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ORIGINAL PAPER

Thermally induced wind patterns in the Sahelian city of Ouagadougou, Burkina Faso

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Abstract The urban surface wind field in the dry-tropical city of Ouagadougou, Burkina Faso was studied based on data collected at one urban and one suburban station during early dry season. An intra-urban thermal breeze, creating almost opposite wind directions at the two sites, was found during nights with high atmospheric stability. The high atmospheric stability suggests a decoupling of the surface wind layer from the layer above, allowing the wind system to develop due to the strong intra-urban temperature gradients in the city. Frequent temporary breakdowns of the thermal wind system were noticed, generally generating a turn in wind direction towards that of the regional wind, thus indicating a re-coupling with a stronger wind flow in the wind layer above.

1 Introduction

Thermally induced wind patterns exist in many different environments where a horizontal temperature and pressure gradient due to uneven heating/cooling of surfaces generates a local wind system (Oke 1987). The most studied of these circulation patterns are sea/land breeze (e.g. Miller et al. 2003) and slope/valley wind systems (e.g. Haiden and Whiteman 2005). Thermal wind systems have also been noted in urban areas with a strong urban heat island (UHI), i.e. where differences in surface characteristics and activity create higher temperatures in the urban area compared with its rural surroundings. The centripetal wind system then created in urban areas is most developed during nights with high atmospheric stability, low wind speeds and a strong radiative cooling and generally referred to as urban heat island circulation (UHIC) or country breeze (Shreffler 1979; Eliasson and Holmer 1990; Barlag and Kuttler 1990–1991; Haeger-Eugensson and Holmer 1999; Savijärvi and Liya 2001; Lemonsu and Masson 2002).

In a few studies, the presence of an intra-urban thermal breeze (IUTB), or a park breeze, has been examined. It is caused by different surface characteristics generating temperature gradients within an urban area, often due to cooler temperatures in urban vegetated areas (Eliasson and Upmanis 2000; Honjo et al. 2003; Thorsson and Eliasson 2003; Jansson et al. 2007; Narita et al. 2009). These thermal wind systems are relatively weak and require strong ground based temperature inversions and high atmospheric stability. During this type of atmospheric conditions, temperature differences of approximately 1.5 K between a park and adjacent built areas created a park breeze of up to 0.5 ms^{-1} in a large park in Gothenburg, Sweden (Eliasson and Upmanis 2000). An IUTB of up to 0.3 ms^{-1} was also found in the same city around a centrally located open gravel area during similar atmospheric conditions (Thorsson and Eliasson 2003).

Though focus in the studies of UHIC or IUTB have mainly have been on cities in temperate regions, some studies have described the complex interactions between UHIC, slope/valley and/or sea breeze wind systems in subtropical cities (Comrie 2000; Oliveira et al. 2002; Brazel et al. 2005). Other studies of urban circulation patterns in cities in subtropics have focused mainly on effects for dispersion of air pollutants (Romero et al. 1999; Ulke 2004; Arkouli et al. 2010). Despite an extensive literature search, the authors found no published studies of UHIC or IUTB in cities in the tropics.

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The UHI in tropical cities often show a maximum during dry season (Roth 2007). Though the UHI generally is slightly weaker compared with temperate cities (Wienert and Kuttler 2005), several studies of tropical cities show considerable UHIs; e.g. Singapore: 5.7 K (Chow and Roth 2006), Dar es Salaam: 2–4 K(Jonsson 2004) and Mexico City: up to 7.8 K (Jauregui 1997). Jauregui (1997) also found intra-urban temperature differences of over 4 K. A study of the dry tropical city of Ouagadougou, Burkina Faso showed that though the nocturnal UHI was relatively small (1.9 K), a strong cool island found in a densely vegetated area caused intra-urban temperature differences of on average 6.9 K within the city (Linden 2010). Offerle et al. (2005) also found large nocturnal temperature differences up to 8 K between an urban and a suburban site in Ouagadougou. Intra-urban cool islands around parks were also found in for example the subtropical cities Tel Aviv (Saaroni et al. 2000) and Taipei (Chang et al. 2007).

As described by Haeger-Eugensson (1999), a strong stabilisation of the air column causes a frictional decoupling of the surface wind layer from the layer above. This decoupling suppresses vertical motion in favour of horizontal motion, which allows the formation of thermal wind systems at the surface. The same atmospheric conditions may also develop a nocturnal low-level jet (NLLJ) at the height of the regional wind layer. The onset of this NLLJ generally coincides with an increase in stability and a decoupling of the wind layers in the evenings (Blackadar 1997). The process of decoupling and development of a NLLJ is also described by Kallistratova et al. (2009). Acevedo and Fitzjarrald (2003) show that an increase in the large-scale winds aloft can cause the surface to reconnect to the wind layer above during the night. A strong NLLJ may thus cause an increased downward turbulence and wind shear which reaches surface level thus decreasing stability and causing a re-coupling of the wind layers. Temporary increases in turbulent downward mixing during stable atmospheric conditions were noticed in connection to studies of nocturnal ozone peaks (Samson 1978; Corsmeier et al. 1997; Strassburger and Kuttler 1998; Reitebuch et al. 2000; Salmond and McKendry 2002; Eliasson et al. 2003). Several of these studies attributed parts of the nocturnal ozone peaks to turbulent downward mixing caused by the evolution of a NLLJ, and noticed that this correlated to a decrease in or breakdown of the stable atmospheric stratification (Corsmeier et al. 1997; Reitebuch et al. 2000; Salmond and McKendry 2002). Lothon et al. (2008) describe the behaviour of a very consistent NLLJ over the Sahel region in West Africa, and show that the best signature of the NLLJ close to surface can be seen as an increase in turbulent kinetic energy and skewness of the air vertical velocity. Impacts of a West African NLLJ are examined by Washington et al. (2006) who show that a NLLJ originating from the Bodélé depression in Chad is likely to play a key role in potential advection of dust over the region.

The local wind field and turbulent diffusion play a major role in dispersion of urban-derived pollutants (Arnfield 2003; Papanastasiou and Melas 2009). Urban thermal wind systems have been linked to episodes of high concentrations of air pollutions, for example; maximum pollution concentrations occurred during periods when a slope-wind system was active in Santiago (Romero et al. 1999). As noted above, UHIC and IUTB are mainly observed during low regional wind speeds and stable atmospheric conditions, which is also when highest concentrations of air pollutants are generally found. This type of wind system could therefore be of great importance for transport and dispersion of pollutants during episodes of poor air quality and should be taken in to consideration during urban planning (Barlag and Kuttler 1990–1991).

In this paper, we compare a central and a suburban site in order to analyse the nature and origin of a local thermal wind system found in the Sahelian city of Ouagadougou, Burkina Faso, located inland on flat terrain. Temporary breakups of this wind system are discussed in relation to decoupling/re-coupling of the surface wind from the wind flow aloft. The potential of intra-urban horizontal temperature gradients for generating a thermal wind system in the city is examined.

2 Study area

Burkina Faso is located in the in the hot semi-arid steppe climate of the West African Sahel region (Fig. 1). The capital, Ouagadougou (12°22′ N, 1°31′ W, 300 masl), has a population of approximately 1.2 million people with a population density of about 660 inhabitants/km^2. Urbanization is projected to generate an exceptional growth of urban dwellers that will quadruple the number of urban inhabitants over the next 30 years (United Nations Population Division 2008). Climate consists of a dry period from October to April with less than 100 mm rain and a wet period from May to September averaging 700 mm of rain (Direction de la Météorologie Nationale 2001). Average monthly temperatures range from 25°C to 33°C. During the dry period there are predominantly north-easterly, very dry, winds from the Sahara desert. Wind speeds are in the beginning of the dry season generally low with a daily average around 2 m/s (Direction de la Météorologie Nationale 2001) but by February wind speeds often increase and dust storms are common.

Previous studies of the urban climate in Ouagadougou have shown large intra-urban thermal variations of up to 9.1 K (Linden 2010), and a generally very high nocturnal

Fig. 1 Location of Burkina Faso with the Sahel area shaded, and a map of the capital Ouagadougou, classified based on local climate zones suggested by Stewart (2010). *X marks*, the *urban* (south) and *suburban* (north) measurement stations

atmospheric stability (Eliasson et al. 2009). Air quality in the city is often very poor as a result of emissions from both local and regional sources (Linden et al. 2007; Boman et al. 2009; Eliasson et al. 2009), and pollutant concentrations vary with atmospheric stability (Boman et al. 2009). Studies of the low troposphere in the Sahel region have shown a consistent year-round nocturnal low-level jet (NLLJ) centred at 400 m aboveground level with wind speeds around 15 ms^{-1} and a maximum at approximately 0500 UTC (Lothon et al. 2008). In November and December, the NLLJ is generally coming from the north or east and present over 90% of the nights. This NLLJ has been detected in locations both N (Niamey, 13° N, also very similar to Ouagadougou in topography and general climate), and south (Nangatchori, 09° N) of Ouagadougou.

The urban structure in Ouagadougou is open and dominated by low buildings, sparse vegetation and many dry, open areas spread out over the city (Fig. 1). Following classifications of local climate zones as suggested by Stewart and Oke (2010), the urban centre consists mainly of open-set midrise building structure. Vegetation is scarce, building materials are mainly modern, such as concrete or tiles, and most roads are paved. Planned residential and commercial areas surrounding the urban centre are mainly of open-set low-rise structure with a higher percentage of local materials such as clay bricks. Outside the city centre only a few main roads are paved. Irrigation is sparse in the city with the exception of high-income residential areas and high-end hotel and business grounds. Located at the outskirts of the city are spontaneous settlements of lightweight low-rise type. These are rapidly growing, very poor, densely inhabited neighbourhoods of temporal houses made of earth bricks with tin roofs where most new inhabitants end up as they reach Ouagadougou. Deforestation caused by heavy search for firewood, food and grazing, has left immediate surroundings of Ouagadougou bare and dry, with little vegetation. A large reservoir (max. depth 2 m, area ~2.2 km^2) stretches along the north part of the city centre. Around the reservoir are more vegetated areas, used for growing food-crops and other plants as well as for animal grazing grounds. A large park/forest (area ~2 km^2) with dense tree cover is situated east of the reservoir.

3 Methods

The results in this study are based mainly on data collected at one *urban* and one *suburban* measurement site, marked in Fig. 1 and shown in Fig. 2. Stations are hereafter in italics. Instrument information is presented in Table 1. Instrumentation at the *suburban* station is located at a height of 1 m above ground (wind 2.3 m) at the Direction de la Météorologie National (DMN). Immediate surround-

Fig. 2 Satellite image and photos of the *urban* (left) and *suburban* (right) measurement stations. *Error marks*, location of the stations

ings are low bush/shrub and the only nearby building is the Met-office located ~100 m to the south-east. To the south and west are open-set low-rise, and to the north and east are open and close set trees. Instrumentation at the station located in *urban centre* is placed at 1 m above roof top level (wind 3.3 m), at a height of 13 m aboveground (wind 15.3 m). Surroundings were of urban character with buildings mainly of similar height as the station but some taller buildings were located in the area.

Identical instrumental set-ups were placed at these two stations to measure wind, incoming and outgoing long and short wave radiation, air temperature and humidity. Wind and radiation data were monitored at a frequency of 4 Hz, with averages logged each minute. Temperature and humidity were monitored at a frequency of 0.2 Hz, which due to the instrument response time would result in a slight time displacement (5–10 s). This is however considered small enough to disregard in the use of temperature data here (10 min averages in calculations of atmospheric stability). Data were collected in 2007 during the period November 23 to December 09. Due to occasional instrumental problems and power failure resulting in data loss, some days were not suitable for use in the analyses. Since the examined wind pattern is nocturnal, a total of 13 days where night time data coverage was >90% at both stations was chosen for further analysis (Table 2).

Both stations were located within the canopy layer, where stratification generally is neutral (Oke 1987). Since the accuracy of temperature measurement was lower than the suggested correction for temperature with height during neutral conditions, no correction was made for the height difference of the temperature measurements. In stability calculations and in correction of wind speed, a zero-plane displacement of two thirds of the building height was used for the *urban* station. To adjust for station height differences, wind speed at the urban station was reduced using a power law relation by Davenport (1965).

Data was divided in two groups of different atmospheric stability at the ground level *suburban* station based on calculations of Radiation Richardson number, $\mathrm{Ri}_{\mathrm{rad}}$ (Mahrt and Ek 1984);

$$\mathrm{Ri}_{\mathrm{rad}} = -\left(\frac{g}{\theta \rho C_{\mathrm{p}}}\right)\left(\frac{Rz}{u^3}\right)$$

were g is the gravitation force (ms^{-2}), θ the potential temperature (K), z the height of measurements above ground surface (m), ρ the air density (gm^{-2}), C_{p} the specific heat of air ($\mathrm{J\ kg}^{-1}\ \mathrm{K}^{-1}$) and u the horizontal wind speed (ms^{-1}). R is expressed in $\mathrm{K\ ms}^{-1}$ and depends on net

Table 1 Information of instruments used for this study

Instrument	Parameter measured	Measurement frequency	Response time	Instrument height (m.a.g.l.)	Measurement accuracy
Ultra sonic anemometer Young 8100	Wind speed (v, u, w)	4 Hz, data saved as 1 min averages	<1 s	Urban: 15.3 m Suburban: 2.2 m	Wind speed: ± 1% Direction: ±2°
Radiation Kipp&Zonen, CNR1	Incoming and outgoing long and short wave radiation	4 Hz, data saved as 1 min averages	<1 s	Urban: 13 m Suburban: 1 m	Daily totals± 10%
Rotronic HYGROMER MP 100A	Air temperature and relative humidity	0.2 Hz, data saved as 1 min averages	10–15 s	Urban: 13 m Suburban: 1 m	T_{air}: ± 0,3 K Rh: ± 2%

Table 2 Description of the nights (between 20:00 and 08:00) included in the analysis. Main wind direction represents the direction from which the majority of measured winds originated. Diurnal ΔT_{air} show the difference between the maximum temperature the previous day and the minimum temperature the described night. Wind speed is adjusted for height

Date	Average wind speed (ms^{-1})		Main wind direction		Average Ri_{rad}		Diurnal ΔT_{air}	Atmospheric conditions
	Urban	Suburban	Urban	Suburban	Urban	Suburban	Suburban	
Nov 23–24	0.5	0.2	NE[a]	N	0.19	0.44	23.1	Extremely stable
Nov 24–25	0.5	0.3	N[b]	N	0.11	0.41	20.5	Extremely stable
Nov 25–26	0.5	0.3	NW[c]	N	0.14	0.37	19.0	Extremely stable
Nov 27–28	0.7	0.4	E[d]	N	0.16	0.45	21.6	Extremely stable
Nov 28–29	0.7	0.4	SW[e]	N	0.15	0.37	20.2	Extremely stable
Nov 30–Dec 01	0.4	0.2	SE	N	0.29	0.77	21.2	Extremely stable
Dec 02–03	1.4	1.3	E	E	0.00	0.00	15.2	Moderately stable
Dec 03–04	1.2	0.9	E	E	0.01	0.01	14.1	Moderately stable
Dec 04–05	0.9	0.7	E	NE[f]	0.01	0.05	12.9	Moderately stable
Dec 05–06	1.1	0.8	E	E	0.01	0.02	14.2	Moderately stable
Dec 06–07	1.1	1.0	E	E	0.01	0.02	13.0	Moderately stable
Dec 07–08	0.8	0.3	SE	N	0.03	0.30	19.0	Transition
Dec 08–09	0.4	0.3	SE	N	0.31	0.52	21.2	Extremely stable

[a] Winds from SE and S for 2 h

[b] Winds from E and S for 4 h, see Fig. 5

[c] Wind direction divided almost equally between NW, W and SE

[d] Wind from SE until 02:00, after that wind from E–NE

[e] Wind direction divided almost equally between SW, SE and NE

[f] Wind from N and NE during 3 h of higher stability

radiation, soil heat flux and actual evaporation. The latter two were unknown here, but as they contribute relatively little and counteract each other, they were considered negligible. This may result in slight errors in the time of transition between stable and unstable conditions but general patterns will not be affected, which allowed us to use Ri_{rad} as a general indication of the atmospheric stability as well as for inter-comparison of the days included in the study. Average nocturnal Ri_{rad} generally exceeded 0.01 during the whole period and remained during the more stable period always above 0.37 (Table 2). Mahrt et al. (2001) show that a thermal wind system (katabatic winds) can start to develop during conditions with Ri_{rad} as low as 0.01. The days in this study were therefore divided in to moderately stable and extremely stable conditions. Seven nights were found to be extremely stable (Nov 23–Dec 01 and Dec 08–09) and 5 nights were moderately stable (Dec 02–07). One night (Dec 07–08) was found to be in the transition between the two stability periods and is therefore treated separately.

To best show the nature of the thermal wind system, time separating night and day was selected to 20:00 (08:00) when treating the data as groups. This is approximately 1 h after atmospheric stability generally starts to increase (decrease) to allow the thermal wind system to be built up (broken down) and thus show effects of the thermal wind system.

In addition to the data presented here, temperatures measured simultaneously at different locations within Ouagadougou were retrieved from Linden (2010), and used to calculate horizontal thermal gradients in the city. These data are based on a total of 37 days of temperature measurements from six stations in 2003 and 20 days from two stations in 2004, during similar climatic conditions (stable atmosphere and low wind speeds), and time of the year as the present study and thus gives a good picture of the intra-urban temperature patterns in Ouagadougou. For information of instrumentation and data treatment, see Linden (2010).

4 Results

4.1 General wind patterns

The extremely stable nights were characterized by low nocturnal winds speeds (average<0.5 ms^{-1} at the *suburban* station), hazy but cloudless skies and large diurnal temperature variations exceeding 19 K. The moderately stable period showed slightly higher wind speeds (average >0.5 ms^{-1} but rarely above 1 ms^{-1} at the *suburban* station), a variable cloud cover and smaller diurnal temperature variations below 16 K (Table 2). Wind speeds are consistently higher at the *urban* station compared with the *suburban*.

Data from the two stations are shown as 12 h wind roses (Fig. 3) for the periods with extremely stable and moderately stable nights respectively. Wind speeds were lower during the extremely stable period but in both periods, wind speeds were higher daytime compared with night time. During the moderately stable period, winds were mainly easterly at the two stations both day and night but with somewhat more north-easterly component at the *suburban* station. In the extremely stable period daytime winds were generally northerly at both stations with a slightly larger variability at the rooftop *urban* station. A more complex wind patterns were visible during night time. There was a clear difference in wind direction between the two stations. At the *suburban* station wind directions were the same as daytime, mainly north and north-easterly while the *urban* station shows a distinct turn towards south-east during the night, though variability is large. This shift in nocturnal wind direction at the *urban* station is also visible in Table 2.

NCEP/NCAR Reanalysis Data (NOAA 2010) was used to get a general idea of the regional wind direction during the period. This show a general regional wind flow from north-east which agrees with day time winds at the suburban station. Due to the low resolution of Reanalysis data which prevent detailed information to be obtained about winds over Ouagadougou, daytime winds at the suburban station were assumed to show regional winds direction. The *suburban* daytime wind direction was retained at both stations during the moderately stable nights and also at the *suburban* station during the extremely stable nights. The exception are the extremely stable nights at the *urban* station where a large share of the observations shows wind directions more or less opposite to the regional wind, i.e. indication of a thermally induced wind system (Eliasson and Holmer 1990).

To further examine winds at the *urban* station during the extremely stable period, the night time period was divided in two parts (20:00–02:00 and 02:00–08:00). Wind roses separated with regards to wind speed (below or above 1 ms^{-1}) are presented in Fig. 4. Winds below 1 ms^{-1} amount to 90% during the first part of the night and 63% during the later part. Weak winds blew mainly from south-east, while higher wind speeds generally originate from between north and east. A similar analysis of winds at the *suburban* station (not shown in graph) shows generally northerly winds in both wind speed classes and a low frequency of wind speeds above 1 ms^{-1} throughout the night.

4.2 Case studies

To better understand the large variability in winds at the *urban* station, case studies showing atmospheric stability (Ri_{rad}) at the *suburban* station together with changes in

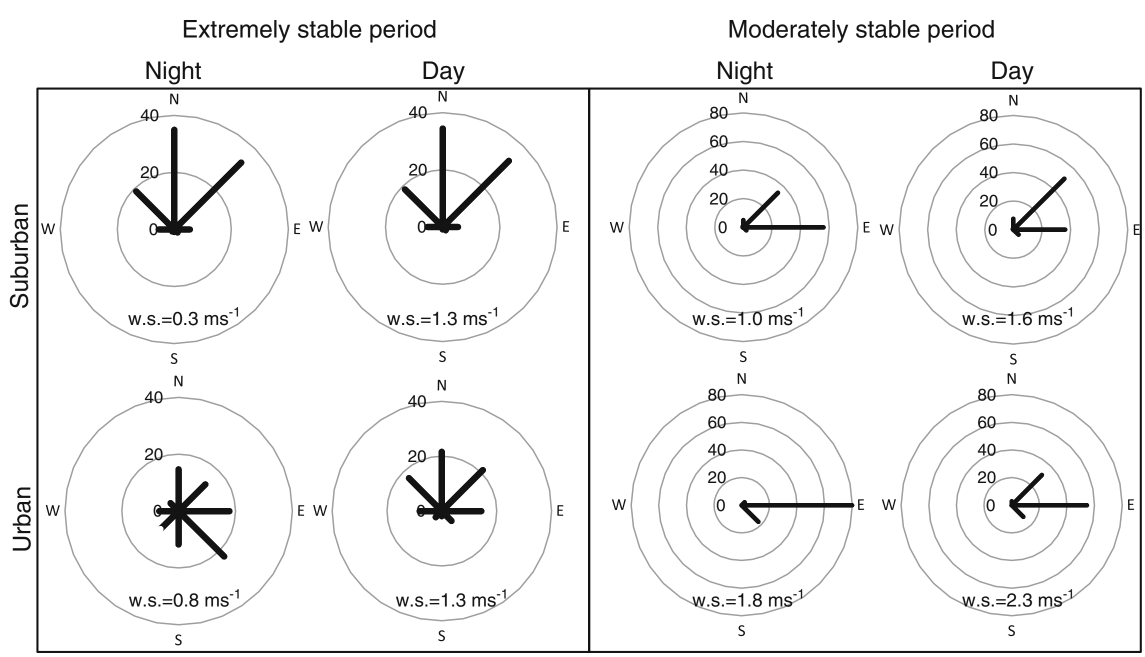


Fig. 3 Winds directions based on 1-min data, divided in eight classes and shown as percentage in each class. Data presented are separated into night (20:00–08:00) and day (08:00–20:00), as well as in to extremely and moderately stable period (days classified according to stability situation the following night). Average wind speed in ms^{-1} for each situation displayed at the base of each wind rose. The similarity between day and night at the *suburban* station during the extremely stable period is correct. Please note the differences in scale between stability periods

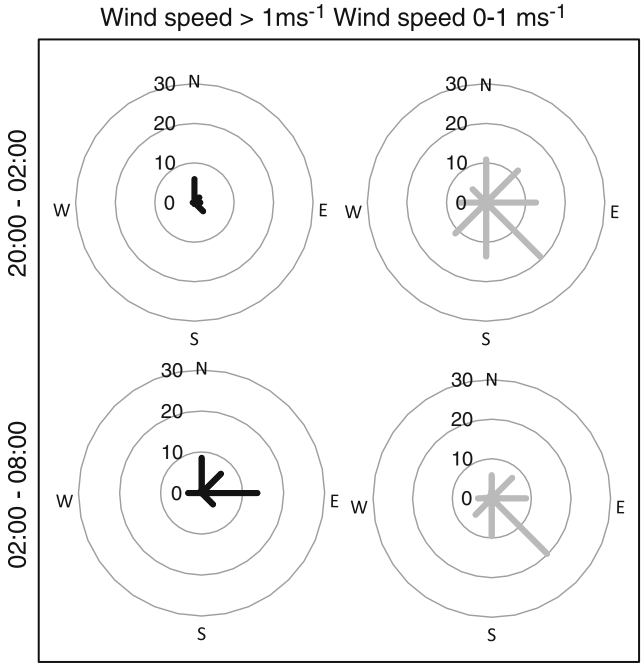


Fig. 4 Nocturnal wind directions at the *urban* station during the extremely stable period, based on 1-min data, divided in eight classes and shown as percentage in each class. Wind direction is also separated in regards to wind speed (w.s.>1 ms^{-1} and w.s.<1 ms^{-1}) and time of night (20:00–02:00 and 02:00–08:00)

wind speed and direction with time at both stations are presented in Figs. 5, 6 and 7. Atmospheric turbulence was analysed but appeared to be strongly affected by fetch roughness which differed depending on direction. Consequently, there was not a clear relation between observed turbulence measurements and atmospheric stability and turbulence is therefore not included in the analysis. Figure 5 shows a night (Nov 24–25) during the extremely stable period. At the *suburban* station the daytime (regional) wind was north-west turning slightly towards the north just before sunset. This direction was retained the whole night. Wind speed decreased considerably at sunset and stayed low throughout the night with one short increase in wind speed at around 3:30 am. Winds at the *urban* station were south-easterly during the day and north in the beginning and the end of the night but with clear change in the middle of the night when it gradually veered to east, south and west before returning to northerly directions. Wind speed decreased at sunset, but stayed higher compared with the *suburban* station until 23:00. Then atmospheric stability increased (Fig. 5 upper panel), wind direction started to turn and wind speed decreased further, suggesting decoupling of the surface layer followed by the start of the thermal wind system. At approximately 3:30 wind direction returned to north, wind speed increased and Ri_{rad} showed weak stability, thus indicating a re-coupling of the wind layers throughout of the night with no obvious thermal wind system presented.

Figure 6 shows a night (Dec 08–09) with unusually high atmospheric stability following a day with low wind speeds. The main wind directions are almost opposite at the two stations (Table 2). At the *suburban* station daytime wind direction was from north-east, backing slightly towards north when wind speeds decreased at

Fig. 5 Radiation Richardson number at *suburban* station and change in wind speed and direction (10-min average) over time on November 24–25 (extremely stable period) at both stations

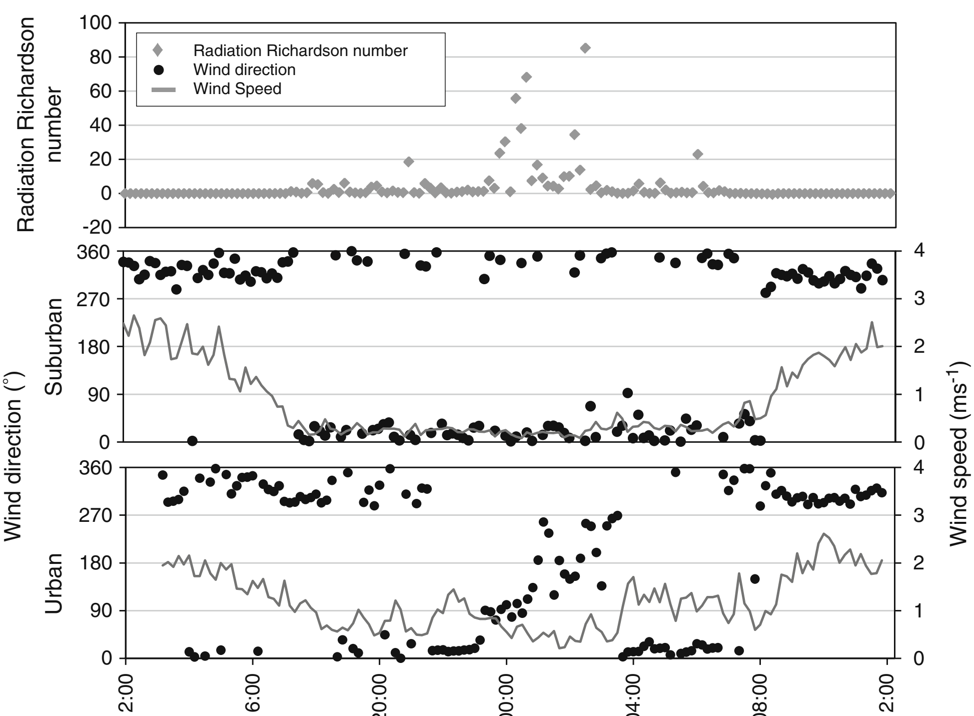
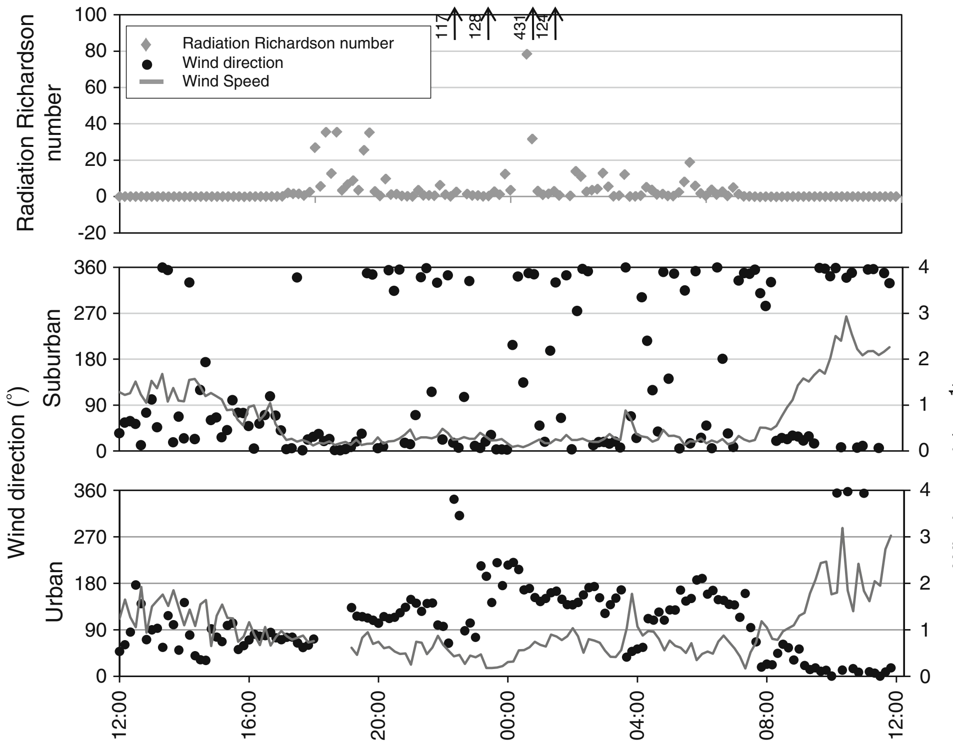
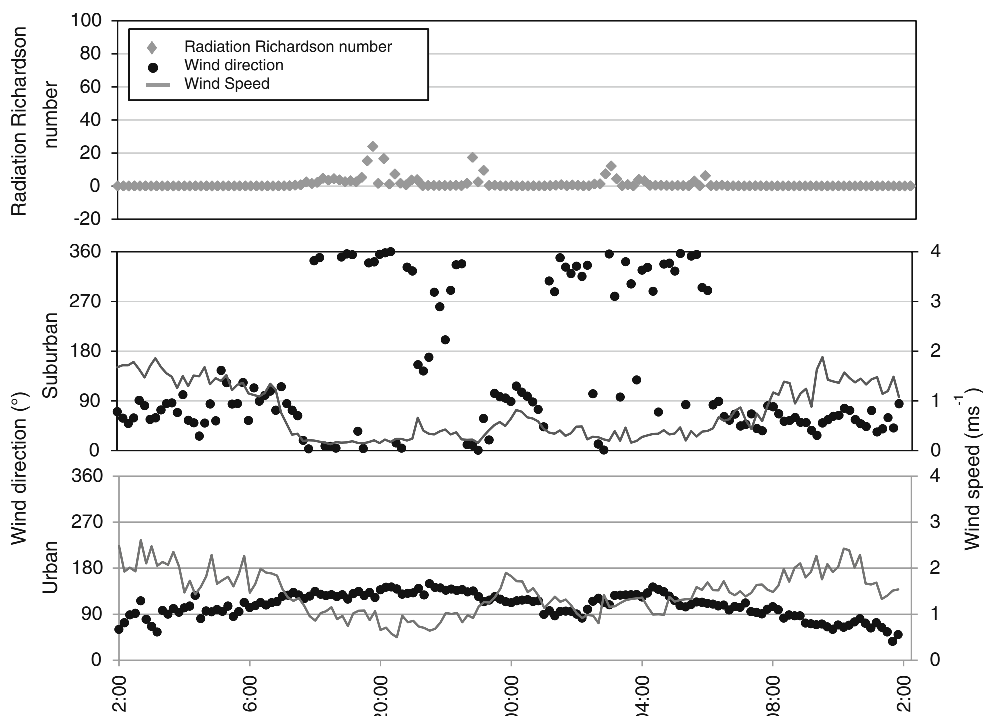


Fig. 6 Radiation Richardson number at *suburban* station and change in wind speed and direction (10-min average) over time on December 08 to 09 (extremely stable period) at both stations



sunset. Wind speed stayed very low throughout the night with a short increase around 3:30. Wind direction remained mainly north until sunrise with some scattered directions especially after midnight where also directions from south occurred. At the *urban* station wind speed slowly diminished until midnight and then it rose to a slightly higher level with a peak just before 04:00. Wind direction turned to south-east about 19:00 simultaneously (the exact timing is unfortunately obscured by a small gap in the monitoring) with the increase in stability (Ri_{rad}). Wind direction remained south-east and even south-west for most of the night except for two short breaks. During

Fig. 7 Radiation Richardson number at *suburban* station and change in wind speed and direction (10-min averages) over time on December 07–08 (transition between moderately and extremely stable period) at both stations. Situation with easterly winds aloft and low wind speeds at the *suburban* station



the first wind backed to east and further to north-west and then veered to east and south-west. Wind speed decreased during this break and was very low when the wind blew from south-west. However, during the second break at 04:00 wind backed to north-east simultaneously with a wind speed increase that also appeared at the *suburban* station. This night the stability was unusually high and the thermal wind system developed within an hour after sunset. The surface thermal wind system then remained most of the night. Breakdown of the thermal wind system occurred only during the two short episodes.

These two case studies (Figs. 5 and 6) confirm a difference in nocturnal wind pattern between the two stations and that an increase in wind speed generally occurs at the same time as a change in wind direction. The extremely stable nights not shown in detail follow the same pattern as the case studies above, though time and duration of changes in wind vary, and thus the periods with a thermal wind system and periods when the thermal wind breaks down. This indicates that deviations from the regional wind direction are accompanied by a decoupling of the lower wind layer from the layer above and development of a local thermal wind system during periods of low wind speeds and high atmospheric stability. An increase in wind speeds is likely connected with a re-coupling of the wind layers. Indications of this decoupling and re-coupling vary both in time of occurrence (though they are more frequent during the later part of the night) and number of occurrences during a night, thus resulting in the large variability in nocturnal wind directions at the rooftop *urban* station (Fig. 3). The local wind system is mainly visible at the rooftop *urban* station during the extremely stable periods.

The last case study presented (Dec 07–08, Fig. 7, Table 2) shows a seemingly different situation during the transition between the moderately and extremely stable periods. These 24 h are not included in either of the stability periods. In this case it was the *urban* station that had a fairly stable wind direction from east-north-east during the day, slowly veering to south-east about 21:00 and backing to east in the morning. Wind speed decreased slowly to a minimum at 20:00, increased again at midnight and was relatively high for the rest of the night. In this case the regional wind direction was similar to the thermal wind at the *urban* station presented in the previous case studies, thus a local thermal wind would generate little change in wind direction in this case. This night it was instead at the *suburban* station where the wind direction changed when stability increased and wind speed ceased. Directly after sunset, the direction backed to north for some hours. At 21:00, it turned to south-east (the same direction as the *urban* station) simultaneously with an increase in wind speed. Then at about 23:00 wind direction returned to north for a brief period at the same time as stability increased and wind speed decreased. This was followed by a wind speed peak and the direction became the same as at the *urban* station. Later wind direction intermittently changed between the north-west sector and east. In this case the thermal wind system was able to appear at the *suburban* site when stability increased. The situation was however such that slight increases in wind speed could cause a breakdown of the thermal wind system and a re-coupling of the surface layer and thus a reestablishment of the regional wind direction at the surface. This pattern can on occasion also be seen during the moderately stable period, and is the reason for the NE winds at the *suburban* station on Dec 04–05 (Table 2), when stability temporarily increases at this station (not shown in graph). Episodes when the local wind system is present at the *suburban* station during the moderately stable period are less frequent and generally at shorter intervals compared with the *urban* station during the extremely stable period.

Simultaneously recorded temperature data showing the distribution of temperature gradients driving the thermal wind system were not available. Instead, temperature data presented in Linden (2010) was used. These data correspond to the same type of weather as in the present study and land cover characteristics remain the same. Data used here was available from all locations at 20:00 h. At midnight, data from the location on the road across the reservoir (height approximately 2 m above the water) was not available. The exceptionally large thermal capacity of water is likely to generate a slow cooling rate at this site. Cooling rate of the water in a lake in the comparable summer climate of Tel Aviv was approximately 0.3 K (Saaroni and Ziv 2003). Cooling rates of other areas with no or much less open water in Ouagadougou was between 0.8 and 1 K for the same time of day (Holmer et al. submitted). Based on this, in combination with the high atmospheric stability and low wind speeds in Ouagadougou preventing turbulent mixing of air from surrounding areas, we assumed that a cooling rate of 0.3 K was applicable for the area across the dam. A cooling rate of 0.3 K was thus used to calculate temperature at midnight at this location.

The temperature gradients calculated on data for the locations where data were available in are shown in Fig. 8. Urban–rural gradient were weak, while intra-urban temperature gradients were relatively strong (see Linden 2010 for more information). This shows that the intra-urban rather than the urban–rural temperature field create the driving force for the thermal wind system that is observed in Ouagadougou. The heat centre at 20:00 was located in the city centre, and cooler areas were densely vegetated. By midnight, the heat centre had moved to the reservoir, with a relatively strong temperature gradient from the city centre, as well as from vegetated areas, towards the reservoir. Thus, the

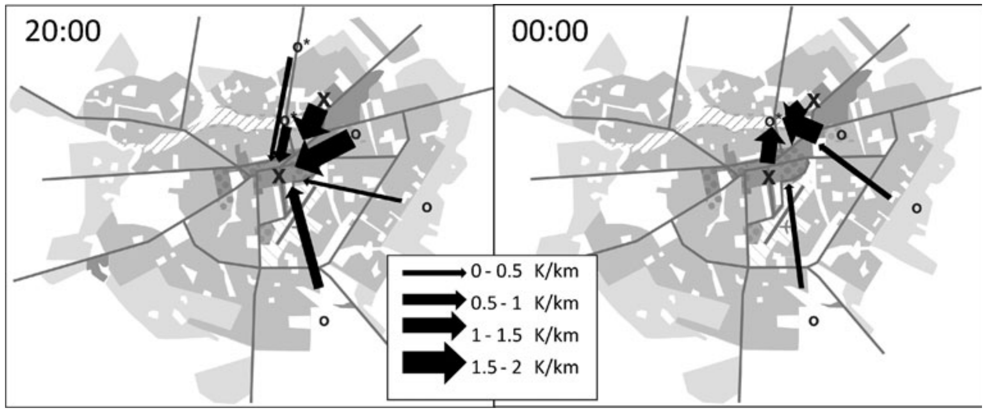


Fig. 8 Temperature gradients at 20:00 and 00:00 in Ouagadougou based on temperatures presented by Linden (2010). Map shading as in Fig. 1. *Arrows* represent the strongest temperature gradient found between measurement points at the times presented. *X marks*, locations for wind measurement in this study; *circles*, locations of temperature measurements; *circles with asterisk*, temperature only available at 20:00. Temperature for the location marked with *asterisk* included in the map for 00:00 have been calculated, see text for method. Please note that *arrows* do not represent winds

directions of the gradients change as the night goes on and so the conditions for the intra-urban thermal wind system.

5 Discussion

5.1 Characteristics of the local wind system in Ouagadougou

A local urban thermal wind system was found in Ouagadougou which generated almost opposite wind directions at the *urban* and *suburban* stations, approximately 4 km apart but both located well within the city limits. The local wind system was observed each night when stability was high (i.e. throughout the extremely stable period, during the transition from moderate to extreme stability and during shorter periods of increased stability during the moderately stable period). This is in agreement with other studies of local thermal wind systems, for example; the atmospheric stability was found to be of great importance to the onset of an UHIC (Haeger-Eugensson and Holmer 1999), and in an UHIC modelled by Savijärvi and Liya (2001) as well as for development of an IUTB (Thorsson and Eliasson 2003). The local wind system in Ouagadougou is likely to be present at both examined locations, though only visible when the thermal wind differed from the regional wind direction. This occurred at the *urban* station during the extremely stable atmospheric conditions, when regional winds were north or north-easterly and the local wind system generated winds from south-east. At the *suburban* location direction of the local wind coincided with regional wind direction during this period. When the regional wind blew from east, the local wind at the *suburban* location was instead north (though local wind was only developed occasionally due to the moderate nocturnal stability during the period with easterly regional winds). Wind speeds were higher at the rooftop *urban* station than at the *suburban* station. Since height differences of the station is accounted for, this difference is likely caused by the higher turbulence caused by the increased surface roughness of the central urban geometry as well as channelling of wind in street canyons, as explained by Munn (1970).

5.2 Connection between surface wind and the wind flow aloft

A decoupling of the surface layer from the layer above allowing development of winds of different characteristics at different heights, is essential for the development of the surface thermal wind system found in Ouagadougou. This is described by Haeger-Eugensson (1999) who shows that a decoupling of wind layers occurs when an increase in atmospheric stability limits the transport of momentum between the layers. Onset of this apparent decoupling in Ouagadougou varies in time. This can be seen in the case studies (Figs. 5, 6 and 7) where the start of the thermal wind system varies. Throughout the nights, several breakdowns or disturbances of the thermal wind system were visible in the case studies when the regional wind replaced the deviating local wind at the surface. This is in accordance with Acevedo and Fitzjarrald (2003) who show that processes such as the increase in the large-scale winds aloft can cause the surface to reconnect to the wind layer above during the night. According to Blackadar (1997) the decoupling of wind layers may be followed by development of a NLLJ at the level of the regional wind. Lothon et al. (2008) show that a NLLJ that develops in evenings is frequent in the Sahel region. The breakdowns of the thermal wind system studied here are possibly, but not necessarily, connected to a NLLJ. Kallistratova et al. (2009)

describe how a NLLJ is likely to show a delay in growth over a city compared with rural areas, and reaches a maximum in the pre-dawn hours. The Sahelian NLLJ reaches a maximum at 5 am (Lothon et al. 2008). Assuming the same development of a NLLJ above Ouagadougou, strengthening of the NLLJ in the later part of the night is possibly connected to the increased frequency of break-downs and higher wind speeds found during the later part of the night in this study.

5.3 Origin of the local wind system

In Ouagadougou, urban–rural temperature gradients were weak while the intra-urban gradients were relatively strong as explained in Linden (2010) and Holmer et al. (2010) and shown in Fig. 8. This shows that the thermal wind system found in Ouagadougou is intra-urban rather than urban–rural. Temperature gradients were strong from the *suburban* station towards the south-west, creating a probable cause for the northerly winds at this station when the thermal wind system was present. At the *urban* station, thermal gradients from locations where temperature was measured to the south-east were relatively weak early in the night. Possibly, more vegetation cover at the airport to the south-east might present cooler temperatures at a shorter distance and thus a stronger gradient. Unfortunately, no temperature measurements were available from this area. Later in the night, the heat centre moved north to the reservoir. A stronger temperature gradient then developed from the urban centre toward this area and provides a probable cause for the winds from the south-east when the thermal wind system was present. Intra-urban wind systems were found around parks in Copenhagen and Gothenburg (Eliasson and Upmanis 2000) and in two parks in Tokyo by Honjo et al. (2003) and Narita et al. (2009). The intra-urban park breeze found in these studies was attributed to the temperature gradients between the cooler park and the warmer urban surroundings. As cooler areas in Ouagadougou were generally densely vegetated or irrigated, the wind system present could fit in to the description of a park breeze. However, a thermal gradient and a wind flow were also found from the sparsely vegetated urban centre towards the reservoir. The term IUTB is therefore a better suited description of the wind system found in Ouagadougou. Temperature gradients found in Ouagadougou were weaker compared with those found by Thorsson and Eliasson (2003). They found temperature differences of 2.1 K over a distance of approximately 300 m, generating an IUTB of 0.3 ms^{-1}. Areas in Ouagadougou where temperature was measured were relatively spread out over the city. If a denser network of temperature measurements was available in Ouagadougou, stronger temperature gradients would likely be found between nearby areas with different land cover.

5.4 Consequences for air quality

As shown by Boman et al. (2009) and Eliasson et al. (2009), airborne particle concentrations in Ouagadougou are alarmingly high. High levels of carbon monoxide have also been presented for Ouagadougou (Linden et al. 2007). Boman et al. (2009) show that levels were especially high during extremely stable atmospheric conditions when high stability and low wind speeds prevent dispersion of locally emitted pollutants. During these conditions, the thermal wind system could play an important role in transportation of pollutants. Spronken-Smith and Oke (1999) discuss the potential positive effects of a park cool island generating a clean, cool air flow from an urban park to the surrounding built-up area. As the wind system in Ouagadougou is an IUTB rather than a strict park breeze, the transport of air might unfortunately include polluted air from for example the urban centre, thereby decrease air quality where air masses are transported to. Another consequence of the more or less opposite directions of the IUTB is that the through-flow of air is reduced and so the ventilation of the canopy layer. The influence of a regional wind flow aloft, such as a NLLJ, causing temporary breakdowns of the stable atmosphere and the IUTB could increase dispersion by turbulent mixing. However, as discussed above, this could also introduce pollutants transported by the NLLJ, such as ozone (Samson 1978; Corsmeier et al. 1997; Strassburger and Kuttler 1998; Reitebuch et al. 2000; Salmond and McKendry 2002; Eliasson et al. 2003), and, perhaps more important in this region, mineral dust (Washington et al. 2006).

6 Conclusions

A consistent IUTB, generating almost opposite wind directions within the urban area, was found in Ouagadougou, Burkina Faso. The IUTB was found each night during a period of extremely stable atmospheric conditions as well as when shorter periods of extreme stability occurred during a period of generally moderately stable conditions. The strong atmospheric stability indicated a decoupling of the surface wind layer from the layer above. This allowed a wind system to be developed by the strong intra-urban horizontal temperature gradients present in the city. Several breakdowns or disturbances of the thermal wind system were visible as scattering or change in wind direction and indicated a re-coupling with the wind flow aloft.

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