Urban Climate and Air pollution in Ouagadougou, Burkina Faso

— An overview of results from five field studies

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Rapid growth of African cities – effects on urban climate and air quality

Almost all of the world population growth over the next few decades is expected to be absorbed by cities in the developing world [1] and managing this urban growth will be one of the world's most important challenges in the future. Africa experiences the fastest urbanization rate in the world, and African cities should prepare for a tripling of urban populations by 2050 [2]. The urbanization process is especially rapid in the sub-Saharan regions, with the most extreme case found in Ouagadougou, Burkina Faso, where the population is expected to grow by 81% over ten years - from 1.9 million in 2010 to 3.4 million in 2020[2].

> "The scarcity of data on urban Africa continues to remain a challenge. Short of timely, objective and accurate city specific data, urban managers will keep on operating in a knowledge vacuum, resulting in uninformed policy- or decision-making, or the wrong scale or focus. […] Good governance can only emerge with reliable and accurate data to inform policy and strategy decisions."
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> **UN Habitat report:**
> **The State of African Cities 2010**
> **- Governance, Inequality and Urban Land Markets**

The rapid growth of a city rates among the most important human impacts on the environment, and has major impacts on both the urban climate and air quality. The urban climate concerns the changes in local climate that is generated when the natural environment is changed due to growth of a city. Understanding and including urban climate processes into the planning of a city could, for example, decrease heat stress and energy demands. The urban climate also affects the air quality in the city. However, relatively little is known about urban climate in developing countries, as relatively few studies focus on these areas. Sub-Saharan Africa in particular suffers from a clear shortage of data [3].

One of the major problems that generally follow rapid urbanization, especially in the least developed countries, is a deterioration of air quality with negative effects for human health. Health problems connected to air pollution often include irritation to the eyes, nose and throat, and respiratory infections, but long term effects may also include for example lung cancer and heart disease. Common air pollution sources in the least developed countries are an old and highly polluting traffic fleet, biomass burning for cooking, and road-dust from unpaved roads. Cities in Sub Saharan Africa are among the most polluted in the world and in great need of air quality management measures for their development [4]. Despite this, systematic measurement and monitoring of urban environmental health risks connected to air pollution are very limited [5]. This lack of studies of urban areas of sub-Saharan Africa may consequently restrict adaptation to the extreme urbanization rate [2].

> "African cities are currently among the most polluted in the world. Industrial pollution, agricultural burning, use of old motor vehicles, poor fuel quality and infrastructure coupled with a lack of enforceable air quality and emission standards have all worsened the situation. Exposure of people to indoor air pollution due to biomass burning in open stove cooking and heating is an additional compromising factor which exacerbates people's cardio-respiratory problems. "
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> **Regional Conference on Better Air Quality in**
> **Sub-Saharan African Cities.**
> **Nairobi, Kenya, July 2006**

In this report, we present and discuss results from an extensive study carried out in collaboration between the University of Gothenburg, Sweden, and the Direction de la Météorologie Nationale in Ouagadougou. In this study we have examined variations over time in air pollution and urban climate, as well as the relationship between these two parameters, in different parts of Ouagadougou, Burkina Faso. Results are also discussed in view of exposure situation, and possible pollution mitigation strategies, both on authority and individual levels, are suggested. Finally, future development as well as applicability of results for the region as a whole is addressed. This report is primarily intended for concerned authorities and urban planners, but may also be of use for members of the general population interested in lowering their air pollution exposure.

Results from these studies have been published in reviewed articles [6-11] as well as a PhD thesis [12]. Those documents also contain more information on instrumentation, measurement sites and techniques.

The urban area of Ouagadougou, Burkina Faso

Burkina Faso is currently showing a very fast progress in human development, climbing from the 2nd lowest human development index in the world to the 9th position between 1970 and 2010. One effect of this development is an extremely rapid growth of the urban areas. The capital, Ouagadougou (12°22N, 1°31W, 300 masl), has grown from 800 000 inhabitants in the year 2000 to approximately two million today, and is expected to continue growing to approximately 3.4 million in 2020 [2].

As a result of this urbanization, the urban area is expanding rapidly, with the proportionally fastest growth in the form of informal spontaneous settlements at the outskirts of the city. These areas are uncontrolled by the authorities and generally lack access to electricity, water, sanitation and infrastructure. A comparison of satellite images over Ouagadougou from 2004 and 2009 presented in figure 1 (left), show that the informal spontaneous settlements have grown approximately 60% over these years, while the planned residential areas have grown approximately 30% in the same time [10,12].

The growth in total length of paved roads, presented in figure 1 (right), was 50% in the same time, though the paving was mainly taking place in high income neighborhoods while the majority of the residential areas remain completely unpaved.

Ouagadougou is located in the hot semi-arid steppe climate of the Sahel region. The climate consists of a dry period, generally receiving less than 100 mm of precipitation from October to April, and a wet period from May to September, averaging 700 mm precipitation [13].

Health statistics for Burkina Faso 2006 [14]

- Life expectancy at birth male/female: 47/48 years old.
- Mortality for children under 5 years of age: 192 per 1000 live births
- Primary cause for death, all ages: Lower respiratory infections (20% of deaths)
- Primary cause for death, children under 5years of age: Pneumonia (23% of deaths)

The most important cause of death in Burkina Faso is lower respiratory infections, amounting to 20% of all deaths [14]. As respiratory infections can be closely connected to exposure to air pollution, this indicates that there is an urgent need for pollution mitigation strategies in Burkina Faso. To the authors' knowledge, no continuous monitoring of air pollution in Ouagadougou is currently set up. The city has also earlier been subject to a limited number of studies of air pollution, mostly based on foreign initiatives e.g. [15,16-18]. Generally these studies show a very poor air quality with extreme levels of mineral dust. Other pollution sources include an old vehicle fleet with a high percentage of highly polluting two-stroke vehicles [15], and the use of biomass as the main household fuel in approximately 80% of the households [19].

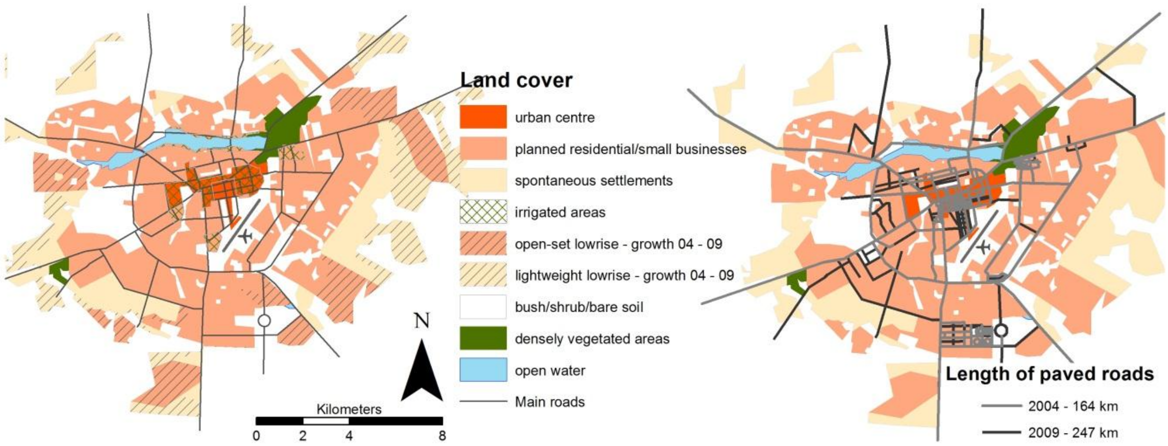


Figure 1. The urban area of Ouagadougou, classified in view of land cover/land use, with urban growth between 2004 and 2009 (left), and increase in paved road surface cover (right)

The urban climate of dry and semi-dry tropical cities

Replacing natural vegetation with urban materials and geometrical forms alters the local climate, such as temperature, humidity and wind patterns, in the urban area. Understanding of these changes in urban climate can be included in the planning of a city and thereby for example decrease heat stress and energy demands. Also the wind patterns are altered, affecting ventilation of the urban air as well as spreading and dilution of pollutants generated in the city.

The great majority of urban climate studies are focused on cities in the temperate regions, where the urban geometry and materials are considered most important parameters for the urban climate. However, considerable differences are likely to be presented in dry and hot regions compared to temperate regions. For example, vegetation or irrigated areas is likely to be more important for the urban climate in arid cities due to the scarcity of vegetation in the surroundings.

Results from our dry season studies in Ouagadougou show an urban climate which differs greatly from that commonly found in temperate cities. This is primarily due to vegetation being the most important parameter affecting the urban climate. Since vegetation cover varied greatly within the urban area, intra-urban differences were much more important compared to urban-rural differences. Another difference was the distinct diurnal wind pattern with very low wind speeds evenings and nights, restricting the ventilation of the urban air, and thus greatly affecting the air pollution levels. The temperature, humidity and wind patterns of Ouagadougou are described in more detail below.

Temperature and humidity patterns in Ouagadougou

One of the most studied features in urban climate is the urban heat island. The urban heat island describes the higher temperatures often found during evenings and nights in an urban center compared to its naturally vegetated surroundings. These temperature differences are caused by a number of different factors, for example the urban geometry (building density) and urban materials, but also factors such as changes in evaporation and evapotranspiration processes due to the removal or introduction of water and vegetation.

As daytime cooling is often desired in hot, dry areas, a dense urban center with narrow streets has traditionally been used to increase shade in these regions. Unfortunately, recent urban settlements in the same regions tend to be more spread out and open, and the much needed cooling effects may therefore be lost.

To characterize the urban climate in Ouagadougou based on spatial and temporal variations of air and ground temperature and humidity in and around the city, we measured at fixed sites and during car traverses in areas showing differences in vegetation cover, buildings, road cover, bare soil and open water. Greatest temperature differences in Ouagadougou were found night time, when vegetated areas were on average 5 °C (on occasion over 9 °C) cooler than un-vegetated areas within the city, while the heat island in the urban center was less than 2 °C warmer than the rural surroundings [6]. The effect of vegetation on temperature patterns in Ouagadougou was consequently more important than that of the urban geometry and urban materials. The cooling by vegetation was most pronounced around sunset and is thought to be caused by as intensive evapotranspiration process caused by the vegetation at this time [11].

During daytime, temperature differences were much smaller. The open water of a centrally located reservoir was the most important cooling factor, lowering temperatures in near surroundings approximately 1.5 °C. An effect of shading in the urban center could not be detected, probably due to the open building structure.

The great importance of vegetation for temperatures in Ouagadougou shows unique possibilities for night time cooling of the urban area with vegetation. Daytime cooling possibilities are more restricted, but introduction of more water or a more dense building structure creating more shade could be effective. However, as water is scarce and expensive in Ouagadougou, the introduction of more open water may not be practically feasible, and future urban planning may instead benefit from focusing on using building designs to increase shading possibilities in the city. These results are likely to be applicable to other cities in similar climate and of similar type.

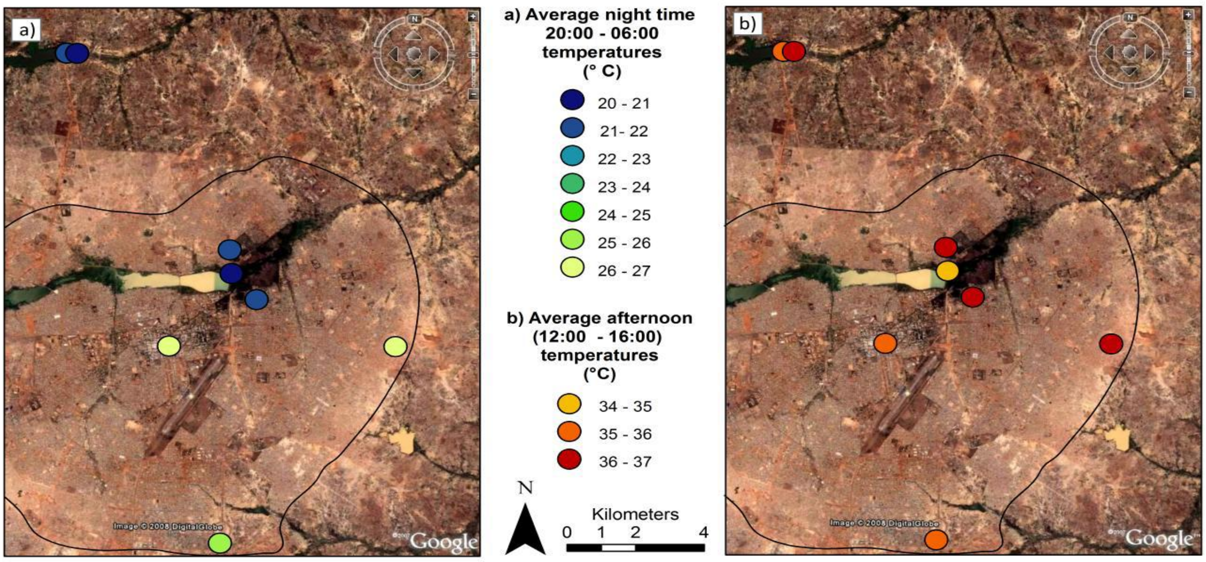


Figure 2. Temperature differences in areas of different land cover in Ouagadougou during a) night time, and b) day time. Note how all areas with a dense or relatively dense vegetation cover (dark surface in the images) are colder during night time, while the coolest point during daytime was near the reservoir. The black line show extent of the urban area.

Wind and atmospheric stability - ventilation of the urban air

The effect of urban structure on the regional wind often generates a very complex wind pattern in the urban area. In general, wind speeds are lower in an urban area compared to the rural surroundings, but buildings can also re-direct winds to increase the wind speed in certain locations. Urban areas may also create their own wind systems. These wind systems can occur during calm and clear conditions when strong temperature differences are present in or around the urban area. During these conditions weak wind systems may develop, blowing from cooler towards warmer areas.

The local wind and turbulence play a major role in ventilation of the urban air. When discussing ventilation, the level of atmospheric stability is often used as a way to describe the movements in the air. If the stability is low the unstable air moves and air from different areas is mixed. If stability is high, the air is not inclined to move. The restricted mixing of the air during stable conditions favors large local differences in the urban climate, and prevents dispersion of locally emitted pollutants. The direction of the wind is also important as pollutants will be transported with the wind.

During our field studies in the early dry season in Ouagadougou, the wind speeds were generally very low, especially during night time. The atmosphere during these calm nights was generally extremely stable, indicating little movement of the urban air. During these extremely stable nights, a local wind system was also found in the city [7]. When this wind system was active, the weak winds present were from south-east in the urban center, and from the north at the Direction de la Meteorologie National, DMN, and is likely to cause stagnation in the center of this local wind system, i.e. the area around the reservoir.

During daytime, the atmosphere was unstable or neutral with higher wind speeds (1.5 – 2 m/s). Thus during daytime the urban air was more ventilated.

The effect of the restricted ventilation on the air quality is discussed further below.

Important features of the dry season urban climate in Ouagadougou:

- Large diurnal variations in temperature, humidity and wind.
- Large nocturnal intra-urban differences over short distances in temperature, humidity and wind.
- The most important climate affecting parameter in evenings and nights was vegetation, causing considerably lower temperatures in densely vegetated areas.
- The most important climate affecting parameter daytime was open water causing slightly lower temperatures.
- Effect of the current type of built structure on temperatures was very limited both day and night.
- Wind speeds were generally very low and atmospheric stability high during evenings and night indicating limited ventilation of the urban air.

Air pollution – sources, spatial and temporal variations

Exposure to air pollution has important health effects, resulting in over 3.3 million deaths worldwide each year due to for example respiratory infections, heart disease, and lung cancer [20]. A large proportion of these deaths occur in the least developed countries and children under five years of age is a particularly vulnerable group. Urban air pollutants that commonly considered to lead to adverse health effects include particulate matter (PM), carbon monoxide (CO), nitrogen oxides (NO_X, consisting of NO and NO_2), volatile organic compounds (VOCs, including for example Benzene and Toluene) and ozone (O_3). PM consist of a mixture of solid particles and liquid droplets from a variety of sources. The coarser fraction of PM (e.g. TSP, PM_{10}) generally originates from mineral dust while the smaller fractions (e.g.$PM_{2.5}$, PM_1, UFP) have various sources, normally dominated by combustion. CO and NO are gases formed during the incomplete combustion of carbon-containing fuels such as vehicle fuels and biomass, while NO_2 is formed during more complete combustion conditions. VOC generally originates from vehicle exhausts or evaporation of liquid fuels, but also from solvents in paint and adhesives, and from biomass burning. O_3 is a secondary pollutant formed by photochemical reactions involving primarily NO_X but also VOC. Due to the many adverse health effects of these and other air pollutants, the World Health Organization has presented air quality guidelines for maximum exposure to selected air pollutants [21], Table 1.

Common air pollution sources in the least developed countries are an old and highly polluting traffic fleet with a high percentage of vehicles with two-stroke engine, the extensive use of biomass burning for cooking and often also a unregulated industry. In many areas, especially in dry areas and during dry season, road-dust from unpaved roads is an important source as well [22-24]. An additional source of airborne dust in dry areas is often transported dust from deserts and dry surroundings.

As human activities in urban areas tend to generate significant amounts of air pollution, the ventilation of the urban air is of great importance for the air quality. If the urban air is poorly ventilated, for example during stable atmospheric conditions with low wind speeds, the pollutants emitted in the city accumulates in the city, increasing importance of urban-derived pollutants for urban air pollution levels [25].

Both seasonal and diurnal differences in sources as well as ventilation of the urban air can cause considerable spatial and temporal variations in the urban air quality, and should therefore be considered when examining potential pollution exposure for inhabitants, as well as in development of pollution mitigation strategies.

Below we will present results from air pollution measurements in Ouagadougou. We will also discuss the results in view of sources, temporal and spatial variations.

Table 1. Air quality guidelines for selected pollutants. Mainly from WHO [21].

Pollutant	Exposure duration: limit	
PM_{10}	annual mean:	10 μg/m^3 [21]
	24-hour mean:	25 μg/m^3
$PM_{2.5}$	annual mean:	20 μg/m^3 [21]
	24-hour mean:	50 μg/m^3
CO	15 minutes:	100 mg/m^3 [26]
	30 minutes:	60 mg/m^3
	1 hour:	30 mg/m^3
	8 hours:	10 mg/m^3
Benzene	annual mean	5 μg/m^3 [27]
NO_2	annual mean:	40 μg/m^3 [21]
	1-hour mean:	200 μg/m^3
O_3	8-hour mean:	100 μg/m^3 [21]

Air pollution situation in Ouagadougou

In our studies we found that levels of air pollution in Ouagadougou was high in general with extreme levels of larger airborne particles, PM_{10}, consisting mainly of mineral dust. Average pollution levels found in Ouagadougou are shown in table 2 and 3.

In comparison to the WHO air quality guidelines for PM_{10}, measured levels are constantly exceeded in Ouagadougou and the yearly limit of Burkina Faso air quality standard, 200 µg/m^3, was also exceeded frequently, indicating that this limit may also be difficult to meet. The levels of smaller particles were also elevated, with high levels of PM_1 in general, and levels of $PM_{2.5}$ constantly exceeding the WHO guideline.

Levels of benzene, toluene and NO_X show a rapid concentration decrease from the urban street level site to the rural site. Benzene concentrations in urban areas are higher than the European Air Quality Standard, 5 µg/m^3 [27] but decreases rapidly to the rural site. The levels of NO_X do not exceed the guidelines of WHO [21].

We have also examined levels of CO in several microenvironments which show that large variations exist. While background CO concentrations (table 2) do not exceed the air quality guidelines of WHO at any time or location in Ouagadougou, considerably higher levels of CO were noticed in for example traffic, where road side levels in an urban dense traffic situation were around 8.5 ppm, and average levels in traffic were 24 ppm with an peak value of 111 ppm. CO-levels were also measured in wood fuelled kitchens, and very high levels were detected in an indoor kitchen where average level during cooking sessions was 33 ppm, with a peak value of 151 ppm. Levels in outdoor kitchens were also increased during cooking sessions, but only reached approximately one tenth of the values in the indoor kitchen.

*Table 2. Average background levels of CO, PM_1 and PM_{10} in the urban, suburban and rural location during extremely (X-stab) and moderately (M-stab) stable atmospheric conditions. All data from early dry season in 2007 except for values marked with * which are from slightly and moderately stable conditions and recurrent precipitation in May 2010.*

Location/ pollutant	CO (ppm)		PM_1 (µg/m^3)		PM_{10} (µg/m^3)	
	X-stab	M-stab	X-stab	M-stab	X-stab	M-stab
Urban	2.2	1.0	13.9	3.5	161.7	69.0
Suburban	2.2	1.3	NA	5.1*	NA	85.4*
Rural	0.6	NA	7.8	NA	108.0	35.4

Table 3. Average levels of benzene, toluene, nitrogen oxides (NO_X) and ozone (O_3) from one street level site and three background sites in the urban, suburban and rural environment.

Location/ pollutant	Benzene (µg/m^3)	Toluene (µg/m^3)	NOX (µg/m^3)	O_3 (µg/m^3)
Urban street level	20	74	110.2	38
Urban background	7	26	79.2	32
Suburban background	4.1	12.7	36.7	39
Rural background	1.5	5.0	28.9	47

Sources of air pollution in Ouagadougou

Through a principal component analysis of smaller airborne particles, $PM_{2.5}$, collected during our study in early dry season in 2007, we could identify the following air pollution sources as the most important in Ouagadougou [9]

- Mineral dust
- Combustion
- Biomass burning
- Industry

Mineral Dust

Background llevels of PM_{10} were high not only in the urban area, but also in the rural area. This suggests that the region as a whole experiences a high load of dust transported from the Sahara desert. The importance of dust transported from the Sahara desert has been noticed in other cities in the region, such as Accra, Ghana, where background PM_{10} concentrations were similar to those found in Ouagadougou. Approximately four times higher levels of PM_{10} were found in Accra during dust storms with winds from the Sahara desert. Ouagadougou's location closer to the Sahara, indicates that levels here are likely to be considerably increased during dust storm events.

Although transported dust is undoubtedly an important source, comparisons between street level concentrations of larger particles (figure 3) shows four times higher concentrations in an unpaved road in a residential area compared to a nearby paved road. This show that road dust stirred up by vehicles may locally be an equal or larger source compared to transported dust.

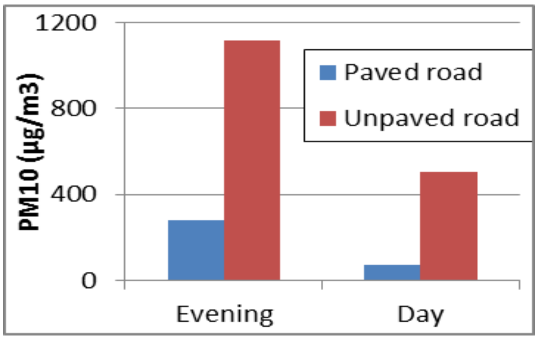


Figure 3. Average levels of PM_{10} from roadside measurements by one paved and one unpaved road located approximately 600 m apart.

Combustion and biomass burning

Combustion generated pollutants are mainly in the form of smaller particles (i.e. PM_1) and gases (i.e. CO, NO_X, Benzene and Toluene). The rapid decrease in all these pollutants from the densely trafficked urban area in Ouagadougou, to the rural area where traffic is sparse (tables 2 and 3) indicates that traffic is a very important source. No influence of leaded gasoline was found.

The similar background CO levels at the heavily trafficked urban and the lightly trafficked traditional suburban site indicate an important source besides traffic at the suburban site. A study of the household fuel use in Ouagadougou [19], show that the middle and low income households almost exclusively use biomass as household fuel. This is the type of households generally found in traditional residential areas in Ouagadougou, which indicate that biomass burning might be an important source of CO in these areas.

Other sources

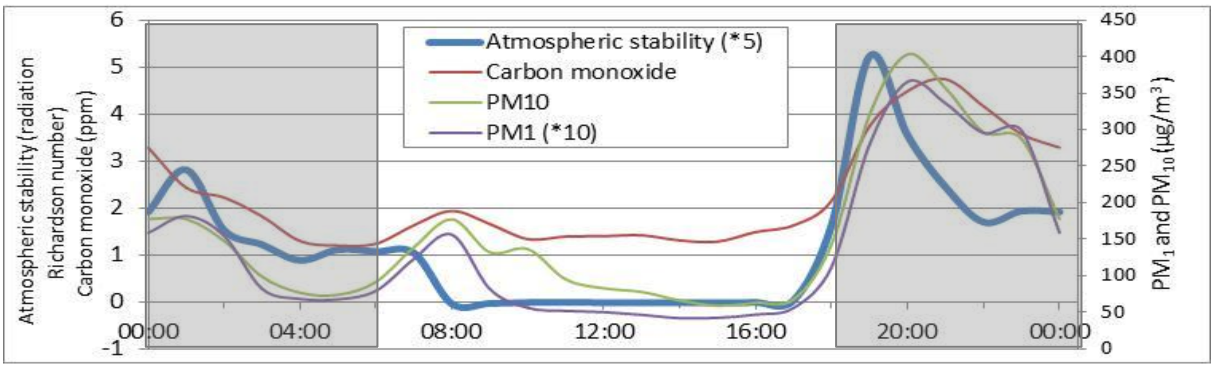
Industry was also indicated as an important pollution source in Ouagadougou [9]. However we did not examine type of industry or emitted pollutant further which makes this an important focus for future studies. The emission of toxic pollutants from the common practice of waste burning in residential areas may further deteriorate the air quality, and should therefore also be examined in future studies.

Temporal and spatial variations in air pollution in Ouagadougou

The weather varies greatly over the year in Ouagadougou, with the dry season in the winter months and the wet season in the summer months. The seasonal changes in regional weather affect both the urban climate and the air pollution of the city. Both levels of transported dust as well as re-suspended dust are likely to increase throughout the dry season.

The atmospheric stability was lower and wind speeds higher during the transition between the dry and wet season. This would increase ventilation of the urban air, dispersing locally emitted pollutants, especially during evenings when the atmospheric

Figure 4. Diurnal pattern in atmospheric stability and concentration of CO, PM_1 and PM_{10}. The shaded parts show extent of the night time. Note the strong increase in stability shortly after sunset, and that the evening rush hour pollution peaks (around 18:30) is coinciding with the highest stability levels and lasts longer compared to the morning rush hour peaks (around 08:00) when stability is low. In order to visualize all curves in the same graph, atmospheric stability have been multiplied by 5 and the PM_1 have been multiplied by 10.



stability was particularly important. However, levels of PM_{10} exceeding air quality guideline of WHO [21] were also found in May, during less stable atmospheric conditions and recurrent precipitation (table 2). This suggests that high levels of PM_{10} are not restricted to the dry season, but may exist throughout the year.

As shown in table 2, pollution concentrations are between 2 to 4 times higher during periods of extreme nocturnal stability. This is caused by the restricted ventilation of the urban air during these periods, preventing dispersion of pollutants emitted in Ouagadougou.

The effects of the large diurnal variations in ventilation of the urban air, as presented in the urban climate section above, also have strong effects on diurnal variations in pollutant concentrations as shown in figure 4. The blue, thicker line in figure 4 shows that the stability was particularly high during evenings. This is also the time when levels of CO and PM were highest.

The great impact of stability is evident when looking at effects of pollutants emitted during rush hour (figure 4). During morning rush hour (roughly 8:00) the stability is low, thus quickly dispersing emitted pollutants and thereby causing a smaller and shorter peak in pollution concentrations compared to evening rush hour (roughly 18:00), when the higher stability strongly increase the level and duration of the pollution event.

The considerable increase in evening pollution levels due to a strong atmospheric stability and restricted ventilation of the urban air shows that pollution sources active during evenings are particularly important for the pollution situation in Ouagadougou.

Considerable spatial differences in pollution levels were also found in Ouagadougou, especially during evenings when atmospheric conditions were stable and prevented air from different areas to be mixed.

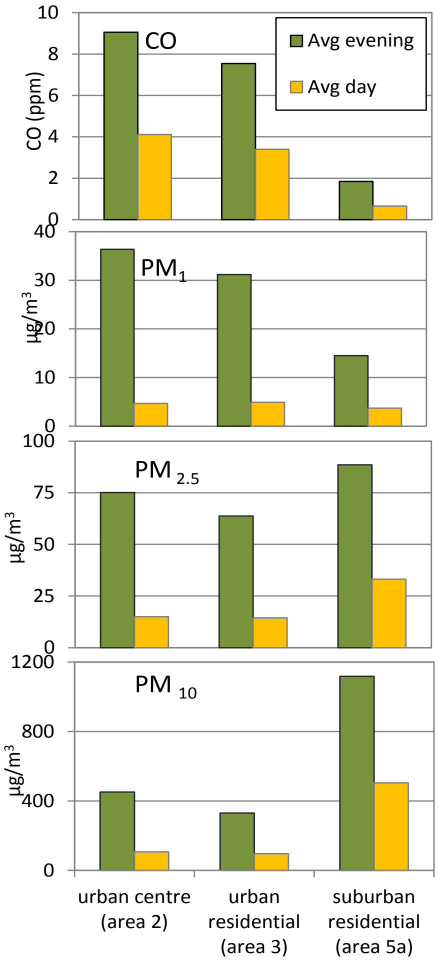


Figure 5. Average levels of CO, PM_1, $PM_{2.5}$ and PM_{10} from roadside measurements in the urban centre, a central paved and vegetated residential area and a suburban unpaved and scarcely vegetated residential area

Variations in roadside levels of CO and PM are displayed in figure 5. Traffic related pollutants in Ouagadougou, such as CO and PM_1 were around four times higher in the urban center, while dust particles were three times higher in the unpaved compared to the paved areas. Levels were between two and seven times higher during evenings due to the restricted ventilation at this time.

Characteristics of the air pollution situation in Ouagadougou

- High pollution levels in general with extreme levels of dust
- Most important sources: Mineral dust (transported and re-suspended road dust), combustion (traffic), biomass burning (household fires) and industry.
- Strong seasonal variations in pollutants connected to weather and sources (mainly dust from dry surroundings)
- Considerably increased pollutant concentrations during periods when nocturnal atmospheric stability is high, limiting ventilation of the urban air.
- Large spatial variations in pollutant concentrations within the city, especially when atmospheric stability is high.

Potential high exposure situations for urban inhabitants

As the most important cause of death in Burkina Faso is respiratory diseases [14], which is one of the main adverse health effects connected to air pollution exposure, the poor air quality situation found in Ouagadougou is a problem in need of attention. In developing countries where large socioeconomic differences are common, and where tradition often create considerable differences in daily activities between gender the differences in exposure situation within regions, countries or even cities are likely to be important [28]. As both spatial and temporal variations in air pollution are large in Ouagadougou, it is evident that potential exposure situation varies within the population and that this needs to be considered for accurate exposure assessment. In this section our results will be discussed in view of potential high exposure situations for the Ouagadougou inhabitants.

Exposure to mineral dust

Exposure to mineral dust has been shown to have adverse health effects, for example increase daily mortality [29,30]. The high background levels of mineral dust in Ouagadougou due to dust transported from the Sahara desert are likely to affect all residents. However, levels are still likely to vary greatly with the area of residence due to the importance of re-suspension of road dust in unpaved areas. Our analyses show that the great majority of the middle and low-income residential areas are completely unpaved, thus generating high levels of dust in these areas compared to the high- income paved areas.

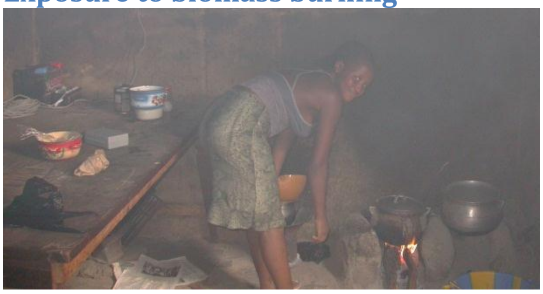
The paved road coverage has increased with approximately 50% in Ouagadougou between 2004 and 2009 but many areas remain completely unpaved. Other road dust abatement strategies exist, such as road oiling or spreading dust binding chemicals. These strategies are often cheaper compared to paving, but have – to our knowledge – not been tested or applied under climatic conditions such as in Ouagadougou.

Exposure to traffic

Traffic generated pollutants are also known to have important adverse effect on health [20]. The effect of this source in Ouagadougou varies greatly throughout the city, due to both traffic density and flow. As the traffic density is often highest with frequent traffic congestions in the urban center and on the main roads in and out of town, these are the areas where the risk for high exposure to emissions from traffic is greatest. However, the levels of CO from traffic quickly decreased with distance from the source (vehicles on the road), and exposure would therefore mainly affect those spending time in traffic and in roadside locations, and may be of less importance to nearby residential and business areas. The exposure to traffic emissions would therefore be greatly dependent on activity pattern and occupation, with heavy exposure for workers who spend time in or near traffic, like for example taxi drivers and traffic police, but also for people who commute long distances every day.

For people spending much time in the traffic, a combination of the elevated concentrations found in Ouagadougou of CO, NO_X and PM_1 may cause impairment of their health, mainly affecting the lungs. The Benzene and Toluene concentrations in the urban center may also be high enough to cause respiratory irritation, headache and dizziness.

Exposure to biomass burning



Another reason for exposure differences within the urban population is the fuel type used. The great majority of the households use biomass fuels, mainly wood. As CO decrease rapidly with distance from source, the persons spending time near the burning fire are likely to have a much higher exposure compared to people in surrounding locations. It is also evident that the ventilation of the kitchen is of great importance, as CO levels in the indoor kitchen exceed levels found in rush hour traffic.

We conducted interviews in Ouagadougou regarding the health of members in households using wood as main fuel. This shows that in the majority of the households, both children and women were having health problems that can be connected to biomass burning. Exposure to biomass smoke is well known to increase risk for acute lower respiratory infections in children, which is the single most important cause of death for young children [31]. As the great majority of the households in the unpaved residential areas use biomass as fuel, it is likely that the person in charge of the cooking and children in these household have an extreme exposure both to mineral dust and to biomass burning.

Other exposure sources and sinks

There are indications that industry is an important source as well [9]. The type of pollutants from the industry in Ouagadougou were not examined in detail , but it was evident that both location and distance was important as the area downwind from the industrial area in the north part of the city showed a higher influence of industrial pollutants compared to the city center [9].

Another often important source, especially in developing countries, is emissions of toxic pollutants from waste burning. This was not examined in this study, but waste burning was noticed in several locations, and may further increase pollution exposure in these areas.

Studies have also shown that vegetation can effectively reduce levels of air pollution [32]. Lower pollution levels were noticed in areas nearby vegetated areas in Ouagadougou [9], especially when the wind was originating from the direction of the vegetated area. The vegetation cover in Ouagadougou is very un-even, with few irrigated areas and very limited vegetation cover where water is scarce. This is likely to be another cause for spatial differences in pollution levels, where levels are likely to be lower in and downwind from vegetated areas.

Exposure differences with socioeconomic situation and gender

Large differences in air pollution exposure are likely to exist in Ouagadougou depending on both socioeconomic situation and gender. The most important differences are summarized below.

Socioeconomic situation

Low and middle income inhabitants of Ouagadougou are likely to suffer from a much higher exposure to mineral dust due to re-suspension of dust from unpaved roads in their residential area, compared to those living in paved and vegetated high income residential areas. Also, exposure to traffic may be higher for low/middle income inhabitants, partly due to increased exposure in low/middle income occupations such as street side vending and taxi drivers, compared to indoor office-work. The means of transport used varies with income, where an air-conditioned closed vehicle may protect the traveler to some extent while walking, biking, travelling on a moped or in a open car leave the traveler fully exposed to pollutants. An additional difference is the fact that only high income households have financial possibilities to use cleaner fuels such as gas or electricity [19] while other households are relying on biomass for cooking.

Gender

The most obvious exposure difference related to gender is that almost exclusively women are in charge of the cooking thus being exposed to emissions from biomass burning. The women in charge of the households examined with interviews reported having health problems that can be connected to exposure to emissions from biomass burning. This is a common problem that is generally found in developing countries [31,33-35]. On the other hand, occupations like taxi driver are male dominated, thus leading to a potentially higher exposure to traffic emissions. Studies have also shown that there is a clear gender difference for children over age of five where girls have a higher exposure in households using biomass fuel [33]. While the majority of children in Ouagadougou attend school from the age of six [36], girls in this region are often required to continue to help with cooking and household chores during off school hours [37]. Boys are to a greater extent engaged in street side vending at traffic lights, thus spending more time in sites extremely polluted by traffic.

Future development of urban Africa

It is well known that the greatest health impacts from air pollution worldwide occur among the poorest and most vulnerable populations. Although Ouagadougou may be an extreme case, millions of people over the world are likely to live under similar exposure situations. As the great majority of world population growth is expected to be absorbed by urban areas in developing countries, most of the rapid demographic growth of African cities will results in the proliferation of spontaneous informal settlements[2]. Approximately 900 million people lived in informal settlements in 2005, and the number is projected to rise to approximately 1.5 billion in 2020 [38]. Urban traffic is expected to increase with urban growth, and the proportion of household depending on biomass is not expected to decline drastically in the near future[39]. Studies from other sub Saharan cities indicate that re-suspension of dust from unpaved roads is a common problem in these regions [5,18,23,24]. The air pollution sources will of course vary, but limited financial means available for dust abatement, cleaner vehicle emissions and household fuels etc. is likely to create increasingly harmful exposure situations for the rapidly growing populations of these areas. This shows an urgent need for development of air pollution abatement strategies in order to reduce air pollution exposure for the increasing number of people living in these cities.

Possibilities for improving comfort and air quality in Ouagadougou

Based on the results in our study, we will finish this report by discussing possible future development of Ouagadougou, and present strategies for improving both human comfort and air quality of the city. To clearly identify air pollution mitigation strategies suitable for Ouagadougou, our suggestions are presented both in the text and in a table in Appendix 1. We also present an estimated risk for elevated pollution levels in different areas in Ouagadougou in Appendix 2.

Urban climate

The strong evening evaporative cooling of vegetation presents - if included in future urban planning - a unique opportunity for lowering nocturnal temperatures in Ouagadougou. However, Burkinabe locals often claim that nocturnal temperatures during the early dry season are too low for comfort. A relief from daytime heat stress may instead be preferred in Ouagadougou, and introducing more open water surfaces would potentially reduce heat stress daytime. However, poverty is high and water scarce, thus greatly limiting possibilities for this kind of stress relief. The rapid urban growth presented in figure 1 show that the informal spontaneous settlements have experienced the fastest growth, a pattern that most likely will continue in the future. These areas presented the warmest temperatures both day and night.

Due to the influence of atmospheric stability on ventilation of the urban air, the high frequency of extremely stable night time conditions should be taken into consideration in air pollution mitigation strategies for Ouagadougou, but also for other rapidly growing cities in the Sahel region. The connection between stability and pollution levels show that special focus should be on evening emissions in Ouagadougou since the concurrent increase in stability restricts ventilation and thus dispersion of pollutants at this time, while daytime emissions are more rapidly dispersed.

Air quality

This study shows an alarming air pollution exposure situation for the majority of the inhabitants in Ouagadougou today, especially among the low and middle income population. The number of inhabitants suffering from this air pollution exposure is unfortunately likely to greatly increase in the future due to the extreme population growth in combination with limited financial possibilities for planned urban growth, dust abatement strategies such as paving roads, as well as for decreasing traffic emissions.

The poor air quality is likely to result in considerable adverse health effects for the population, and is probably an important contributing factor to the high mortality caused by respiratory diseases. Reducing the air pollution exposure is thus of great importance to the well-being for the inhabitants of Ouagadougou.

There are several mitigation strategies that could be implemented in order to improve the situation – both on personal and authority levels. Some could be immediately implemented while other could be gradually implemented as the financial situation of the country allows for investments.

On the following page are some suggestions of mitigation strategies that could be applied in Ouagadougou.

Suggestions for air pollution mitigation strategies suitable for Ouagadougou:

- As the ventilation of the city air is generally very poor in evenings, all emissions that could be prevented at this time could greatly reduce general pollution levels. For example, if biomass burning could be restricted to the daytime hours when ventilation is better, general levels would be reduced, especially in residential areas. This would in practice mean that cooking and waste burning should mainly take place in the daytime. The same practice could possibly also be considered when regulating other sources, such as industrial emissions and traffic.

- The transfer from the commonly used simple stoves for wood burning towards better stoves and cleaner fuels should be encouraged. Relatively cheap and easy improvements of traditional stoves could greatly reduce both fuel consumption and emissions, thus decrease both exposure and costs.. Households should also place their fire outdoor, in a well-ventilated place in order to reduce exposure for the cook. If this is not possible, ventilation should be increased by any means possible.

- Road dust abatement strategies, such as paving, should be applied. This is a rather long term and costly, but necessary, mitigation strategy. Other, considerably cheaper, road dust-binding methods exist and are under development, and although this might be a cheaper solution compared to paving, expert advisors should be involved in order to assess suitability for this region and climate.

- In order to limit emissions from traffic, the use of unnecessary high oil content in fuel used for the high number of two-stroke mopeds in Ouagadougou should be prevented. Possibilities for inhabitants to travel with public transport should be increased. Traffic flow should be facilitated by preventing traffic congestions. Commuters could limit their exposure by avoiding traveling at rush hour if possible, and by travelling on routes where traffic is lighter, as well as by choosing to travel by public transport where available.

- Increasing vegetation cover could improve air quality since vegetation can effectively reduce levels of both larger and smaller particles. This could be done on a city-wide scale as well as on small scale, such as in gardens.

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Appendix 1

Suggestions for air pollution mitigation strategies suitable for Ouagadougou

Pollution source	Mitigation strategies – authority*	Mitigation strategies – population*
Mineral dust	Paving roads Other surface treatment methods	Lower vehicle speed
Traffic emissions	Increase public transport Prohibit high oil mixture in fuel Facilitate traffic flow	Use public transport when available Request public transport when not available Use lower oil mixture in fuel
Biomass burning	Financially aid improvement of stoves Subsidize cleaner fuels	Invest in more efficient stoves Place fire in a well-ventilated place outdoors Cook only during daytime – not evenings
Industry	Regulate emissions Re-locate industry to locations not affecting densely inhabited areas	-
Waste-burning	Facilitate recycling and disposal of waste Use industrial waste burning as a source of energy	Recycle waste Burn only during daytime – not evenings

*In addition to this, increasing vegetation can effectively reduce levels of air pollution. This could be done on a city-wide scale as well as on small scale.

Appendix 2

Estimated risk for elevated pollution levels in different areas with examples of areas in Ouagadougou

Risk for elevated pollution due to local sources in the city	Area description	Example area	Mitigation strategies
Very low	Paved roads, vegetated, low traffic, clean household fuels (electricity or gas)	Zone du bois	None needed
low	Paved roads, vegetated, medium traffic, clean household fuels (electricity or gas)	Kouloba	If needed – facilitate traffic flow or re-direct traffic
medium	Some roads paved, some vegetation, medium traffic, mixed household fuel type	Goughin	Facilitate traffic flow or re-direct traffic. Pave roads Encourage use of cleaner household fuels and improved stoves Increase vegetation cover
High, urban	Paved roads, some vegetation, dense traffic	City centre	Facilitate traffic flow or re-direct traffic Cleaner vehicles
High, suburban	Unpaved roads, low to medium traffic, low vegetation, biomass as main household fuel	Somgande	Pave roads Encourage use of cleaner household fuels and improved stoves Increase vegetation cover