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Nocturnal Cool Island in the Sahelian city of Ouagadougou, Burkina Faso

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ABSTRACT: Relatively little is known about the urban climate processes of the fastest growing cities in the world today. Described in this paper are urban–rural and intra-urban variations in air temperature and humidity in one of these cities; Ouagadougou, Burkina Faso. Measurements were collected from car traverses and fixed site measurements during two field studies. The aim of the study was to determine the influence of land use on the urban climate in this hot-dry region, with a focus on the role of vegetation and of a large centrally located reservoir.

Analyses of results show that vegetation is the most important factor in the nocturnal urban climate in Ouagadougou, while effects of built up and paved areas are limited. Average urban–rural temperature differences demonstrate that while the evening urban heat island (UHI) reached only 1.9 °C, the cool island in a densely vegetated area was 5.0 °C cooler than the dry rural reference. Temperature differences of the same magnitude persisted throughout the night between vegetated and non-vegetated areas, regardless of urban or rural setting. Cooling from the open water of the reservoir was the most important parameter during daytime, while during evenings and nights, direct effects of the open water of the reservoir are very limited, and the availability of water, allowing enhanced vegetation cover, is of much greater importance compared to the water itself.

The results presented here show that the urban land cover, together with climatic region, can create significant differences in the physical properties driving the urban climate in a dry-tropical city compared to those commonly found in temperate cities. Copyright © 2010 Royal Meteorological Society

KEY WORDS oasis effect; urban vegetation; open water; urban heat island; sub-Saharan Africa; arid climates

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1. Introduction

1.1. Background

The great majority of the world's future population growth is expected to be absorbed by urban areas of developing countries. Cities in the least developed countries, many of which are located in dry-tropical sub-Saharan Africa, are projected to triple in size over the next 30 years (United Nations Population Division, 2008). It is well known that the rapid growth of an urban area is among the most important anthropogenic impacts on the environment, and that it has a profound impact on the urban climate. Thorough understanding and inclusion of urban climate processes in the planning of a city could, for example, decrease heat stress, energy demands and air pollution levels, thus improving health and comfort. However, while the urban climate processes in temperate climates are widely studied, relatively little is known about urban climate in tropical areas. A review shows that less than 20% of all urban climate studies are from (sub) tropical areas, and that only a handful of these are from the dry-tropical regions of sub-Saharan Africa (Roth, 2007). As many of the most rapidly urbanizing countries are located in these regions it is of greatest importance that they are thoroughly studied.

1.2. Thermal variations in arid urban areas

Differences in physical properties between urban and rural areas located in arid *versus* temperate or humid regions may provide very different climatic responses (Jauregui, 1997; Pearlmutter *et al.*, 2007). The most intensely studied urban climate feature is the increase in air temperature in a city compared to rural surroundings, referred to as the urban heat island (UHI) (Souch and Grimmond, 2006). Though studies of the urban climate in hot-arid areas may still be too few to draw generalised conclusions, several investigated cities show an UHI effect; for example, Phoenix, USA (Fast *et al.*, 2005; Brazel *et al.*, 2007), Pune, India (Deosthali, 2000), Tucson, USA (Comrie, 2000), Cairo, Egypt (Robaa, 2003), Eilat, Israel (Sofer and Potchter, 2006) and Ouagadougou (Offerle *et al.*, 2005). The UHI is generally slightly weaker in tropical compared to temperate areas (Wienert and Kuttler, 2005) and seasonal variations in UHI in tropical climates are regularly maximized during dry periods (Jauregui, 1997; Jonsson, 2004). A dense building structure in hot-arid climates can, during daytime, create a

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cooler environment due to a reduction in radiation loading (Oke, 1982; Johansson, 2006). This type of urban design has traditionally been used in hot-arid climates to mitigate heat stress. Unfortunately, recent urban settlements in the same regions tend to be more spread out and open with a much higher SVF, and the much needed cooling effects may therefore be lost (Johansson, 2006). Furthermore, a change from traditionally used local building materials (clay brick, straw) to modern materials such as concrete and metals affect surface thermal properties, such as heat capacity and conductivity, and consequently impact local climate (Offerle *et al.*, 2005). They discuss that if increased urbanisation in Ouagadougou leads to an increased reliance on modern materials, this will affect the surface energy balance by decreasing albedo and increasing heat storage, leading to higher night-time urban temperatures. The impact of building materials was also discussed by Nasrallah *et al.* (1990), who report that Kuwait City, generally dominated by local building materials and scarce vegetation, does not exhibit a UHI, and suggests the lack of differences in thermal properties between the urban and rural landscapes as a possible explanation.

1.3. Effect of vegetation in arid urban areas

While urban geometry and thermal properties of urban surfaces are regarded as the two main parameters influencing urban climate in temperate areas (Oke, 1987; Arnfield, 2003), irrigated vegetation has been suggested as a more important factor in dry climates (Jonsson, 2004; Pearlmutter *et al.*, 2007). Through a combination of shade and increased latent heat flux due to the evapotranspiration process, vegetation can cause cooler temperatures. This effect is often noted around vegetated areas near sources of water in otherwise more arid surroundings, and commonly referred to as the oasis effect (Saaroni *et al.*, 2004). A similar cooling effect of parks in urban areas has been well established in temperate climates (Eliasson, 1996; Spronken-Smith and Oke, 1998). This park cool island (PCI) has been suggested as mainly a daytime phenomenon; shading is only effective during the day, evapotranspiration due to the photosynthesis process is mainly active during daytime, a dense canopy layer could obstruct radiation cooling during night, and relative humidity is generally significantly higher at night causing less evaporative cooling (Spronken-Smith and Oke, 1999; Potchter *et al.*, 2006). The type of vegetation also greatly influences the cooling effects, as irrigated parks in a hot-arid climate daytime stand out as significantly cooler than their surroundings, while areas with dry dead grass or bare soil can be hotter than their environs (Spronken-Smith and Oke, 1998). Jonsson (2004) identified vegetation as the most important factor in the urban climate of Gaborone, and showed afternoon temperature differences of up to 4 °C between sparsely vegetated areas (central business district) and an irrigated park, while after sunset the irrigated park showed no cool island. In Tel Aviv, a park containing tall trees provided cooler temperatures by up to 3.5 °C during daytime, while night-time temperatures were at most 1.2 °C cooler (Potchter *et al.*, 2006). Exceptions exist, however, as Jauregui (1991) showed that a park with lush vegetation and dense tall trees in Mexico City displayed a PCI of up to 4 °C compared to a built up area during night-time, while daytime temperatures were slightly higher in the park. Jauregui (1991) suggested that this daytime pattern may be due to a lower albedo of the park exceeding effects of the evapotranspiration and that nocturnal thermal differences were developed due to a reduction of long wave radiation loss as well as lower wind speeds in the built up area, thus allowing a more rapid cooling of the park area. A nocturnal peak in PCIs was also noticed in the hot summer climate of Sacramento, CA, by Spronken-Smith and Oke (1998). In their study, a PCI of up to 6.5 °C was measured at night in dry, savannah type parks, while irrigated, densely treed parks showed a PCI that was most intense in afternoons. The nocturnal PCI intensity peak was explained by the lower thermal admittance and an open geometry allowing strong radiative cooling in the dry, savannah type park, whereas a combination of shade and evaporative cooling created the afternoon peak in the irrigated park.

The heat flux due to plant photosynthesis in vegetated areas has been considered limited compared to other factors in an urban environment (Oke, 1987). It is through the photosynthesis process that plants open their stomata to let CO_2 in to be fixated into carbon containing acids for growth. As plants open their stomata to let CO_2 in, water evaporates at a rate quicker than CO_2 enters (Raven *et al.*, 2005). This is called plant transpiration and causes additional cooling through evaporation. In arid environments, studies of plant physiology show that many different types of plants can adapt to water stress by closing stomata during periods of large vapour pressure deficit, thus restricting water loss through transpiration (Maroco *et al.*, 2000; Gao *et al.*, 2002; Gindaba *et al.*, 2004; Ma *et al.*, 2004). Stomata are instead opened when vapour pressure deficit decreases. This is often referred to as *midday depression* and prevents cooling by evaporation during the hottest part of the day, while a stronger evapotranspiration process is active when vapour pressure decreases in evenings. Furthermore, in a hot-arid climate, a higher proportion of plants might use a drought-adapted type of photosynthesis process called crassulacean acid metabolism (CAM) (Raven *et al.*, 2005). With this type of photosynthesis, CO_2-fixation takes place during the night, and stomata stays closed throughout the day for water saving purpose. The evapotranspiration process instead becomes active as vapour pressure deficit decrease before sunset and during nights. Saaroni *et al.* (2004) suggested reduced plant transpiration as part of the reason for no daytime cooling effect of vegetation found in a desert oasis. However, to the author's knowledge, this has never before been discussed as significant for the urban climate in arid cities.

1.4. Effects of open water in arid urban areas

Knowledge of how lakes and reservoirs within arid cities affect the urban climate is still limited as very few studies have been presented. Saaroni *et al*. (2000) explain how open water is likely to act through two main processes; evaporation, which increases humidity and decreases temperature due to latent heat flux, and sensible heat flux between the water and air. If the water temperature is cooler than the air, an open urban water body in a hot-arid climate could decrease heat stress by contributing to cooler days. An increase in humidity that could potentially decrease comfort is not likely to reach levels that cause discomfort in an arid climate. The ameliorating effects of open water have been noticed in seashore cities in tropical climates, for example Singapore (Tso, 1996) and Tel Aviv (Saaroni *et al*., 2000). The effect of a small urban lake on heat stress was investigated in Tel Aviv, showing a significant reduction in heat stress – though the effect was restricted to the near surroundings of the lake (Saaroni and Ziv, 2003). A secondary effect of availability of water in otherwise arid areas might be that the increased availability of water allows nearby surroundings to be more densely vegetated.

1.5. The present study

This paper describes results from a study of the urban climate in the rapidly urbanising Sahelian city of Ouagadougou during dry season. Data were collected during car traverses and at fixed site stations with the aim to examine urban–rural as well as intra-urban thermal variations in relation to different types of land use in and around the city. A special focus of this paper is to describe the climatic effects of vegetation and of a large anthropogenic reservoir located near the urban centre.

2. Study area

The capital of Burkina Faso, Ouagadougou (12°22′N, 1°31′W, 300 masl), is located in the hot semi-arid steppe climate of the Sahel as shown in Figure 1. The climate consists of a dry period from October to April, with the Harmattan wind blowing in from the Sahara to the north and north–east, and a wet period from May to September averaging 700 mm of rain (Direction de la Météorologie Nationale, 2008). Average daily temperatures range from 25 °C to 33 °C. Ouagadougou has approximately 1.2 million inhabitants today with a population density of about 660 inhabitants/km^2. Urbanisation in Burkina Faso is projected to generate an exceptional growth of urban dwellers that will increase the number of urban inhabitants by four times in the next 30 years (United Nations Population Division, 2008). The urban structure in Ouagadougou is spread out and generally dominated by low buildings and sparse vegetation, with many dry, open areas spread out over the city.

Figure 1. Location of Burkina Faso and Ouagadougou. This figure is available in colour online at wileyonlinelibrary.com/journal/joc

3. Methods

Data were collected during two field studies; October–December 2003 and November–December 2004, with the aim to describe the urban climate of Ouagadougou. In 2003, measurements of air temperature and humidity were collected during car traverses in nine different urban sites and one rural site (Figure 2, Table I). A suburban reference station measuring temperature, humidity and wind was placed at the Direction de la Météorologie National (DMN). Air and ground temperature was continually measured at fixed locations in and around the city during both 2003 and 2004 (Figure 2, Table II).

3.1. Measurement locations

Twelve areas were chosen in 2003, and three additional in 2004, for measurements during car traverses and fixed site measurements. The examined areas were chosen according to their land use and proximity to the reservoir. The areas are described in Tables I and II, with location shown in Figure 2. Ouagadougou is located on very flat land, and altitude differences between measurement locations were less than 15 m.

During car traverses, air temperature and humidity were measured travelling in a loop starting and ending in the urban center covering area 1–10 (Figure 2, Table I). The small *urban centre* (1) lacks narrow street canyons and consists mainly of buildings two to five floors, with some taller constructions up to ten floors high. Mainly modern building materials such as concrete, asphalt and metals are used in this area. Also within the city are several very open areas, like *urban open* (2), mainly covered by sand or bare soil. *Traditional residential* areas (3 and 9) consist mainly of

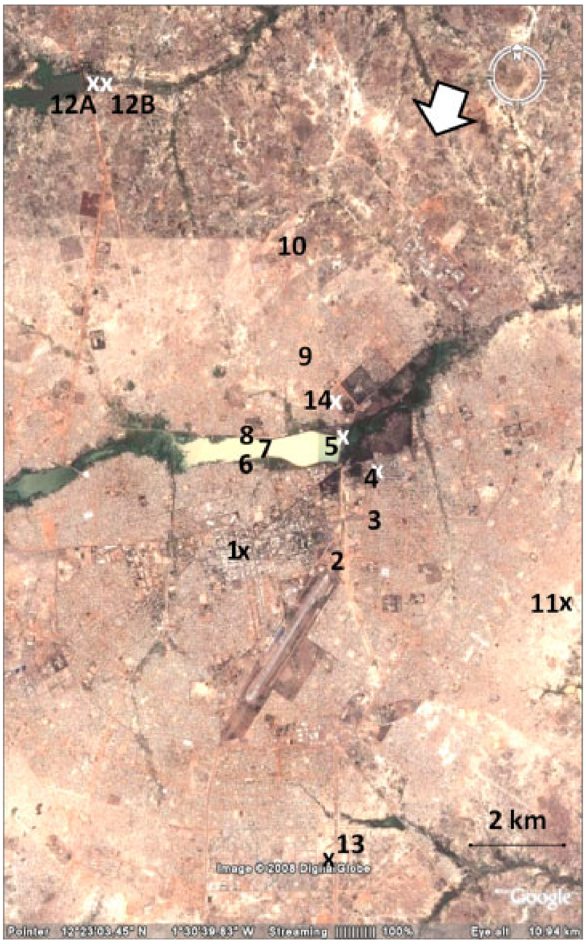


Figure 2. Satellite image of Ouagadougou with location of measurements (Google Earth). Car traverses covered area 1–10. 'X' marks location of fixed site measurements (see Table I and II for description). White arrow indicates main wind direction. This figure is available in colour online at wileyonlinelibrary.com/ijoc

single-family houses with a high percentage of aggregate from local materials such as clay bricks. In wealthier *modern residential* areas (4), irrigated, green gardens often surround single homes built with modern materials. A large shallow *reservoir* (5–8), approximately 2.2 km^2, constructed in the 1960s, stretches along the north side of the urbancentre. The depth of the reservoir varies over the year, and during this study is less than 2 m. Irrigation in Ouagadougou is mainly manual (i.e. water being carried in buckets from nearby water sources). The water in the reservoir enables manual irrigation of nearby surroundings which are therefore generally vegetated, and often used for growing food-crops and other plants, as well as for animal grazing grounds. A large, protected but un-irrigated, park/forest (approximately 2 km^2) with natural forest vegetation is situated east of the reservoir (*forest/reservoir,* 5). The park consists of dense, large trees and dry ground vegetation. The *rural reference* (10) was located north of the city in a dry, open, semi-protected zone where anthropogenic activities are prohibited to prevent exploitation. However, heavy foraging for firewood, food and grazing have left these areas bare, with very scarce and dry vegetation. This area typically represents the rural surroundings of Ouagadougou.

Air temperature was measured continuously at five fixed sites in 2003 and four in 2004 (Table II). In 2003, four of the fixed sites measurements were placed along the car traverse route (1, 4, 5 and 14). A fifth site was located in the *suburban spontaneous settlements* (11), which are rapidly growing in the outskirts of the city and uncontrolled by the government. These are very poor, densely inhabited neighborhoods of temporary houses made of earth bricks with tin roofs where most new inhabitants end up as they reach Ouagadougou. Streets are almost absent except for the sandy tracks created by the inhabitants. Due to the risk of theft, fixed measurement points could not be placed at other interesting areas such as 7 or 10.

In 2004, three additional sites were placed north and south of the city to further examine the extent of the urban influence and if important thermal variations were present outside the urban area. One site was placed at the same location as 2003 in the *urban centre* to enable comparison between the years. Two sites were placed in a *rural, vegetated* (12A and B) location, several kilometers north of the city limits by a fenced in, relatively lush green agricultural research centre, Institute de l'Environnement et des Recherches Agricoles, *INERA,* near a smaller reservoir. One site was placed in a *rural, dry* (13) location south of the city by a drought research centre; Comite Permanent Inter-Etats de Lutte Contre la Secheresse dans le Sahel, *CILSS*. This site is very open and dry with only one larger building approximately 100 m to the south east. Ground temperature was measured in two areas in 2003 (4 and 11) and in all areas in 2004 (Table II). Soil samples were collected in all areas in 2004 and used to determine soil moisture. A *suburban vegetated* reference station (14) continually measuring air temperature, humidity and wind was placed at the DMN in 2003, along the car traverse route.

3.2. Measurements

Instrumentation used for measurements of temperature, humidity and wind is described in Table III. In 2003, car traverses were carried out twice daily during week days, resulting in a total of 34 traverses. Each traverse took approximately 70 min to complete. Starting times were selected to 13 : 00, to cover the hottest time of day, and 20 : 00, 2 h after sunset, to cover the period when local thermal variations are generally at a maximum (Oke, 1987). The vehicle speed during measurements was kept at around 30 km/h and reasonably similar during all traverses. Measurements were collected at five to ten points in each selected area depending on area size, and at each point data were collected over 5 s. During traverses, instruments were mounted on top of the car at a height of 1.7 m and shielded in a reflective tube which allowed air to flow freely around the instruments. The same instrumental setup was used at the reference station at DMN. Additionally at DMN, wind speed

Table I. Description and photos of areas examined during car traverses.

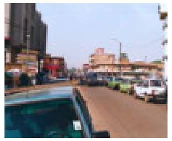
Area photo	Area description	Shortest distance to reservoir (km)	Distance to urban centre (km)	% Green vegetation	% Built up and paved	% Bare soil	% Open water
	**1. Urban centre**. Most 3–5 floor and some taller buildings, mainly modern building materials, wide streets, some large trees, scarce ground vegetation, paved roads, gravel sidewalks and open areas.	1.7	0	5	89	7	0
	**2. Urban open**. Dry open area near city centre, mainly covered by sand and dry soil, scarce trees, dry ground vegetation and no paved roads	2.1	2.1	11	8	81	0
	**3. Urban traditional residential**. Mostly larger single-family houses with surrounding brick wall, sometimes irrigated garden, mainly local building materials, some larger trees and most roads gravel	2.0	2.7	6	56	39	0
	**4. Urban modern residential**. Larger private homes and embassies of mainly modern building materials with walled irrigated gardens, large trees and bushes, paved roads	1.0	3.1	36	49	15	0
	**5. Forest/reservoir**. Dense natural forest vegetation with large trees and bushes on east side, water on the west, irrigated hotel garden to the north and paved road	0	2.9	50	5	5	40
	**6. Reservoir, south side**. Water on north side of the road, water-logged grass field on south, buildings about 100 m inland and paved road	0	2.0	22	25	7	46
	**7. Reservoir-bridge**. Narrow 400 m long paved road/bridge across the middle of the reservoir with water on both sides	0	2.3	19	10	13	57

Table I. (*Continued*).

Area photo	Area description	Shortest distance to reservoir (km)	Distance to urban centre (km)	% Green vegetation	% Built up and paved	% Bare soil	% Open water
	**8. Reservoir, north side**. Water on south side of the road, buildings and some vegetation on the other side and gravel road	0	2.5	9	20	27	44
	**9. Suburban traditional residential**. Single-family homes, mainly local building materials, no paved roads, few trees, scarce ground vegetation, few irrigated home gardens and livestock grazing in area	1.6	4.5	2	50	48	0
	**10. Rural dry, north**. Open area with scarce, very dry vegetation or dry bare soil and livestock grazing, no larger trees or buildings, no paved roads	3.6	6.2	2	1	97	0

Areas are classified in view of land cover and shortest distance to reservoir and urban centre (for locations, see Figure 2). This table is available in colour online at wileyonlinelibrary.com/ijoc

Table II. Description and photos of areas examined with fixed site measurements.

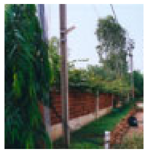
Area photo	Area description	Shortest distance to reservoir (km)	Distance to urban centre (km)	% Green vegetation	% Built up and paved	% Bare soil	% Open water
	**1. Urban centre**. Area description in Table I, sensor located slightly towards the south of the centre of car traverse measurements with soil measurement on gravel sidewalk	1.7	0	5	73	22	0
	**4. Urban modern residential**. Area description in Table I, sensor located slightly to the north of the centre of car traverse measurements with soil measurement on grassy roadside	1.0	3.1	47	41	12	0
	**5. Forest/reservoir**. Area description in Table I, sensor located at the north/east corner of the reservoir on grassy hotel grounds, no soil measurement	0	2.9	49	13	11	27

Table II. (*Continued*).

Area photo	Area description	Shortest distance to reservoir (km)	Distance to urban centre (km)	% Green vegetation	% Built up and paved	% Bare soil	% Open water
	**11. Suburban spontaneous settlements**. Very poor, densely inhabited area, houses made of clay bricks with tin roofs, gravel roads, few trees, no ground vegetation, soil measurement on gravel track	5.4	7,0	1 (0.5, –, 58, 3, 38, 1)	66	32	0
	**12A. Rural vegetated north, yard**. Agricultural research centre near small reservoir, natural vegetation, trees and some irrigated fields. Measurements in yard, soil measurement on gravel road.	0.4	–	64	3	30	2
	**12B. Rural vegetated north, nature**. As above. Measurements in nearby natural vegetation, soil measurements in dry naturally vegetated soil.	0.5	–	58	3	38	1
	**13. Rural dry, south**. Drought research centre in dry, open area south of the city, scarce vegetation, mostly bare, dry soil, one building 100 m to the south east and soil measurement in bare soil	8.7	6.6	6	4	90	0
	**14. Suburban vegetated (DMN)**. Reference station with dry vegetation, some trees, limited irrigation, dense forest to the east, gravel road, one building to south east and no soil measurement	1.1	4.0	44	17	39	0

Areas are classified in view of land cover and shortest distance to reservoir and urban centre (for locations, see Figure 2). This table is available in colour online at wileyonlinelibrary.com/ijoc

Table III. Information of instruments used for measurements.

Instrument	Parameter measured	Measurement frequency	Response time	Location	Comment
Rotronic HYGROMER MP 100A	Air temperature Relative humidity	Car traverses: 1 s Suburb.ref. stn: 1 min	10–15 sec, (lower at higher wind speeds)	Car traverses, Suburb. Ref. stn	Accuracy during calibration: T: ±0, 2 °C Rh: ±0, 6%
Thermo couple wire Shielded T-type 0.51 mm (Omega engineering)	Air temperature	Car traverses: 1 s Suburb.ref. stn: 1 min	1-2 sec	Car traverses, Suburb. Ref. stn	Accuracy during calibration: T: ±0, 3 °C
Anemometer Four cup	Wind speed	1 min	1–2 sec	Suburb. Reference station	Threshold 0.2 m/s
Tinytag Plus Gemini Data Loggers	Air and Soil temperature	10 min	<10 min	Fixed measurement locations	Accuracy during calibration: T: ±0, 2 °C at 20 °C T: ±0, 3 °C at 50 °C

was measured with a cup anemometer. General wind direction was obtained from DMN. Weather and cloud cover were described at the beginning and end of each traverse. To eliminate the influence of the natural changes in temperature and relative humidity during the car traverses, the average temperature change was calculated for the duration of the traverse in measurements from locations covered both at beginning and end of traverse in area 1 and fixed site measurements passed (in areas 1, 4, 5 and 14). Based on this temperature change, data were corrected for time of measurement so that all data could be regarded as simultaneous. Car traverse temperature data are presented in graphs as urban–rural difference ($\Delta T_{\mathrm{ux-r}}$).

Continuous measurements of air temperature were collected with Tiny Tag data loggers at a height of 3 m and frequency of 10 min for 37 days at four fixed sites in 2003, and for 20 days at four sites in 2004 (one placed at the same location both years). Continuous measurements of soil temperature were collected at a depth of 5 cm in areas 1, 4, 5, 11, 12 and 13 for the same duration as air temperature. Basic sun/shading patterns over the soil temperature measurements were described. In 2004, soil samples were collected, from which soil water content was determined. Data from fixed site measurements are presented in graphs as hourly mean temperatures.

For thermal analyses of car traverses, data from the thermocouple wire were primarily used due to the much quicker instrument response time. However, technical problems during daytime traverses disqualified data from the thermocouple wire, thus daytime analyses are based on Rotronic data. This may cause a slight displacement of actual measurements compared to intended locations. Due to the slow vehicle speed and comparatively long time spent in each area, this error is estimated to be low with insignificant effects in general analyses.

Comparison of temperatures in area 1 showed that temperatures were very similar between the two years (hourly means differed on average 0.2 °C night-time and 0.5 °C daytime). The similarity between the years is assumed to apply to all locations which can therefore be compared.

Statistical analyses of simple and stepwise multiple regression was carried out to examine the effects of different land cover as well as the shortest distance to reservoir and urban centre (chosen as the central marketplace) on temperature data. Data from 12A and B were not analysed in regard to distance from the city centre since their location is several kilometers outside of the city limits. Due to this, 12A and B are not included in the multiple regression analysis. Each area was classified in regards to the proportion of the area covered by *green vegetation, built up and paved, bare soil* and *open water* (Tables I and II). To determine land cover in areas covered by traverses, satellite images were analysed on a radius of 400 m from the centre of the area which allowed all measured points within to be covered with a minimum of 50 m to the margin. For the fixed site measurements, statistical analysis was made on a 400, 300, 200 and 100 m radius from the measurement point, but calculations show best correlations on a 400 m radius which was therefore used in further analysis. To be able to treat temperature data from both traverses and fixed site stations as one dataset in statistical analyses, data were treated as follows: Temperature departure from the mean temperature measured at three fixed stations passed during the car traverses (1, 4 and 5), at the time of each car traverse, was calculated for each area. Fixed site measurements for days not covered by traverses were excluded from statistical analyses. To include areas covered in 2004, data were based on departure from 2004 temperatures in area 1, which was measured both years. Data were then corrected by the average departure of this area from the average temperature in areas 1, 4 and 5 in 2003. Day and evening data were treated separately. A comparison of the statistical results for fixed site measurements at the time of traverses *versus* using data from all day or night showed minimal differences caused by selection of time periods.

Daytime results based on data where traverses and fixed site measurements are treated as one dataset (as in statistical analyses) should be considered with some caution, primarily since a slight heating of the radiation shields used for fixed site measurements might create a positive bias in temperature compared to car traverses where ventilation is forced due to the speed of travel. Furthermore, the differences between the two years are comparatively large during daytime measurements, especially in relation to the smaller magnitudes in daytime temperature differences between the areas.

4. Results

The weather situation in Ouagadougou was reasonably consistent during both field campaigns, dominated by high pressure and stable atmospheric conditions with hazy but cloudless skies and no precipitation. Though slight variations existed, nights were generally calm and clear with wind speeds less than 0.2 m/s and daytime wind conditions were more turbulent with mainly north-easterly winds, on average 1.4 m/s. Diurnal air temperature at reference stations varied between 17 and 40 °C (13–37 °C) and relative humidity between 12 and 98% (10–70%) in 2003 (2004). The relative humidity was used to calculate specific humidity, which will be used in further analyses.

Temperature differences between urban areas (1–9) and rural (10), $\Delta T_{\mathrm{ux-r}}$, during day and night-time car traverses in 2003 are displayed in Figure 3. Variance within areas is mainly temporal. A Wilcoxon signed ranks test showed that most areas were significantly different ($p = 0.05$) compared to the rural reference area. Exceptions are shown with hollow marks in Figure 3. Average diurnal variations from fixed site air temperature measurements are shown in Figure 4. Standard deviations for these hourly data were on average 2.4 °C (max. 3.5 °C).

4.1. Patterns in temperature and humidity

The greatest thermal differences were found during evening traverses, when the most pronounced thermal characteristic in Ouagadougou is a cool island in the densely vegetated *forest/reservoir* (5, avg. $\Delta T_{\mathrm{ux-r}}$ of −5.0 °C, Figure 3). This cool island greatly exceeded the UHI effect in the *urban centre* (1, avg. $\Delta T_{\mathrm{ux-r}}$ of 1.9 °C, Figure 3). Hence the average intra-urban thermal difference between these two areas, located 4 km apart, was 6.9 °C. The maximum thermal difference between these two areas during the same evening traverse occurred on November 21 when ΔT was 9.1 °C. Fixed site measurements showed an average difference between the two areas for the same time of day of 6.4 °C (Figure 4). The thermal difference between the two areas stayed in similar magnitude until sunrise (avg. $\Delta T = 5.6$ °C). Other areas

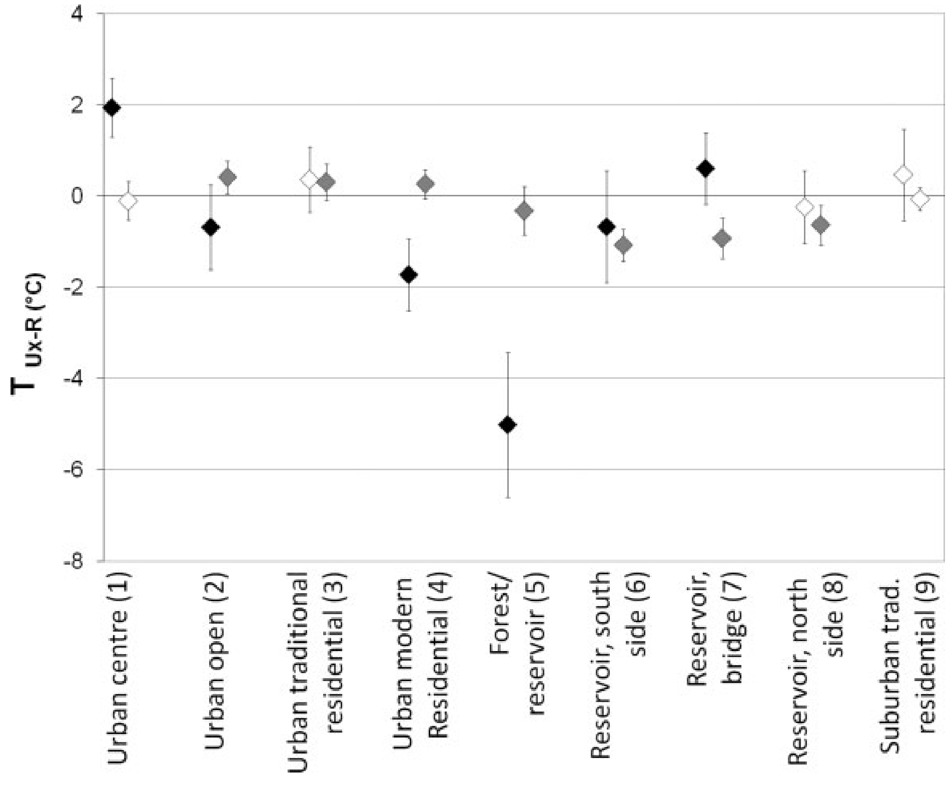


Figure 3. Mean urban–rural temperature differences ($T_{\mathrm{ux-r}}$) in °C for areas examined during daytime (grey) and evening (black) car traverses. Error bars describe one standard deviation. Black marks represent evening values. Areas not significantly different to rural area are presented by hollow marks.

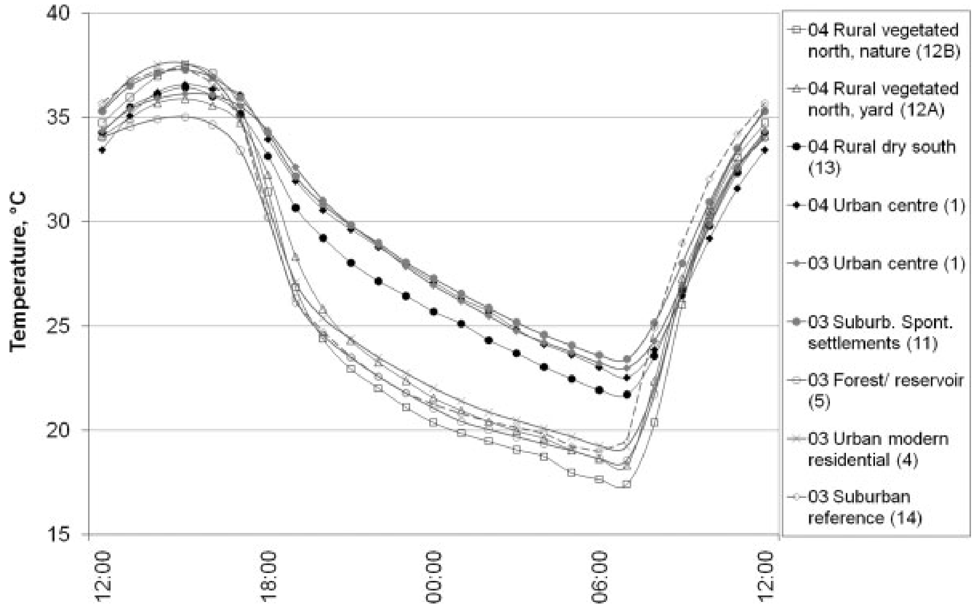


Figure 4. Hourly mean of diurnal temperatures from fixed site measurements in 2003 and 2004. All sites are measured with the Tinytag instrument except the Suburban reference station (for instrument specifics, see Table III).

covered by fixed site measurements could be divided into two groups which follow the same general pattern in view of nocturnal temperatures (Figure 4). Very similar to the warmer area 1 was the *suburban spontaneous settlements* (11) and comparable, but slightly cooler, was the *rural dry, south* (13), while the other colder areas, similar to area 5, were u*rban modern residential* (4), *rural vegetated north*, both yard (12A) and nature (12B), and *suburban vegetated* reference (14). The average nocturnal (sunset to sunrise) difference between the two groups was 5.1 °C. An additional distinction between the groups was that the warmer areas were all covered by less than 10% vegetation, while the cooler had vegetation coverage of 44% or larger. The two areas with the highest percentage of built up and paved areas (1 and 11) displayed the warmest nocturnal temperatures, though one of the least built up areas, 13, was only slightly cooler than these two. A similar distinction, though slightly less clear, can be seen in the car traverse data where the coldest areas were the ones with highest vegetation coverage. Also slightly cooler than the rural reference was the *urban open* area (2). However, while the warmest evening car traverse temperatures were found in the densely built area 1, temperatures were not increased in any of the relatively built up residential areas (3, 4 or 9).

For daytime temperatures, the significance of open water for cooler daytime temperatures was clear in car traverses (Figure 3) where all areas in connection to the reservoir were significantly cooler than the *rural dry north* (10). This was also visible in fixed site measurements (Figure 4) where the *forest/reservoir* (5) was the only area distinctively cooler than the others. Evening thermal patterns from car traverses (Figure 3) near open water were generally cooler compared to the rural area, with the exception of the area mainly covered by open water; the *reservoir, bridge* (7).

Specific humidity levels were higher in evenings compared to days (Figure 5), with relatively high humidity in all areas around the reservoir and those covered by a large proportion of vegetation. Daytime high humidity levels were measured in all areas near the reservoir, but not in vegetated areas located away from the reservoir (Figure 5). Differences in specific humidity levels between evening and day (ΔH) in the two areas affected by vegetation but not by the reservoir (*Urban modern residential,* 4, and *Suburban vegetated* reference, 14) clearly exceeded that in other areas with a $\Delta H = 4.0$ g/kg in area 4 and 14, while ΔH in other areas ranged from 1.9 to 3.0 g/kg (Figure 5).

Soil temperature, water content, and shading patterns are displayed together with corresponding air temperatures in Figure 6. Soil moisture was generally very low where measured, ranging between 0.5 and 4.1%. Direct solar radiation and soil moisture seem to be determining factors for soil temperature. When exposed to solar radiation, lower soil water content appears to correspond to larger diurnal soil temperature differences. No direct connection between soil and air temperature is apparent.

4.2. Statistical analyses

Statistical analyses showed a clear cooling influence of *green vegetation* on evening temperatures, greatly exceeding the influence of all other parameters (Tables IV and V). Given the major influence of vegetation on evening temperatures, little room is left for independent influence of the other parameters. While *built up and paved* show a significant positive effect on evening temperatures in simple regression analyses (Table IV), multiple regression analyses showed that the independent influence of this parameter was very limited, and negative (Table V). *Bare soil* showed a higher independent influence in the multiple regression analysis, slightly

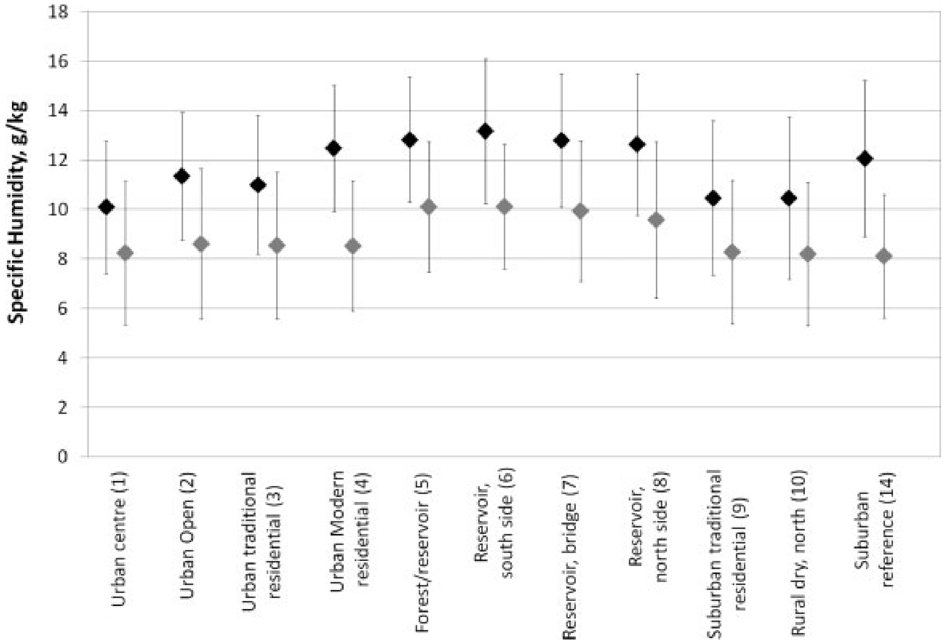


Figure 5. Mean specific humidity in g/kg from daytime (grey) and evening (black) car traverses and from the suburban reference station. Values from the suburban reference station are from the same time of day/evening as the traverses. Error bars describe one standard deviation.

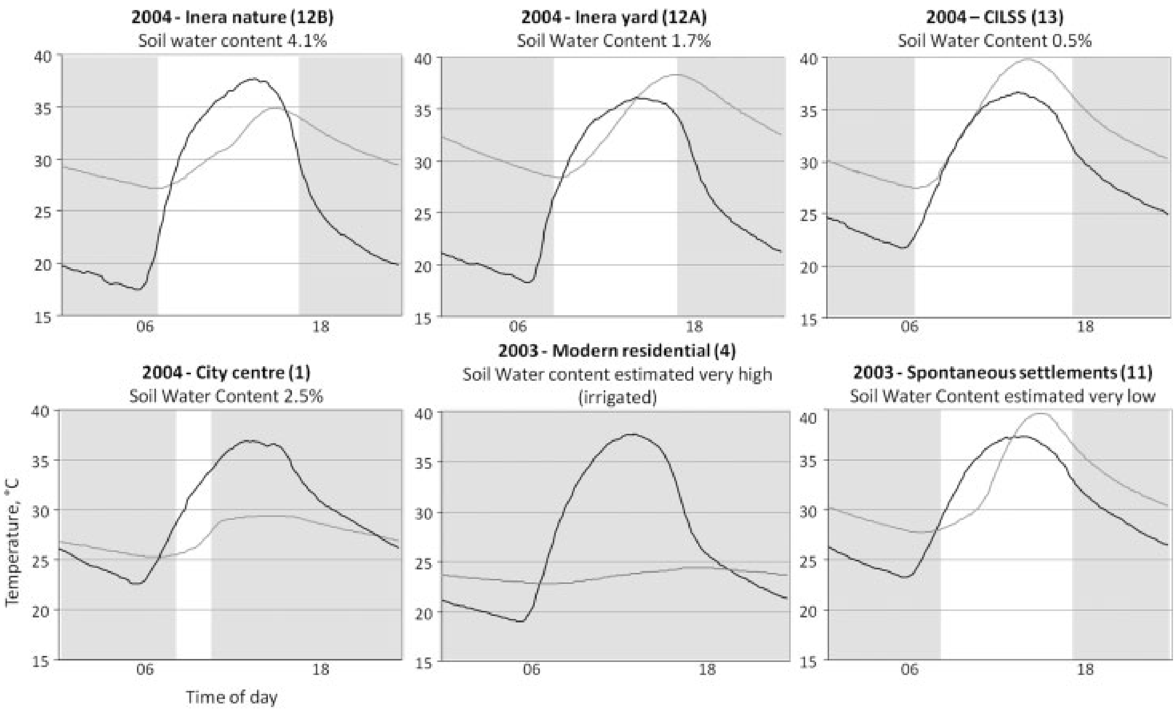


Figure 6. Diurnal soil (grey) and air (black) temperature as well as soil water content by weight at the examined locations in Ouagadougou. Shaded areas correspond to when the surface above soil measurement shaded from to direct radiation from the sun.

cooling the evening temperatures. However, in the simple regression analysis, effects of *bare soil* pointed to a very limited warming influence instead. The amount of *green vegetation* and *built up and paved* were more closely correlated ($R = -0.47$) than *green vegetation* and *bare soil* ($R = -0.39$). The lesser dependence of *bare soil* would thus allow a larger influence on evening temperatures. *Open water* was not significant for evening temperatures, and an increasing *shortest distance to reservoir* indicated an increase in temperatures. *Distance to urban centre* showed a very limited cooling influence on evening temperatures.

For daytime analyses, the most important parameter is availability of *open water*, cooling daytime temperatures. An increase in *shortest distance to reservoir* pointed to an increase in daytime temperatures as could be expected. The only other parameter affecting daytime temperatures

Table IV. Simple regression analysis based on temperature data from traverses and fixed site measurements *versus* land cover as well as shortest distance to reservoir and urban centre.

	Variable	Linear regression equation	R^2
Evening data	Green vegetation	$y = 3.60 - 0.11X$	0.74**
	Built up and paved	$y = -0.61 + 0.05X$	0.28**
	Shortest distance to reservoir	$y = 0.05 + 0.53X$	0.17**
	Bare soil	$y = 0.29 + 0.02X$	0.04**
	Open water	$y = 0.96 - 0.003X$	*0.00*
	Distance to urban centre	$y = 1.59 - 0.05X$	*0.00*
Day data	Open water	$y = -0.04 - 0.03X$	0.33**
	Shortest distance to reservoir	$y = -0.71 + 0.16X$	0.09**
	Distance to urban centre	$y = -0.98 + 0.15X$	0.06**
	Bare soil	$y = -0.69 + 0.008X$	0.04**
	Built up and paved	$y = -0.59 + 0.005X$	0.02*
	Green vegetation	$y = -0.58 + 0.006X$	0.01*

Land cover is based on percentage of area covered by the different parameters in a circle with radius 400 m from measurement point. Parameters placed in order of decreasing R^2 value.
* $p < 0.05$; ** $p < 0.01$.

Table V. Stepwise multiple regression analysis between temperature data from car traverses as well as fixed site measurement, and land use parameters as well as shortest distance to reservoir and to urban centre as shown in Table I and II.

	Variables included in final model	R^2	Beta coefficient
Evening data	Green vegetation	0.75	−1.021
	Bare soil	0.81	−0.410
	Shortest distance to reservoir	0.81	0.221
	Distance to urban centre	0.82	−0.141
	Built up and paved	0.82	−0.122
Daytime data	Open water	0.35	−0.576
	Green vegetation	0.43	0.367
	Shortest distance to reservoir	0.46	0.227

Land cover is based on percentage of area covered by the different parameters in a circle with radius 400 m from measurement point. Limit for in/excluding variables: 0.05.

was the amount of green vegetation, which showed a warming influence. Correlation between *open water* and *green vegetation* was very low ($R = 0.09$), allowing a greater independent influence of *green vegetation* on daytime temperatures compared to other parameters.

5. Discussion

5.1. Thermal effects of vegetation in Ouagadougou

The superior impact of green vegetation on the urban nocturnal thermal climate in Ouagadougou over all other land use parameters is evident. Strong intra-urban nocturnal temperature differences and a strong nocturnal cool island in the densely vegetated *forest/reservoir* area (5) are created most evenings, and sustained throughout the nights during the measurement periods (Figures 3 and 4). This pattern persists if including all other areas; regardless of urban or rural setting, the great majority of the cooler areas are covered with a large proportion of green vegetation. Spronken-Smith and Oke (1998) show results similar to this study (a PCI most intense in evenings and nights) in savannah and forest type parks in the hot summer climate of Sacramento, CA, while irrigated areas were mainly cooler during afternoons. A daytime cooling of vegetation does, however, not seem to be effective in Ouagadougou, and statistical analyses instead indicate a weak warming influence of green vegetation. This may be caused by lack of irrigation in most vegetated areas examined, together with the type of vegetation present. Studies of plant physiology have shown that plants can shut down their stomata and respiration process for water saving purposes during periods of large vapour pressure deficit and low soil moisture. This normally occurs around noon time and is often called midday depression. For example, Gindaba *et al.* (2004) show that native Ethiopian trees during water stress showed high level of midday depression. A study of Sahelian C4 grasses also shows that daytime stomatal closure is an important survival strategy for plants in the arid Sahelian climate (Maroco *et al.*, 2000). In this study, soil moisture was low in all examined areas, daytime temperatures generally exceed 35 °C and no precipitation fell during the measurement periods, indicating a high level of water stress is likely for all non-irrigated vegetation in Ouagadougou. Due to the water stress in this region during large parts of the year, it is also probable that parts of the vegetation are using CAM−photosynthesis, further decreasing daytime evapotranspiration. These two factors contribute to limited daytime cooling through the evapotranspiration process and instead enhanced effects during evening and nights, which would explain the strong nocturnal cooling influence of vegetation. An evapotranspiration process mainly active around sunset would correspond to greatly increased humidity levels in evening measurements in these areas. This pattern is evident in the two examined areas which are affected by vegetation but not of the reservoir; 4 and 14 (Figure 5). In these areas, diurnal humidity differences greatly exceed differences measured in other areas, thus supporting the idea of limited daytime cooling from vegetation evapotranspiration, but an important effect in evenings and nights. A midday depression in the evapotranspiration process would allow other parameters, such as a decreased albedo in densely vegetated areas, to be of higher importance, thus resulting in higher temperatures as indicated in statistical analyses. A greater importance of albedo over evapotranspiration cooling was also suggested as a reason for the high daytime temperatures in parks found by Jauregui (1991) and by Grimmond *et al.* (1996).

As irrigation would decrease water stress, the midday depression in plant transpiration would probably not be necessary where irrigated, thus latent heat absorption from plant transpiration would be active during the daytime, causing afternoon cool islands, as shown by Jonsson (2004) and Spronken-Smith and Oke (1998). The irrigated area in this study, *urban modern residential* (4), does not however follow this pattern. A reason for this might be that vegetation in this area still suffers from water stress during midday, due to the high daytime temperatures. A higher thermal admittance of paved streets in this area could further contribute to higher air temperatures, and the large trees could prevent ventilation of heated air as well as lowering albedo.

Daytime, areas with relatively high vegetation coverage that show lower temperatures are 5, 6, 7 and 8 (Figures 3 and 4). These are also covered by a large proportion of *open water* which was the most important cooling parameter during daytime, as also indicated by the positive beta coefficient for *shortest distance to reservoir*. The availability of water for manual irrigation in these areas may limit the need for midday depression, thus allowing evaporation cooling from vegetation during daytime as well. Furthermore, daytime temperatures in these areas are most likely primarily affected by the stronger influence by open water of the reservoir, as daytime wind speeds are higher creating a near surface mixing of thermal effects. The nocturnal cool island found in area 5 is instead likely to reflect influence by the forest rather than the reservoir, despite the fact that the area is covered by a large proportion of open water as well as vegetation. This is due to the combination of very calm nights and the high nocturnal thermal differences between this area and *reservoir, bridge* (7) (Figure 3). Such a temperature gradient could create thermally induced winds from the cooler towards the warmer area on calm and clear nights such as those during this study, as also presented by Thorsson and Eliasson (2003). The transportation of air has also been discussed by Spronken-Smith and Oke (1999) who suggest that the potential effects of a nocturnal PCI are not mainly gained inside the park but rather from the horizontal flow of cooler air into the surrounding area.

5.2. Urban heat island, building geometry and materials

Built up and paved areas, commonly considered primary factors in creating an UHI effect (Souch and Grimmond, 2006), appeared to have a warming effect on evening temperatures in Ouagadougou (Table IV). However, the multiple regression analysis showed that the independent influence was very limited (Table V). The Beta coefficient also indicates a cooling influence on evening temperatures. This is likely to be a misleading result of the very limited effect in combination with interaction of other parameters, rather than a true cooling influence of built up and paved areas on evening temperatures.

The UHI in the *urban centre* (1), the only area in this study with pronounced urban structure, is rather limited (Figure 3). Furthermore, equally high nocturnal temperatures are found in the *suburban spontaneous settlements* (11, Figure 4). Though the percentage of *built up and paved* coverage is similar in these areas, both building materials and geometry differ greatly. While the majority of the buildings in the urban centre are several floors and made with modern building materials, buildings in area 11 are mainly small single room homes made of earth bricks with tin roofs, and paved roads are nonexistent. This is in contrast to findings by Offerle *et al.* (2005) and Nasrallah *et al.* (1990), who discuss that the use of local materials would prevent increased nocturnal temperatures. Results from this study indicate instead that it is not the type of material or geometry, but rather presence or absence of vegetation that creates thermal differences. Though lack of vegetation is the most important parameter for increased nocturnal temperatures, an absence *of built up and paved* areas might have some effect as well. This can be seen in the non-vegetated, open areas, *urban open* (2), *rural dry north* (10) and *dry rural south* (13) (Figures 3 and 4). In a dry environment, effective radiative cooling at night due to a low thermal admittance of dry soils could cause open areas to cool to lower nocturnal temperatures than built up areas (Jonsson, 2004). As multiple regression analysis indicates, *bare soil* has a cooling influence on evening temperatures (Table V), generating higher temperatures in these areas compared to densely vegetated areas, but cooler than those in densely built areas. The slightly higher vegetation cover in area 2 compared to area 10 is a likely cause for the slightly lower temperatures in area 2. The mixed results of *bare soil* in statistical analyses (Tables IV and V) is, like *built up and paved*, likely a result of a complex interaction of many different factors creating the urban climate variations in this city.

During daytime, Offerle *et al.* (2005) show that, despite a higher albedo, daytime surface temperatures of bare undisturbed soil in the rural area could exceed surface temperatures in the residential and central area by 15 to 20 °C due to differences in thermal characteristics. Temperatures in drier soils exposed to solar radiation in this study exceed air temperatures by several degrees in the afternoon and throughout the nights (Figure 6). The great significance of direct solar radiation is evident especially in the *urban centre* (1), where the only factor that seems to affect soil temperature is the short exposure to solar radiation in the morning. However, no clear connection between soil and air temperature can be seen. For example, the smallest variations in soil temperatures were found in area 4, which display among the largest diurnal air temperature variations, while the opposite is true in area 11 and 13 (Figure 6). As soil temperatures are directly influenced by solar radiation which is likely to differ on short distances, the soil temperature will be inhomogeneous over larger areas. As the wind moves the air over this mosaic of different surfaces, the effect of each soil surface parcel on air temperature will be limited. This is also shown in a study by Eliasson (1996) where local surface temperature has little effect on air temperature due to the horizontal transport of air.

Since building structure in the Ouagadougou urban centre lacks the deep canyon structure, a canyon cool island effect as discussed by Johansson (2006) is most likely lost. Still, a limited shading effect by the buildings and few trees could possibly be the reason for lower daytime temperatures in the *urban centre* (1) compared to the open bare soil in the nearby *urban open* (2, Figure 3).

5.3. Thermal patterns around the reservoir

The significance of open water for lower daytime temperatures is evident in all areas in close proximity to the open water of the reservoir (areas 5–8, Figures 3 and 4). Statistical analyses also show a cooling influence of water and that temperatures increase with *shortest distance to reservoir*. Daytime data thus follow the expected pattern where the open water causes lower air temperatures due to latent heat absorption through evaporation, and by sensible heat transport if the water is colder than the air, as also explained by Saaroni and Ziv (2003). The stronger, predominantly northeasterly daytime winds in Ouagadougou are probably the cause for the stronger temperature decrease on the south side of the reservoir compared to the north (Figure 3).

Nocturnal effects of the reservoir are less clear. Simple regression analysis indicates that the impact of the reservoir (though not significant) on nocturnal temperatures is cooling (Table IV). Since the reservoir in Ouagadougou is shallow, water will be heated during day thus causing a sensible heat transfer from the water to the air during night. Expected effects would therefore be a warming influence on evening air temperatures. However, if excluding all areas but the area mainly covered by open water (*reservoir, bridge*, 7) in the statistical analyses, the influence of open water is slightly warming. In this area, measurements are collected on a narrow bridge above the water and therefore strongly influenced by the water. In the nearby *reservoir, south side* (6), which has similar vegetation cover but less open water than area 7, the temperature was lower. The warming effect of the open water on temperatures in area 6 is likely concealed by the stronger cooling influence of vegetation cover. This indicates that the primary effect of the open water is in fact warming but that effects are limited. The low nocturnal wind speeds preventing dispersion of the heated air above the water into surrounding areas further limits the spatial extent of effects. As the availability of water for manual irrigation allows more green vegetation in the reservoir surroundings, this secondary effect is a likely cause for the lower temperatures in all nearby areas (area 5, 6 and 8, Figures 3 and 4). A daytime cooling and a slight, spatially limited, night-time warming effect of open water is also presented in Tel Aviv by Saaroni *et al.* (2000).

Since direct effects of the reservoir appear to be more pronounced during daytime, while evening effects are complex and spatially limited, the main importance of the water itself is likely to be during daytime when cooling is much needed. For nocturnal influence, the usage of available water for manual irrigation thus enhancing nearby vegetation cover is of much greater importance compared to the water itself.

5.4. Implications for the urban climate of Ouagadougou

This study shows that *built up and paved* areas are not the major factors influencing the urban climate in Ouagadougou, hence the expected extreme urbanisation rate would not necessarily implicate a negative effect on the urban environment. This is in contrast to a study by Offerle *et al.* (2005) showing a large UHI in Ouagadougou that will intensify with increased urbanisation. The reason for the different results is likely found in the choice of rural reference. As discussed by Grimmond *et al.* (1993), selection of rural reference in urban–rural comparisons could significantly affect results. The rural area used in the study by Offerle *et al.* (2005) is located in the area here called *Suburban vegetated* (14), one of the nocturnally cooler areas with a relatively large coverage of vegetation, while the rural reference in this study is located outside city limits in the *rural dry north* (10), part of the warmer, dry Ouagadougou rural surroundings. As these two areas differ greatly in nocturnal temperatures it is likely that they would yield very different results for the UHI and thus greatly affect conclusions for future development.

The superior influence of vegetation (nocturnal) and open water (daytime) over all other land use parameters presented in this study could create great possibilities for enhancing comfort for the inhabitants. Introducing more open water surfaces, thus increasing potential for more green vegetation, would potentially reduce heat stress both day and night. However, as poverty is high and water scarce, possibilities for environmentally sound urban growth are limited. The increase in poor urban population is instead likely to create larger areas like the *suburban spontaneous settlements* (11), where temperatures, despite the use of local building materials, are among the highest both day and night. Continued overusage of unprotected rural areas for firewood, grazing and food search is likely to leave rural surroundings bare and dry. The predicted rapid urban growth in Ouagadougou is therefore likely to result in negative effects for both inhabitants and environment regardless of effects on the UHI.

6. Conclusions

Results from this study show a nocturnal cool island that considerably exceeds the UHI effect in the city of Ouagadougou, Burkina Faso. Average urban–rural temperature differences from car traverses demonstrate that while the evening UHI reach only 1.9 °C, the cool island in a densely vegetated area is 5.0 °C cooler than the dry rural reference. Temperature differences of the same magnitude persist throughout the night between vegetated and non-vegetated areas regardless of urban or rural setting.

Green vegetation is the most important land-cover parameter for generating nocturnal temperature variations, and results indicate that the great effects of vegetation are generated by a strong evapotranspiration cooling during evenings. The percentages of *built up and paved* areas and *distance to urban centre* show little influence on the nocturnal thermal variations. While vegetation is the superior factor during evenings and nights, effects were greatly reduced during daytime, probably due to a limited daytime evapotranspiration process. The open water of the reservoir is instead the most important parameter during daytime, generating cooler temperatures in all areas in close proximity to the reservoir. Nocturnal effects of the open water of the reservoir are very limited, and the usage of available water for irrigation, thus increasing nearby vegetation cover, is probably of much greater importance compared to the water itself.

Results presented here show that the urban land cover together with climatic region can create significant differences in the physical properties driving the urban climate in a dry-tropical city compared to those commonly found in temperate cities.

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