Tel-Aviv city center and the coastal location of Jaffa Park over the course of the study period (July 1–22, 2011) for the daily time periods during which questionnaires were administered (14:00, 17:00, and 20:00 LST). Calculations are based on 10-min average wind speeds. Radiation data are based in all cases on values for concrete paving

wind data (10-min averages), measured at a roof-level station in the city, using attenuation functions derived by Pearlmutter et al. (2007). Calculations for the coast were based on meteorological data measured near the park (Fig. 9b). Radiation data are based on values for concrete paving.

The results, in both the city and the park locations, indicate "hot" conditions for the mid-day hours, "warm" for the late afternoon and "comfortable" for the evening hours. At the same time, thermal stress is significantly more moderate in the park than the inner city, with ITS values lower by as much as 15 % during the mid-day and late afternoon hours. This is a reflection not only of higher air temperature in the heart of the city but also of the stronger winds at the coastal location (in both cases, the calculation is made assuming an unshaded

Table 1 Average measured weather conditions (air temperature, relative humidity, global radiation, 10-min average wind speed and upper gust), calculated ITS, subjective thermal sensation (based on questionnaires with a 7-point scale), and the correlation (R^2) between the thermal comfort and subjective thermal sensation (values significant at the 95 % level are italicized) for the summer daily periods in which questionnaires were administered (standard deviation values appear in parentheses)

	Noontime	Afternoon	Evening	All measurements	Correlation (R^2) with the subjective thermal sensation
Air temperature (°C)	27.4 (±0.8)	27.3 (±0.9)	27.0 (±0.8)	27.2 (±0.8)	
Relative humidity (%)	70.1 (±5.8)	75.5 (±4.5)	76.2 (±5.1)	74.1 (±5.7)	
Water vapor pressure (hPa)	25.6	27.4	27.1	26.7	
Global radiation (W/m^2)	755 (±87)	67 (±35)	0	270 (±350)	
Wind speed (m/s, 10-min average)	4.62 (±0.5)	3.47 (±0.6)	2.30 (±1.0)	3.46 (±1.2)	
Wind speed (m/s, upper gust average)	5.96 (±0.6)	4.67 (±0.8)	3.35 (±1.3)	4.65 (±1.4)	
ITS (W)–calculated with average wind	428.3 (±76.1)	103.9 (±62.0)	17.2 (±21.4)	183.1 (±186.0)	*0.43*
ITS (W)–calculated with upper gust	414.0 (±73.9)	93.2 (±63.3)	5.9 (±23.2)	171.0 (±185.3)	*0.43*
Subjective thermal sensation	5.47 (±0.99)	4.47 (±0.71)	3.91 (±0.52)	4.62 (±1.00)	

Table 2 Average values (and standard deviation) of ITS (watts), subjective thermal sensation (on a 7-point scale), and thermal preference (% from all respondents) for observations in grass-covered lawn areas, the paved concrete plaza, during different periods of the day in summer

	Index of Thermal Stress (W)		Thermal sensation		Thermal preference (%)					
	Lawn	Plaza	Lawn	Plaza	Lawn			Plaza		
					Cooler (%)	No change (%)	Warmer (%)	Cooler (%)	No change (%)	Warmer (%)
Mid-day (14:00)	357.6 (±21.4)	498.9 (±32.2)	5.44 (±0.99)	5.50 (±0.99)	58	42	–	72	28	–
Afternoon (17:00)	78.4 (±51.4)	129.4 (±61.5)	4.28 (±0.61)	4.64 (±0.75)	22	78	–	62	38	–
Evening (20:00)	11.3 (±21.1)	23.0 (±20.1)	3.90 (±0.51)	3.92 (±0.53)	8	84	8	8	84	8
All	149.6 (±154.7)	216.4 (±209.2)	4.54 (±0.98)	4.69 (±1.01)	29	68	3	47	50	3

pedestrian standing in the middle of an open space). The relieving effect of the wind is further expressed when ITS is calculated using the upper wind gust, with the resulting value in the daytime some 5 % lower than the ITS value calculated for 10-min averaged wind speeds. The results are in agreement with Johansson and Emmanuel (2006), who indicated the dominant effect of the sea breeze and shade on thermal comfort in the tropical city of Colombo, Sri Lanka.

Thermal stress and perceived thermal sensation

Based on surface temperature data for grass and concrete estimated using the function and empirically derived coefficients described above (Eq. 5), ITS was calculated and compared with simultaneous thermal sensation responses (Fig. 10). It can be seen that the overall relationship has an R^2 of 0.43, indicating that ITS is a fairly reliable predictor of perceived thermal sensation, given the size of the sample. In addition, this relationship is nearly identical, in terms of both the slope and the intercept of its regression line, to that found previously by Pearlmutter et al. (2014) for a more arid region of Israel. In both cases, an ITS value of 0 W, representing thermal equilibrium, corresponds precisely with a "comfortable" thermal sensation vote representing perceived thermal neutrality, and in both cases the limit of thermal acceptability (i.e. the transition from "comfort" to "warm") is reached at an ITS value in the range of 140–160 W.

The strength of the correlation remains largely unchanged whether the calculation is based on 10-min average wind speeds or the upper wind gust (see Table 1). This further indicates the dominant effect of solar radiation and wind speed on the subjective sensation of thermal stress (as summarized by Jendritzky et al. (2012)).

On average, over the periods during which the 300 questionnaire responses were recorded, users reported feeling relatively comfortable during their stay in the park (Table 1). A substantial number of comfort and near-comfort votes were reported even when respondents were directly exposed to solar radiation. Still the range of comfort perceptions varied considerably between time periods. The average comfort vote for the mid-day period (14:00) was 5.47, which corresponds precisely to the transition between "warm" and "hot". In the late afternoon, before sunset (17:00), the average vote was 4.47, exactly one category lower on the scale (and marking the transition between "comfortable" and "warm" categories). For the evening (20:00), the average comfort perception of the respondents was 3.91, well within the "comfortable" category and close to the sensation of thermal neutrality (Table 1).

Regarding the comfort preferences of the respondents (Table 2), at noontime 58–72 % preferred cooler conditions—which, although representing a large majority, indicates that over one quarter of respondents did not prefer any change even at mid-day in summer. In the late afternoon, 22–62 % preferred cooler conditions and 38–78 % did not prefer any change, whereas in the evening only 8 % preferred cooler conditions, another 8 % preferred warmer ones and most of the respondents, 84 %, preferred no change.

Variations in thermal stress, sensation and preference by location

Thermal comfort conditions were further compared between the grass-covered lawn area and the paved concrete plaza. As expected, the reference measurements in the park (see "Estimation of ground surface temperature") indicated that there were no significant differences in the air temperature, humidity or wind speed between the paved concrete plaza and the adjacent lawn area. However, differences in the thermal comfort conditions, as calculated according to the ITS, are seen to be significant during the hours of high thermal stress (see Table 2).

The regression lines seen in Fig. 10 for the separate data sets representing respondents located in the concrete plaza and the grass-covered area, respectively, diverge from the overall relationship only to a small extent. The "concrete" subset has a slightly lower R^2, and its slope (0.0032) is virtually identical to that found previously by Pearlmutter et al. (2014). Both the R^2 and slope of the "grass" subset are slightly higher, but these

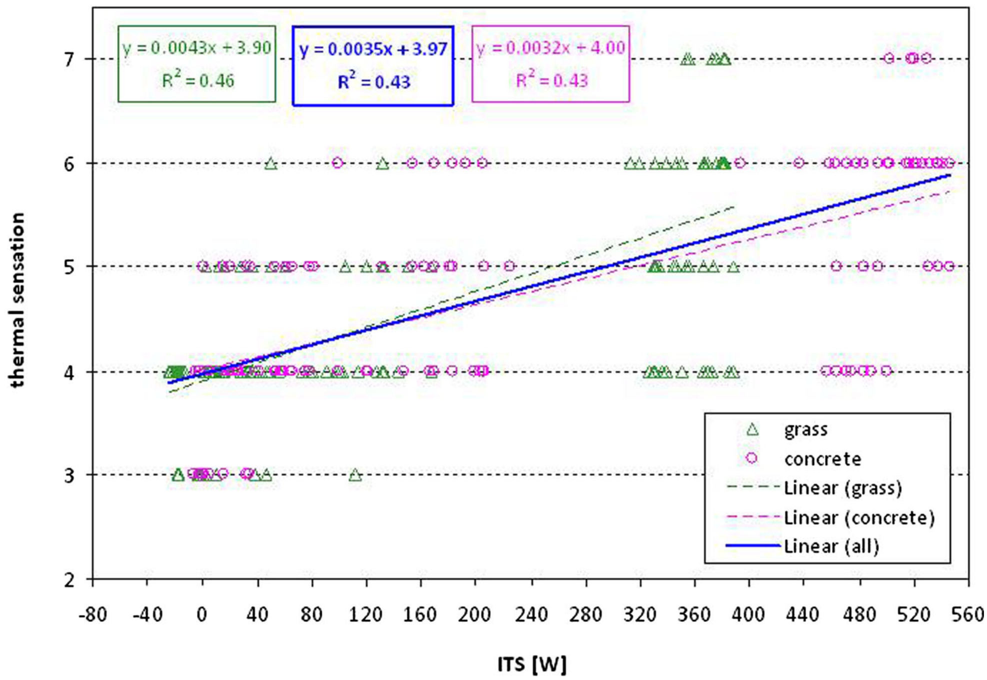


Fig. 10 Scatter plot of data representing the relation between reported thermal sensation and the Index of Thermal Stress, with separate regression lines for the sub-groups of respondents in the concrete plaza, the grass-covered area, and the overall sample

differences are minor given the level of uncertainty contained in the sample. This suggests that any difference in the subjective thermal perception of these two types of surroundings, beyond what is reflected by the human-biometeorological measure (ITS), is marginal.

It can be clearly seen that during the mid-day hours (represented by the right-hand cluster of data points in Fig. 10, in the ITS range of 320–480 W), the observations made in the grass have systematically lower ITS values (averaging under 360 W) than those made in the concrete plaza (nearly 500 W). The subjective thermal sensation of the 50 respondents in the lawn during these mid-day hours averaged 5.44, a bit lower than for those in paved plaza (5.50). Likewise, when averaged over all hours, the 150 respondents in the lawn had an average thermal sensation of 4.5 (i.e. between "comfortable" and "warm"), once again somewhat lower than the average value of 4.7 in the paved plaza (Table 2). While this may indicate that those in the grassy area perceive just as high a thermal sensation even though their surroundings are less stressful (in terms of ITS), the relatively small difference between the regression lines of the two sub-samples indicates that thermal perception is nevertheless fairly well aligned with thermal conditions. In fact, it is likely that the slightly steeper slope of the "grass" line is largely an artifact of the limited range of ITS in the data upon which it is based.

The differences between the two locations are clearly expressed by the thermal *preferences* (as opposed to thermal sensation) of the respondents (Table 2). Whereas over two thirds of the respondents in the lawn felt satisfaction (i.e. preferred "no change" in their thermal environment), and only about 30 % expressed a preference for cooler conditions, in the paved plaza half preferred 'no change' and almost half preferred cooler conditions.

These differences are most pronounced in the noon and afternoon hours as no difference in preferences between the two locations is seen in the evening, after sunset. It can be hypothesized that glare from the highly reflective concrete plaza, which would be expected to impair users' visual comfort, also impinges on their sense of thermal comfort, especially under the intense radiation at mid-day in summer, and this would further explain the negligible differences in the thermal preferences during the evening hours.

The 300 respondents were also asked to evaluate the overall attractiveness, on a 5-point scale, of the park and its different parts. The average grade of those queried in the lawn areas (4.30) was higher than that of the respondents in the paved plaza (4.16). Moreover, the lawns were graded as the most aesthetically pleasing part of the park and the sea as the second. When users were asked about their opinions regarding the use of fresh water for the lawn's irrigation, 72 % expressed opposition to this practice, presumably due to the shortage of water in Israel and the intense campaigns to educate the public about sustainability and water conservation. However, of the 72 % who opposed the use of fresh water for irrigation, more than two thirds said that they would not give up the large lawn areas to save water. Thus, although the majority of the park users surveyed oppose the careless use of drinking water in the park, when asked to prioritize among the two, most of them (78 %) preferred to maintain the vast lawns. To support their positions, users argued that the lawns add to a sense of relaxation and create pleasant vistas and views to the sea and thus should be kept large and wide.

The above results suggest that users' satisfaction with non-thermal aspects of the park enhances their subjective perception of thermal comfort in the lawns, in agreement with the studies of Knez and Thorsson (2006, 2008), who showed that subjective thermal perception depends not only on the physical conditions but also on psychologically and culturally based perception as well, including appreciation of the aesthetic quality of the place. A similar conclusion has been shown for Damascus, Syria, a hot dry city located in the Mediterranean region (Yahia and Johansson 2013).

Discussion and conclusions

The setting in which this case study was conducted presents significant environmental challenges: persistent discomfort conditions are exacerbated by urban effects (Saaroni et al. 2000), and the region is highly vulnerable to regional and global warming trends (Saaroni et al. 2003; Ziv et al. 2005; Shohami et al. 2011), with heat waves liable to become more frequent and extreme (Giorgi 2006). According to some forecasts, the aggravation of heat stress is likely to be accompanied by a decrease in rainfall over the coming decades (Krichak et al. 2011; Intergovernmental Panel on Climate Change IPCC (2013).

Against the background of these climate-related environmental risks, and considering the heightened attention to sustainability in urban planning, it was expected that the design of a new park in a region suffering from heat stress and chronic water shortage would focus on ameliorating heat stress and minimizing the use of fresh water. However, the major features of the park are fully exposed grass lawns and paved surfaces.

Based on the observational evidence presented, we found, as expected, the dominant relieving effect of the sea breeze on the human-biometeorological conditions in comparison to the inner city, with ITS values lower by as much as 15 % during the mid-day and late afternoon hours. This may be contrasted with the results of Andrade et al. (2011), who found that most people preferred lower wind speeds in all seasons in two open leisure areas of Lisbon, Portugal. We would argue that the relatively high level of thermal satisfaction results not only from the sea breeze effect but also from socio-cultural aspects. The latter are related to the high aesthetic satisfaction of the users in the new Jaffa-slope park and their appreciation of the picturesque landscape built in their disadvantaged neighbourhood, as expressed in their enthusiasm regarding the beauty of the park and in fact its very existence and their objection to give up the large lawn areas to save water (see "Variations in thermal stress, sensation and preference by location"). Accordingly, there is heavy usage of the park even under heat stress conditions and direct solar exposure. The socio-cultural explanation is in agreement with previous studies indicating the important role of aesthetics and emotional evaluations of a place in shaping the perception of comfort in different climate conditions including the Mediterranean region (Knez and Thorsson 2006, 2008; Lin et al. 2011; Yahia and Johansson 2013).

In terms of microscale thermal stress, based on empirical data including the radiant surface temperature of grass and concrete, the study has indicated that ITS is a fairly reliable predictor of perceived thermal sensation and that this relationship is nearly identical to that found previously by Pearlmutter et al. (2014) for arid areas. It has also shown that although there are no significant differences in air temperature and relative humidity at head height above the grass and concrete, the level of human-biometeorological stress differs between them—and these differences are in general agreement with the differences in subjective human perception of users in the two areas, with a moderating effect of grass indicated in both cases.

The scale of these differences in thermal comfort between grass areas and paved surfaces is modest, however, and this intensifies the question of whether the size of such expansive lawns represents a sustainable design approach. It is seen that the users of this park are prepared only to discuss the theoretical need to reduce the use of fresh water, and—following the principle of "NIMBY" (Not In My Back Yard)—are not willing to accept the proposition that the extent of these lawn areas in their local neighbourhood park should be compromised. Therefore, designers and other stakeholders have a crucial role in integrating broader environmental considerations in the planning process, ensuring that the long-term implications of global and regional warming, water scarcity and aggravated thermal stress are not ignored.

We would propose that the case of this coastal park offers a unique opportunity for in-depth study of the human aspects of thermal comfort perception, which should be further pursued to include a survey of individual variables (e.g. age, ethnicity, gender, occupation) as well as clothing and activity (e.g. relaxing vs. sports activities). As this research was conducted during the first year of the park's operation, further studies are needed to understand its impact on users within a long-term temporal perspective. This could reveal to what extent peoples' perceptions are influenced by their enthusiasm for the changes that the park has introduced to this complex neighbourhood and to its image. Furthermore, observations should be made in the winter season, characterized by cold stress that is intensified by the strong winds near the sea (Israel Meteorological Service 2013), since parks in sub-tropic and mid-latitude regions, including the Mediterranean coasts, are heavily used in both summer and winter seasons. Finally, adaptive planning is needed for such vulnerable regions that are already experiencing climate change and which expect further aggravation in thermal comfort.

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