ABSTRACT

Africa has recently been singled out by UN Habitat as the fastest urbanizing continent in the world. The most extreme case was found in the Sahelian city of Ouagadougou, Burkina Faso, where the population is expected to almost double over the next ten years. 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 both the urban climate and air quality. Few studies have been focused on cities in the Sahel region, and the lack of information may consequently hinder adaptation to the extreme urbanization rates of these often heavily polluted cities.

The main objective of this thesis was to study the nature of, and relationship between, urban climate and air pollution in Ouagadougou, Burkina Faso. Specific objectives were to; examine spatial variations in daily temperature and humidity patterns during early dry season with focus on effects of different land cover; to examine the influence of atmospheric stability on the intra-urban air temperature patterns, the urban wind field and on air pollution levels; and to examine spatial variations in air pollution levels. An additional objective was to document the status and potential development of synoptic meteorological stations in Burkina Faso. Empirical data used in analyses were collected during five field studies between 2003 and 2010. Meteorological and air pollution parameters were measured at fixed sites and through car traverses in areas of different land cover, activity, traffic density and road surface.

The most distinct features in thermal patterns found in Ouagadougou were strong intra-urban nocturnal cool islands in vegetated areas, caused by evening evaporative cooling by the vegetation. Extremely stable nocturnal atmospheric conditions were observed during 80 % of days examined in early dry season, during which spatial patterns in temperature and humidity as well as in air pollution were most pronounced. An intra-urban thermal breeze generating almost opposite wind directions within the city was found during all extremely stable nights. Air pollution situation in Ouagadougou were characterized by; important spatial variations, high pollution levels in general, and extreme levels of coarse particles, commonly exceeding WHO air quality guidelines in all areas. Important sources were re-suspension of road dust, transported dust, traffic and biomass burning. Documentation of meteorological stations show that observations were made by well trained staff following a strict set of procedures. However, many risk factors potentially affecting data quality were found, such as many manual steps in data handling and limited funding for maintenance of the instrument park.

In contrast to the many studies identifying urban built structure as most important land cover parameter for the nocturnal urban climate, vegetation was the dominating parameter in Ouagadougou. The strong influence of vegetation shown in this study should be carefully considered in all urban climate studies, especially in (semi) arid regions. In urban-rural comparisons, this is particularly important for the location of the rural area where vegetation often is dominant. The high frequency of extremely stable atmospheric conditions and the intra-urban thermal wind system show a very restricted ventilation of the urban air and limited dispersion of urban-derived pollutants. Large spatial differences in pollution levels found in the city are likely to create important differences in exposure situation within the population. When using data from synoptic meteorological stations in Burkina Faso, the many risk factors found should be considered. Findings presented in this thesis could used in order to increase comfort and health in urban planning, as well as in development of strategies for air pollution mitigation in this region, especially when considering the ongoing extremely rapid urban growth. The information of status and potential development of observational data may be valuable for more reliable predictions of future changes in climate in the region.

Keywords: Sub-Saharan Africa, Sahel, (semi) arid, nocturnal cooling, urban vegetation, evening evaporative cooling, cooling rate, atmospheric stability, thermal wind, carbon monoxide, particulate matter, road dust, exposure differences.

PREFACE

The following Papers are included in this thesis:

I. Lindén J 2011 *Nocturnal Cool Island in the Sahelian city of Ouagadougou, Burkina Faso*. International Journal of Climatology 31 (4):605-620. DOI:10.1002/joc.2069

II. Holmer, B., Thorsson, S., Linden, J. 2011. *Evening evaporative cooling in relation to vegetation and urban geometry in the city of Ouagadougou, Burkina Faso*. Submitted to International Journal of Climatology

III. Linden, J., Holmer, B. 2011. *Thermally Induced Wind Patterns in the Sahelian City of Ouagadougou, Burkina Faso*. Theoretical and Applied Climatology, Early publication online DOI: 10.1007/s00704-010-0383-7

IV. Lindén J., Thorsson S., Eliasson I., 2008. *Carbon Monoxide in Ouagadougou, Burkina Faso – A Comparison between Urban Background, Roadside and In-traffic Measurements.* Water Air Soil Pollution. 188. 345–353. DOI: 10.1007/s11270-007-9538-2

V. Lindén J., Boman, J., Eliasson I., Holmer, B., Thorsson S. 2011 *Intra-Urban Air Pollution in a Rapidly Growing Sahelian City – potential effect on exposure differences*. Submitted to Environment international.

In all Papers except Paper II, I was the lead author with main responsibility from idea and design through field work, analysis and writing. In Paper II, the majority of the field work was carried out by me and I participated in analysis, discussions as well as the writing of the Paper. The Papers, conducted in close collaboration with colleagues at the department of Earth Sciences (Paper I-V) and department of Chemistry (Paper V) at University of Gothenburg, are based on data collected during five field studies between 2003 and 2010 in Burkina Faso with permission and assistance from Direction de la Méteorologie Nationale in Ouagadougou. Papers are hereafter referred to by their roman numbers.

Peer reviewed Paper not included in this thesis:

J. Boman, J. Lindén, S. Thorsson, B. Holmer, I. Eliasson, 2009*. A tentative study of urban and suburban fine particles ($PM_{2.5}$) collected in Ouagadougou, Burkina Faso.* X-Ray Spectrometry. 38 (4) 354–362 DOI: 10.1002/xrs.1173

Conference proceedings:

Lindén J., Eliasson I., Thorsson S., Lindqvist, S. 2006. *Urban climate and air pollution in Ouagadougou, Burkina Faso.* 6th International Conference on Urban Climate, Gothenburg, Sweden, June 2006

Lindén J. 2009. *Nocturnal Cool Island and a thermal wind system – two features of the local climate in Ouagadougou, Burkina Faso*. 7th International Conference on Urban Climate, Yokohama, Japan, 29 June – 3 July 2009

Lindén J. and Holmer B. 2010. *Mopeds, Unpaved Streets and Air Quality in Ouagadougou, Burkina Faso.* 10th Urban Environment Symposium, Gothenburg June 2010.

INTRODUCTION

Rapid growth of urban areas in the developing world is expected to absorb almost all of the world population growth over the next few decades (UN Development Programe 2010), and managing the urban growth in the developing world will be one of the world's most important challenges in the next few decades. In an extensive report by UN Habitat (2010), it is stated that Africa is the fastest urbanizing continent in the world, and that African cities should prepare for a tripling of urban populations by 2050. The urbanization process is especially rapid in the sub-Saharan regions, with the most extreme case found in the Sahelian city 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.

It is well known that the rapid growth of an urban area rates among the most important anthropogenic impacts on the environment, and that it has a profound impact on both the urban climate and air quality. The urban climate concerns the changes in local climate, for example in temperature, humidity and wind patterns, generated in an urban area by alteration of the natural environment due to urbanization. Thorough understanding and inclusion of urban climate processes in the planning of a city could, for example, decrease heat stress and energy demands. The urban climate is also important for air quality as, for example, the urban wind field and the atmospheric stability greatly affect dispersion of urban-derived pollutants. However, relatively little is known about urban climate in developing countries. A review from 2007 shows that less than 20 percent of all urban climate studies were from (sub) tropical areas, and that sub-Saharan Africa in particular suffers from an obvious shortage of data (Roth 2007). Very few studies of the urban climate of cities in sub-Saharan Africa have been published since then.

One of the major problems that generally follow rapid urbanization, especially in areas with limited financial means, is a deterioration of air quality with adverse effects for human health. At the Better Air Quality Sub-Saharan Africa regional conference in Nairobi 2006, it was concluded that cities in Sub Saharan Africa are among the most polluted in the world and in great need of air quality management measures in their development (CAI-SSA 2006). Despite this, systematic measurement and monitoring of urban environmental health risks connected to air pollution has received very limited attention (Arku et al. 2008).This lack of studies of urban areas of sub-Saharan Africa may consequently restrict adaptation to the extreme urbanization rate (UN Habitat 2010).

Africa, and especially the Sahel region, has also been portrayed as one of the most vulnerable regions to impacts of global climate change due to poverty, a heavy reliance on subsistence rain-fed agriculture and a lack of economic and technological resources limiting possibilities for adaptation (Kandji et al. 2006, Boko et al. 2007). According to the IPCC Fourth Assessment Report, the annual rainfall in West Africa has decreased 20 to 40 % from the period 1931-1960 to 1968-1990 and projections for future climate change indicate that West Africa is very likely to warm during this century, decreasing the length of the growing season and yield potential in many parts of West Africa (IPCC 2007). However predictions are very uncertain, with some of the main models disagreeing even on the sign of the change (SWAC 2010). Considerable progress has recently been achieved in dynamical and statistical downscaling of climate models in the Sahel region, though meteorological observational networks need to be extended and maintained in order to further improve predictions for future climate change (Paeth et al. 2011).

Objectives of this thesis

To increase knowledge and understanding of the urban climate and air pollution in rapidly growing cities of the semi-arid Sahelian region, the main objective of this thesis was to study the nature of and relationship between these two parameters in Ouagadougou, Burkina Faso. Empirical data of meteorological and air pollution parameters used in analyses were collected during five field studies between 2003 and 2010, with the following specific objectives:

- To study urban-rural and intra-urban spatial variations in daily temperature and humidity patterns during early dry season, with focus on effects of different land cover, i.e. vegetation, built-up/paved, open water and bare soil (Paper I, II)

- To study the influence of atmospheric stability on the magnitude of intra-urban air temperature as well as implications for the urban wind field and air pollution levels (Paper II, III, and V).

- To study urban-rural and intra-urban spatial variations in air pollution levels, focusing on particulate matter and carbon monoxide, in order to examine general levels, possible sources and to discuss potential exposure situation (Paper IV, V)

Due to the importance of high quality observational data for accurate regional climate change predictions, an additional objective was to document the status and potential development of national meteorological stations in Burkina Faso in order to examine potential development and to describe what should be considered when using the observational data.

The findings presented in this thesis could act as a valuable tool in increasing comfort and health, if used in future urban planning, as well as in development of strategies for air pollution mitigation in this region, especially when considering the ongoing extremely rapid urban growth. The information of status and potential development of observational data may be valuable for more reliable predictions of future changes in climate in the region.

OVERVIEW OF THE STATE OF THE ART

Urban climate in (semi) arid cities

The urban climate has been studied for over 100 years. The main focus has been spatial and temporal thermal variations, with the urban heat island (UHI) – warmer temperatures in the urban centre compared to surrounding undeveloped rural areas – as the most studied feature. The different temperatures often found in built, compared to natural, environments are caused by a number of different factors. Primarily, the radiation balance changes due to the urban radiative geometry and thermal properties of the urban materials, but other factors such as changes in evaporation and evapotranspiration processes, due to the removal or introduction of water and vegetation, as well as changes in natural wind patterns, also affect the urban climate (e.g. Arnfield 2003)

Pearlmutter et al. (2007) show that arid cities are under-represented in the literature, and that considerable differences in urban climate processes are likely to be presented in comparison to temperate regions, mainly due to differences in heat and moisture balance in the different climates. For example, vegetation or irrigated areas are more likely to be an important parameter in arid cities due to the scarcity of vegetation in surroundings. They also discuss that places characterized by harsh thermal extremes present unique opportunities for microclimatic enhancement.

Urban thermal variations in relation to land cover

Variations in the thermal environment, both urban - rural and intra - urban, are most pronounced during calm and clear nights with stable atmospheric stratification. This is due to a restricted ventilation of the urban air and a strong radiative cooling during these conditions, allowing temperature differences to be built up between areas of different thermal properties. Increased nocturnal temperatures are often found in dense urban structure, primarily due to increased absorption of short-wave radiation and storage of sensible heat by urban materials, and to multiple reflection in urban street canyons further increasing absorption of short wave radiation and reducing long wave radiation lost to the atmosphere (Oke et al. 1991). In contrast, during daytime, a dense building structure in hot-arid climates may create a cooler environment due to a reduction in radiation loading in narrow street canyons, and the use of lightly colored materials, especially roofs, can increase albedo thus reducing amount of solar radiation absorbed (Oke 1982, Johansson 2006, Pearlmutter et al. 2007). This type of urban design has traditionally been used in hot-arid climates to mitigate heat stress. Unfortunately, recent urban settlements in developing countries tend to be more spread out and open, and choice of materials depends on availability and cost rather than thermal characteristics, thus the much needed cooling effects may therefore be lost (Johansson 2006).

Urban built geometry and materials have long been considered the most important factor in generating thermal variations in all urban areas (Souch and Grimmond 2006). However, a more limited impact of building materials in the Sahel regions was suggested by Offerle et al. (2005) who show that the common use of local building materials, such as clay bricks, in residential areas in Ouagadougou, limits heat storage thus a having a lesser impact on the local climate. This was also mentioned as a cause for the lack of UHI found in Kuwait City by Nasrallah et al. (1990). In arid climates, the influence of urban vegetation has been suggested as more important for the urban climate of cities in (semi) arid regions (Jonsson 2004, Pearlmutter et al. 2007). Jonsson (2004) identified vegetation as the most important factor in the urban climate of Gaborone. He showed afternoon temperature differences of up to 4 °C between sparsely vegetated urban areas and an irrigated park, but also stronger cooling after sunset in a vegetated residential area compared to a dry residential area. A review by Bowler et al. (2011) of research on vegetation cooling in urban areas show that little information exists on the night time effects of urban vegetation and research has instead focused mainly on daytime effects. This is due to that many effects by vegetation are active mainly during daytime; potential shading effect is only effective during the day, evapotranspiration due to the photosynthesis process is commonly considered to be mainly active during daytime, and relative humidity is generally significantly higher at night causing less evaporative cooling. Of the few studies of nocturnal effects of urban vegetation, Spronken-Smith and Oke (1998) suggests that an area with short plants or open bare ground may cool rapidly at night due to its higher radiative cooling rate in the hot summer climate of Sacramento, CA, while a contrasting study by Jauregui (1991) shows that a park with dense large trees was hotter during the day and considerably cooler at night when compared to the urban surroundings. Saaroni et al. (2004) also found no daytime cooling effect of vegetation in a desert oasis and suggested reduced daytime plant transpiration as a possible cause. Several studies in hot (semi) arid environments show that due to heat stress, the evapotranspiration process for plants often ceases during the hottest part of the day for water saving purposes (Franco and Luttge 2002, Hu et al. 2009), and instead continues after sunset (Domec et al. 2006, Fisher et al. 2007), thus potentially cooling the evening environment by latent heat storage in the process.

Higher UHI intensities have been found during the dry, compared to the wet, season in cities with distinct seasonal variability in precipitation; for example Mexico City (Jauregui 1997) and Gaborone (Jonsson 2004). This is explained by the higher amount of cloud cover, but also by higher thermal admittance due to increased soil water. The amount of vegetation in (semi) arid areas is likely to vary greatly over the year, with a higher vegetation cover during the wet season compared to the dry, thus affecting the thermal patterns. The impact of vegetation is discussed by Jonsson (2004), where the lower vegetation cover during the dry season increases albedo and facilitates longwave radiation loss from the surface, allowing faster cooling of the rural area and thus causing higher urban rural differences during the dry, compared to wet, season. Cooling due to evapotranspiration by vegetation regarding seasonal variations was not discussed.

In order to unify descriptions of the urban environments to better enable comparison of different studies, Stewart and Oke (2009) proposed a classification in “local climate zones” (LCZ). It was divided into four series and building structures, vegetation and thermal properties of the ground are taken into account. An altered version which included tests to classify towns in temperate climates was presented a year later (Stewart and Oke, 2010). In this later version of the classification, types of urban structure ranges from compact high-rise to sparsely built, with a set amount of vegetation/natural surface in each type of climate zone. The importance of a thorough description also of the rural area used in urban-rural comparisons have also been discussed by Grimmond et al. (1993), who show that selection of an irrigated versus non-irrigated rural site can cause significant differences in urban-rural analyses.

Urban wind field

The roughness of the urban landscape influences the regional wind pattern and generally reduces wind speed within the urban area, though local areas with higher wind speeds and eddy circulations may also be created (Munn 1970). The urban wind and turbulence field is as a consequence very complex and varies in time and over space (Roth 2000).

Little information is available of the wind fields in Sahelian cities. The large scale African Monsoon Multidisciplinary Analysis (AMMA) initiative, launched in 2005, have however generated a number of studies of the regional airflow above the Sahel region. For example Lothon et al. (2008) describe the behavior of a very consistent nocturnal low-level jet (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 skewed air vertical velocity. This NLLJ was present approximately 80 % during the dry and moistening season, and 60% during the wet season. Impacts of a Sahelian NLLJ are also 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.

In order for a NLLJ to be created, low surface wind speeds and stable atmospheric stratification in the surface layer air column generating a frictional decoupling of the surface wind layer from the wind layer above (where the NLLJ is developed) is required (Blackadar 1997, Haeger-Eugensson 1999, Kallistratova et al. 2009). Acevedo and Fitzjarrald (2003) show that the increase in vertical wind shear due to development of large-scale winds aloft, such as a NLLJ, can in turn cause a re-coupling of the wind layers, increasing downward turbulence thus decreasing stability and causing a re-coupling of the wind layers. The re-coupling of lower and upper wind caused by evolution of a NLLJ has also been discussed in relation to nocturnal ozone peaks (Corsmeier et al. 1997, Reitebuch et al. 2000, Salmond and McKendry 2002). Peaks in ozone were in these studies correlated to a decrease in or breakdown of the stable atmospheric stratification and were linked to vertical turbulent mixing of the air column.

During conditions favorable for creation of a NLLJ, i.e. low regional wind speeds at surface level and stable atmospheric conditions, local thermal surface wind systems may be created in urban areas where uneven heating or cooling of the different surfaces in and/or around the urban area causes strong horizontal temperature and pressure gradients (Hidalgo et al. 2010). The most studied of these thermal circulation patterns are sea/land breeze in waterfront cities (e.g. Miller et al. 2003) and slope/valley wind systems in cities with varied topography (e.g. Haiden and Whiteman 2005). Thermal wind systems have also been noted in urban areas with a strong UHI. The urban-rural temperature gradients then create a flow from the cooler rural areas towards the warmer urban center, 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). A few studies have also noted the presence of an intra-urban thermal breeze (IUTB) as a result of different surface characteristics generating temperature gradients within an urban area (Eliasson and Upmanis 2000, Honjo 2003, Thorsson and Eliasson 2003, Jansson et al. 2007, Narita 2009). This type of thermal wind system may also be referred to as park breeze, since it is sometimes found around urban parks or vegetated areas with lower temperatures compared to surrounded built-up areas.

The local wind field and turbulent diffusion play a major role in dispersion of urban-derived pollutants (Roth 2000, Arnfield 2003, Papanastasiou and Melas 2009). An increase in air pollution concentrations during stable atmospheric conditions with low wind speeds have been noticed as an important factor for air pollution concentrations in several studies in (semi) arid African cities, for example Addis Ababa (Etyemezian et al. 2005), Ouagadougou (Boman et al. 2009, Eliasson et al. 2009) and Gaborone and Dar es Salaam (Eliasson et al. 2009), but also during the cold and wet season in the north African city of Cairo (Zakey 2008). As urban thermal wind systems occur during stable atmospheric conditions, these local wind patterns are potentially important for transport and dispersion of pollutants during episodes of poor air quality. This is noted by Romero et al. (1999), for example, who found maximum pollution concentrations during periods when a slope-wind system was active in Santiago, Chile. It is suggested that the urban wind field and potential thermal wind systems and should be taken in to consideration in urban planning due to the importance of ventilation and transport of the air pollution (Barlag and Kuttler 1990-1991, Eliasson 2000).

Air pollution in urban sub-Saharan Africa

Fenger (2007) presents a schematic presentation of the typical development of air pollution levels in a developing country where rapid increases in pollution levels follow the initial stage of economic development, followed by a stabilization in pollution levels due to initiation of emission controls as economic development continues, and finally a reduction when a high level of development is reached and high technology is applied. Due to the rapid urbanization process in combination with limited financial means, most sub Saharan cities are likely to currently experience the initial stage of this development curve.

Sources of air pollution in African cities differ from those in developed regions. Other than road-vehicle emissions, a generally dominant source in urban areas (Sawyer 2010), studies of urban air quality in Sub Saharan Africa have pointed to the importance of other factors besides traffic, in particular biomass burning and mineral dust (Etyemezian et al. 2005, Arku et al. 2008, Dionisio et al. 2010).

Approximately three billion people in the world rely on biomass as household fuel (Smith and Mehta 2003). Almost all households that rely on biomass burning are located in developing countries, where the use of open fires or simple stoves without chimneys, often in poorly ventilated areas leads to extreme levels of indoor air pollution (Fullerton et al. 2008). Though the use of biomass as household fuel may be more common in rural areas, it is also widely used in low-income urban areas. For example, a study of household energy in Ouagadougou, Burkina Faso show that over 80 % of urban dwellers used biomass as the main household energy (Ouedraogo 2004). The third pollution factor mentioned above, mineral dust, generates coarser particles with an aerodynamic diameter <10 mm (PM_{10}). A study of the long range transportation of dust show that West Africa is the region most affected by dust transported from the Saharan desert (the world's largest source of aeolian soil dust) but least studied (De Longueville et al. 2010). Etyemezian et al (2005) found a high content of soil related particles in PM 10 in Addis Ababa, Ethiopia, but suggests that most of the geological material found in PM10 was due to re-suspension of road dust connected to the prevalence of unpaved roads. Unpaved roads were also found to be important for levels of PM in the three African cities Ouagadougou, Dar es Salaam and Gaborone by Eliasson et al (2009) and Accra (Arku et al. 2008, Dionisio et al. 2010). In addition to resuspension from vehicles on unpaved roads, the traffic fleet in developing countries generally consist of a large proportion of highly polluting old, poorly maintained vehicles and a high numbers of two-stroke vehicles (Baumbach et al. 1995, Gwilliam 2003). A review of studies of air pollution from traffic show that, compared to the large volume carried out in the developed world, studies in developing countries are scarce, especially in Sub-Saharan Africa (Han and Naeher 2006). A fourth potential pollution source was shown in a study of Ouagadougou by Boman et al. (2009) who connected a relatively limited part of the air pollution to the industry in the city.

Both traffic emissions and biomass burning emit known health-damaging pollutants, including respirable particulate matter (PM), carbon monoxide (CO), volatile organic compounds (VOCs) and nitrogen oxides (NO_X) (e.g. Han and Naeher 2006, Naeher et al. 2007). Air pollution has been connected to multiple adverse effects for human wellbeing such as increased hospital admissions and life years lost due to asthma, acute respiratory infections, heart disease, and lung cancer among others (e.g. Kunzli et al. 2000, Brunekreef and Holgate 2002). However, the great majority of studies of health effects from air pollution exposure are focused on more developed regions, while the greatest health impacts from air pollution occur among the poorest and most vulnerable populations (Fullerton et al. 2008). For example, the most important health effect of indoor air pollution is the increased risk for acute respiratory infections in children, which is the single most important cause of death in children aged less than 5 years in developing countries (Bruce et al. 2000, Smith et al. 2000). In cities in Sub-Saharan Africa, poverty in combination with often extreme urbanization rates has created exceptionally poor air quality. Despite this, systematic measurement and monitoring of urban environmental health risks connected to air pollution has received very limited attention (Arku et al. 2008). Except for exposure in households using biomass as fuel, which mainly affect women in charge of cooking and their young children, studies of exposure to air pollution tend to treat populations as homogenous within regions or countries which may provide a poor representation of the actual situation. Östlin et al (2006) state that as poverty is known to cause ill-health through unhealthy living and working conditions, and risk factors may differ considerably between women and men in developing countries, differences within and between countries need to receive more focus in health research.

Climate change – impact in the Sahel region

The Sahel region has been mentioned as one of the regions most vulnerable to climate change in the world (Kandji et al. 2006, Boko et al. 2007). This is mainly due to the heavy reliance on subsistence rain fed agriculture, which is the far most important economic activity and main source of income and livelihood of the fast growing population in the region, and due to the inability to adapt to changes due to a lack of economic and technological resources for example (Ingram et al. 2002, Tarhule and Lamb 2003, Kandji et al. 2006, Boko et al. 2007). Changes to a warmer, drier climate are also likely to affect the urban population, mainly due to decreased food and water security, but also due to an increased heat stress or increase levels of transported dust if vegetation cover decreases, while a wetter climate may for example increase risk of flooding, for example.

Climate models show little consensus in predicting future climate change over West Africa, but most point to a warmer climate with decreased precipitation. This lack of agreement of climate change predictions for the Sahel region greatly limits possibilities for making long term model projections for the region as a whole (SWAC 2010). Simulation of future climate change scenarios requires not only global circulation data of meteorological parameters, but also high quality observational data describing both present-day and historical climate conditions (IPCC 2007). The quality of data series is often referred to as the homogeneity of the series, where a homogeneous climate time series is defined as one where variations are caused only by variations in weather and climate (Conrad and Pollak 1950). However, there are often many other factors affecting the data series, such as changes in the local environment around the station caused by urbanization or erosion, changes in instrumentation or location of the station, new formulas for calculations and changes in procedures during data collection (Peterson et al. 1998). Additionally, systematic errors can arise because of varying reporting methods and units adopted by different national meteorological agencies (IPCC 2007).

The data issue creates a major constraint in studies of the African climate, due to insufficient access to information technologies, irregular and often low density of meteorological stations and inhomogeneous data series (Desanker and Justice 2001). Lanzante et al. (2003) found that temporal variations in data from African meteorological stations were very problematic with large temporal inhomogeneities. A review by Paeth et al. (2011) of progress in regional downscaling of projected changes in precipitation for West Africa show that considerable progress was recently achieved in dynamical and statistical downscaling. However, observational networks in West Africa need to be extended and maintained in order to validate high-resolution regional climate models and to feed downscaling methods.

STUDY AREA

The capital of Burkina Faso, Ouagadougou (12°22N, 1°31W, 300 masl) currently has approximately two million inhabitants. As mentioned above, Ouagadougou is pointed out as the most rapidly growing area in the world, expecting to reach 3.4 million inhabitants in 2020(UN Habitat 2010). Burkina Faso was among the top 25 countries with the fastest progress in human development in the 2010 Human Development Report (UN Development Programe 2010). However, despite the rapid improvements it is still a poor country, showing the 9th (2nd in 1970) lowest human development index in the world.

Urban structure and land cover

Figure 1 shows the Ouagadougou area classified in respect to type of urban structure. Also depicted is the presence of vegetation and open water with growth of planned residential of an open-set mid-rise type (classification according to Stewart and Oke, 2009) as well as spontaneous settlements (lightweight low-rise) areas specified. The urban structure in Ouagadougou is generally sprawled out and dominated by low buildings and sparse vegetation, with many dry, open areas spread out over the city. The urban center 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. As a result of rapid growth, urban spatial change is mainly in the form of spontaneous settlements of lightweight low-rise type rapidly growing at the outskirts of the city. These areas are uncontrolled by the government and generally lack access to electricity, water, sanitation and infrastructure (De Jong et al. 2000). Buildings are simple, often made of clay with corrugated steel roofs.

Figure 1. Location of Burkina Faso with the Sahel area shaded (upper left corner), and a map of the capital Ouagadougou, classified based on land use according to LCZ suggested by Stewart (2009), with additional information about irrigated areas and urban growth between 2004 and 2009.

Deforestation caused by heavy foraging for firewood, food and grazing, has left surroundings of Ouagadougou bare and dry, with little vegetation, while the natural, denser vegetation is only preserved in smaller protected areas. A large reservoir (max. depth 2 m, area ~2.2 km2) stretches along the north part of the city centre (figure 1). Around the reservoir are more vegetated areas, used for growing food-crops and other plants as well as for animal grazing grounds. A large protected but un-irrigated park/forest (area ~2 km2) with a generally dense tree cover is situated east of the reservoir.

Climate and air quality

Ouagadougou is located in the hot semi-arid steppe climate of the Sahel region (Figure 1). According to the Koeppen classification, Ouagadougou has a BSh climate (hot steppe climate) but close to the border of an Aw climate (Savannah climate). As shown in figure 2, 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 (DMN 2001).

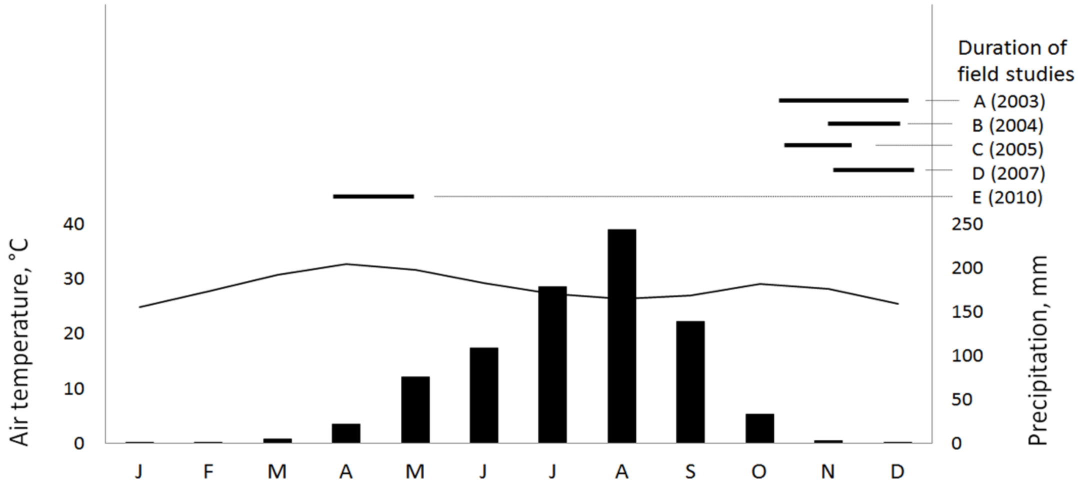

Figure 2. Average monthly temperature and precipitation in Ouagadougou (data from www.worldclimate.com; average 24h temperature between 1924-1990 and precipitation between 1902-1990). Duration of field study A to E is marked as black lines above the graph (see description of field studies in methods section).

During the dry period, the dominating Harmattan winds are predominantly north-easterly and very dry. Daily temperatures vary from 25 °C during the wet season to 33°C at the end of the dry season. Skies during the dry season are often hazy and dust-laden with recurrent dust storms from the Sahara desert later in the season. Visibility is generally reduced to nearly half during dry season compared to the wet period (DMN 2001). Figure 3 shows a satellite image over the Ouagadougou area retrieved from Google earth. The top part of the image is from the end of the rainy season, while the bottom part is from the end of the dry season. The haziness in the lower part of the image

Figure 3. Satellite image retrieved from Google earth showing the eastern outskirts of Ouagadougou at the end of the wet season (October 1st, top half) and at the end of the dry season (march 31st, bottom half) in 2009. Note the denser ground vegetation cover (green areas) in the top part, and the haziness of the skies in the bottom half.

is likely to be caused by the high level of dust in the air during the dry season. The variation in vegetation cover between the dry/wet season is also evident in this image as trees (dark green points) exist in both images, while ground vegetation (green fields) in open areas only exist in the top part of the image and bare soil covers open areas in the bottom part.

Rapid urban growth combined with limited financial means has resulted in poor air quality in the city (Boman et al. 2009, Eliasson et al. 2009). According to Boman et al. (2009), pollution consists primarily of high levels of mineral dust, mainly caused by re-suspension of road dust from unpaved roads, but also from dust transported with regional air flow from the Sahara desert. Other pollution sources include an old vehicle fleet with a high percentage of highly polluting two-stroke vehicles Bultynck (1999), and the use of biomass as the main household fuel in approximately 80% of households (Ouedraogo 2004). One of the adverse health effects closely connected to air pollution is lower respiratory infections, which is the most important cause of death in Burkina Faso, amounting to 20% of all deaths (World Health Organization 2006).

A study of Impact assessment of climate change by Ouedraogo et al. (2006) shows that as the climate in Burkina Faso is already hot and dry, the future scenarios of decreasing precipitation and rising temperature will be very harmful for crop production and seriously affect the food security. Their study also shows that, in 2003, rain fed subsistence agriculture dominated the economy in Burkina Faso, employing 86% of the total population. Better predictions of climate change would thus be of great value in Burkina Faso as well as the Sahelian region in general.

Monitoring of climate and air pollution in Burkina Faso

A network of meteorological stations was established over 100 years ago in Burkina Faso starting with precipitations gauges placed in the colonized French cities. Today precipitation is measured in approximately 150 locations in Burkina Faso, and ten synoptic meteorological stations measuring temperature, humidity, precipitation, wind, pressure and radiation are located in Bobo-Dioulasso, Bogande, Boromo, Dedougou, Dori, Fada N'gourma, Gaoua, Ouagadougou, Ouahigouya, and Pô (figure4). At these stations data is collected on hourly or 30 min basis, with daily averages reported to the main meteorological office in Ouagadougou. One fully automatic synoptic meteorological station intended to deliver data via automatic satellite communication was installed around year 2000 Markoye in the north-east corner of the country. This station was however not functioning between 2003 and 2007. Its current status is unknown.

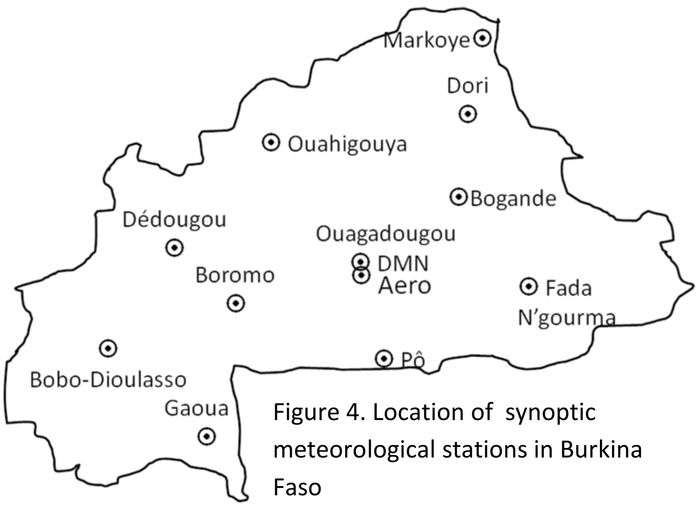

Figure 4. Location of synoptic meteorological stations in Burkina Faso

No continuous monitoring of air pollution in Ouagadougou is currently set up. Ouagadougou have also earlier been subject to some studies of air pollution, mostly financed by foreign initiatives (e.g. Bultynck 1999, Diallo 2000, Jonsson et al. 2004, Eliasson et al. 2009).

METHODS

Most data collected during field work for this thesis is used for analyses in Paper I to V. The description of methods in this introductory part of the thesis is therefore aimed to provide an overview, with references to Paper I to V for a more detailed description of the areas chosen, measurements, instrumentation and data analyses. The general aim and focus of each field study will be described, followed by a more detailed description of new analyses and of data only presented in this introduction.

Overview of the field work

Shown in figure 5 are locations of all measurements of meteorological as well as air pollution parameters were measured in and around Ouagadougou, Burkina Faso. An overview of the methods used to realize the objectives is presented together with some example photos taken during measurements in table 1. Ouagadougou is located on very flat land, and altitude differences between selected areas were less than 15 m.

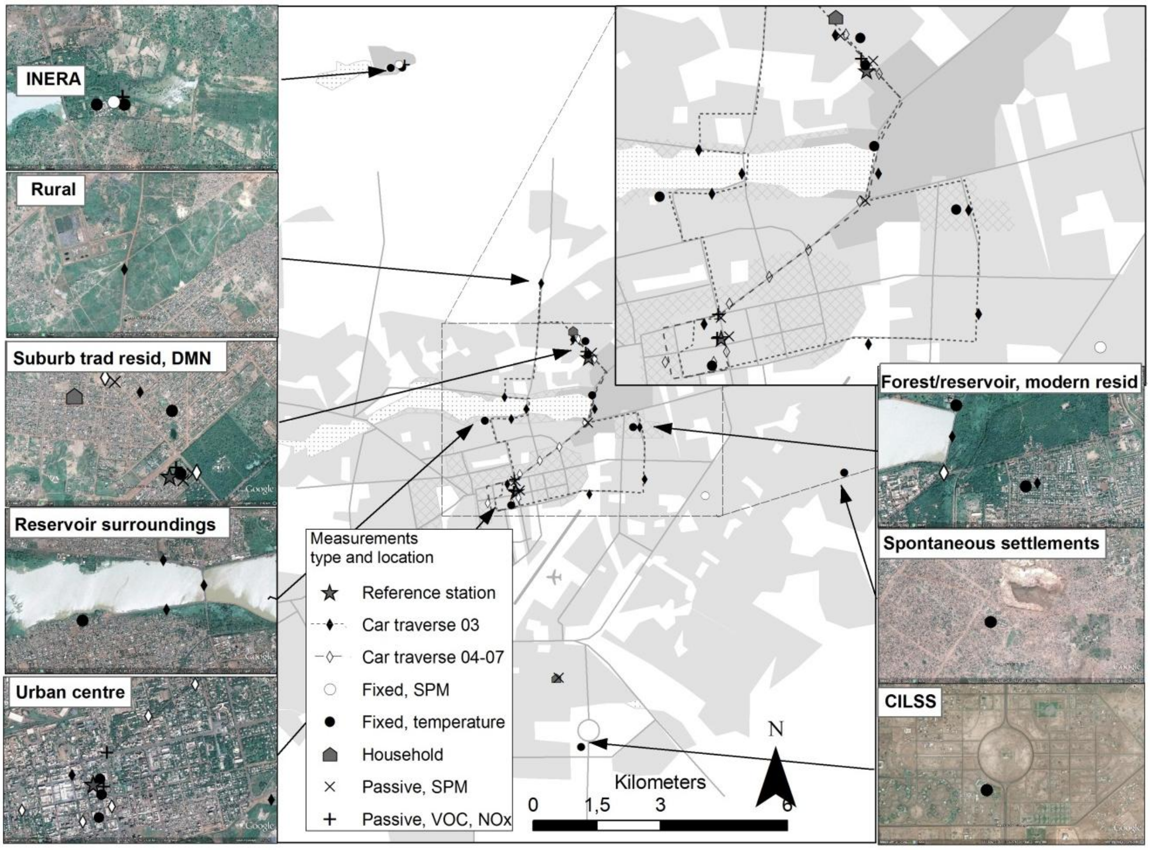

Figure 5. Location of measurements during all field studies with satellite images showing the land cover in the most important areas. Please note that all satellite images except for CILSS are from the end of the wet season thus showing a denser vegetation cover compared to that present during the field studies. For more information about instrumentation and details about areas and methods regarding meteorological measurements, please see Paper I, table 1-3, Paper II, table 1-2, and Paper III, table1, and regarding air pollution measurements, please see Paper IV, table1, and Paper V, table 1-2.

Areas covered during meteorological measurements were chosen in order to characterize the impact of different land cover (vegetation, built/paved, bare soil and open water) on spatial and temporal variations in urban climate. Areas differed in vegetation cover, where more vegetated areas covered were the high income, paved and vegetated *modern residential* areas, the *forest*, in *reservoir* *surroundings*, at the Direction de la Météorologie National (*DMN*), and at an agricultural research facility 10 km north of the urban centre (*INERA*). Low vegetation cover was found in the *urban centre* (names in italic are shown as satellite images in figure 5), the middle to low income unpaved *traditional residential* areas, the informal *spontaneous settlement* as well as at dry, open areas, mainly covered by bare soil, to the south (*CILSS*) and north (*rural*) of the city. These areas also differed in view of urban structure, where the urban centre was of open-set midrise type (Stewart and Oke 2010), planned residential areas of open-set lowrise type, and in the informal spontaneous settlements of light-weight lowrise type. The effects of open water were examined in the reservoir surroundings. For a detailed description of areas please see Paper I, table 1 and 2, Paper II table 1 and Paper III, figure 2

In order to cover variations in air pollution, areas with different human activity and land use (residential/business etc.) as well as traffic density and road surface type were selected for measurements. Activity as well as traffic increased from the rural *INERA* area towards the *urban* area. Areas also varied in use, from the relatively undeveloped *INERA*, to *suburban* and *urban* residential to the urban business area. Unpaved roads were found in the *suburban traditional* residential area, while most roads were paved in remaining areas where air pollution measurements were collected. For a detailed description of areas please see Paper IV, figure 2 and Paper V, table 1.

Table 1. Overview of methods used to realize the specific objectives, showing parameters, measurement type, field study (for description of field studies see below), and some example photos of measurements in different areas. For more information about instrumentation and details about areas and methods regarding meteorological measurements, please see Paper I, table 1-3, and Paper II, table 1-2, Paper III, table1, and regarding air pollution measurements, please see Paper IV, table1, and Paper V, table 1-2.

Specific objective	Parameters measured	Type of measurements (parameter: # of areas)	Field study	Example photos
Spatial variations in temperature and humidity	Air Temperature (T_a) and humidity (H) Ground temperature (T_g)	Car traverses (T_a+ H: 12) Continuous at fixed sites (T_a:10, T_g: 6)	A, B and D	
Stability and wind	Air Temperature and humidity Wind (v, u, w) Radiation (in & out going long & short wave)	Reference stations (all: 2)	D and E	
Air pollution	Particulate matter (PM) Carbon Monoxide (CO) VOC (Benzene Toluene) Nitrogen oxides (NO_X) Ozone (O_3)	Car traverses (CO+PM: 7-9) Continuous at fixed sites (PM:2) Passive diffusive samplers (PM: 8, VOC + NO_X + O_3: 4) Wood fuelled households (CO: 1 indoor, 8 outdoor)	B - E	

Field studies in Ouagadougou

Five field studies, each lasting between four and eight weeks, were carried out in Ouagadougou between 2003 and 2010. The field studies are referred to in chronological order by letters A to E. as shown in figure 2, field studies A to D were all carried out in the early dry season, between October to December. Field study E was carried out during the transition from dry to wet season in April and May. The author was responsible for planning, preparation and field work in studies A to C, participated in the planning, preparation and field work in study D, and the planning and preparation of field study E (field work carried out by two students; Sandra Cimerman and Andreas Anjelic). The aim and objective for each field study will be described below, with references to the respective Paper for more detailed descriptions of measurement sites, instrumentation and analyses.

Field study A (October 15 to December 12, 2003)

The aim of this study was to examine intra-urban and urban-rural differences in air temperature and humidity in Ouagadougou by car traverses day (13:00) and evening (20:00), and fixed site measurements in areas of different land cover. Wind was measured at the suburban reference station. The field work was active during a period of two months, resulting in a total of 37 days of measurements from fixed site measurements, and 34 car traverses (Paper I, II and III).

Six of Burkina Faso's synoptic meteorological stations were visited and documented by interviews with the head of the station.

Field study B (November 11 to December 08, 2004)

The main aim of this study was to examine spatial and temporal variations in CO and PM in Ouagadougou by car traverses. Data was collected during a total of 13 car traverses travelling twice daily from a suburban traditional residential area with light traffic through areas of different type and traffic density ending up in the urban centre. Stops were made for street side measurements at eight locations along the way. Data of PM from this field study is only presented in this introductory part of the thesis and further described below.

An additional aim was to further examine spatial and temporal variations in air and ground temperature by fixed measurements for a period of 21 days, at sites north and south of the city in different types of non-built up environments, as well as at the same site in the city centre as during field study A to enable comparison (Paper I, II and III).

A fully automatic synoptic meteorological station was visited and documented by interviews with the head of the Direction de la Météorologie National in Ouagadougou.

Field study C (October 24 to November 19, 2005)

The aim with this study was to continue car traverse measurements focusing of CO and PM as during field study B. A ninth site was added to the traverse to further examine differences between nearby areas with paved versus unpaved road surfaces. Urban background variations in CO were measured at an urban reference station (Paper IV and V). In addition, passive diffusive particle samplers measuring relative levels of PM were placed in sites chosen to represent different road surfaces (paved/unpaved), exposure to traffic, and inside/outside the wood fuelled kitchen. Data of PM from this field study is only presented in this introductory part of the thesis and further described below.

A pilot study examining the pollution situation inside a traditional wood fuelled household, using a simple open fireplace located at floor level inside a poorly ventilated building, was also carried out during this study (Paper V).

An additional two of Burkina Faso's synoptic meteorological stations were visited and documented by interviews with the head of the station.

Field study D (November 15 to December 21, 2007)
The aim of this most extensive of the field studies, was to examine physical processes governing nocturnal cooling, the urban wind field and the atmospheric stability conditions. Spatial and temporal variations in air pollution were also examined. Two main stations measuring all meteorological parameters as well as CO and PM were placed in one urban rooftop location and one suburban ground level location. Continuous temperature measurements of air temperature were carried out in five additional areas, with 2 or 3 instruments located in different density of building structure within each area. Furthermore, passive diffusive samplers measuring NO_X, O_3 and VOC were placed at both reference stations, as well as at street level in a heavily trafficked location and at a rural site. At the rural site, measurements of PM were also carried out, as well as CO for a limited time period (Paper II, III and V).

Car traverses travelling the same route as during field study B and C, but with an increased number of parameters and locations covered at each street side stop. Data of wind, temperature and humidity as well as CO and PM was collected at each stop. CO was measured at three nearby locations during each stop to examine small scale variations near traffic. Where possible, the locations for CO measurements were placed on each side of the street as well as at a known distance away from the street (Paper V). Part of the data of PM from this field study is only presented in this introductory part of the thesis and further described below.

Field study E (April 08 to May 12, 2010)
The aim of this field study was to examine variations in atmospheric conditions in connection to levels of CO and PM, and to examine levels of CO in connection to outdoor wood-fuelled kitchens in connection to behavioral patterns of household members. Continuous measurements of temperature, humidity, wind, radiation and CO were collected at the suburban reference station, while PM due to technical reasons was measured in a traditional residential area in the eastern parts of the city. Measurements of CO together with interviews with household members were carried out in 8 households located in the traditional residential area west of the suburban reference station (Paper V).

Data treatment and analyses

Data was mainly used directly for analyses of temporal and spatial variations in the city, but calculations of cooling and humidity rates (change in temperature or humidity per hour, see Paper II), and of atmospheric stability (see Paper II, III, V and below) were carried out. Statistical analyses were also used to determine significance of temperature variations (Wilcoxon signed-rank test, Paper I), to determine significance of influence of different land cover parameters (simple and stepwise multiple regression, Paper I) and of significance of spatial differences in CO (Wilcoxon signed-rank test, Paper IV).

The days covered during the field studies were categorized accorded to nocturnal stability (extremely, moderately or slightly stable conditions). This was primarily based on calculations of Radiation Richardson number, Ri_{rad} (Mahrt and Ek 1984) from measurements during field study D and E (Paper II, III, and V). As this way of calculating Ri_{rad} includes the highly variable parameter wind to the power of 3, resulting stability levels tend to fluctuate largely over short time periods. To minimize the random flux error the calculations of Ri_{rad} were based on hourly averages of meteorological parameters, as also suggested by (Mahrt et al. 1998). This causes lower general levels of Ri_{rad} but limits large short term temporal variations in atmospheric stability and thus gives a more accurate picture of the atmospheric stability. An average nocturnal Ri_{rad} above/below 0.3 were considered extremely/moderately stable. During field study E, Ri_{rad} was consistently below 0.3, but variations in stability still existed, especially in the early hours of the night. Days from this study were therefore classified to moderately/slightly stable when early night Ri_{rad} was above/below 0.002. A high value of nocturnal Ri_{rad} correlated with large diurnal temperature range, where the extremely (moderately) stable days at a non built-up, vegetated site showed a range above (below) 16 K. Based on these temperature range criteria, the days covered during field studies A and B was characterized according to nocturnal stability. During field study C, continuous measurements were only available at the urban reference station. To determine stability during this study, diurnal temperatures found at the urban during the different stability classes were examined. Though differences were less pronounced at this site, all extremely (moderately) stable days during field study A, B and D showed a diurnal temperature range above (below) 12 K. The days during field study C were classified as extremely of moderately stable based on this diurnal temperature range.

The urban growth between 2004 and 2009 in Ouagadougou was analyzed based of satellite images retrieved from Google earth (www.google.com/earth). The satellite images were visually classified in respect of land cover. This classification was used to determine the spatial growth of different type of built urban areas between the two years. Increase in length of paved roads between the two years was also examined as presented in Paper V.

Data and analyses not previously presented

Data not previously presented are results from the passive diffusive particle samplers used during field study C, as well as measurements of PM with the instrument Aerocet 531 from car traverses during field study B, C and D (PM measurements with GRIMM dust monitor are analyzed in Paper V). Results from documentation of the synoptic meteorological stations are also presented.

The passive diffusive particle samplers (http://www.diffusivesampling.ivl.se) are vertically mounted Teflon filters measuring relative levels of PM were placed at a height of 3 m in nine locations around the city. The sites were chosen to represent different road surfaces (paved/unpaved), exposure to traffic, and inside/outside the wood fuelled kitchen described above. A field blank was used for reference. The samplers were exposed during a period of one week, and give a relative value in weight of total suspended particle concentrations in each area. Levels are likely to mainly reflect the presence of larger particles in the air due to their dominant weight over smaller particles.

Levels of PM were measured during car traverses in field study B to D. A total of 20 evening traverses (starting at 17:00) and 22 daytime (starting at 10:00) traverses were carried out. Each traverse lasted approximately 1h, 20 min. A number of street side stops were made during the traverses during which measurements with a laser aerosol spectrometer (Aerocet 531, Metone instruments inc., Oregon, USA) measuring concentration of airborne particles with an interval of 2 min were collected for 4 minutes in field study B and C, and 6 minutes in field study D. In this analysis, spatial variations in PM_{10} were examined from seven street side locations covered during car traverses, starting in an unpaved residential area, and then travelling through paved streets with varying traffic density ending up in the urban centre. Data from evening traverses wasdivided according to atmospheric stability situation resulting in 12 extremely stable and 8 moderately stable occasions. Daytime data was treated as one group since daytime conditions are more turbulent, regardless of nocturnal stability.

In order to describe an example of what could be expected of data series collected in a Sahelian country and what should be considered when using the data, eight of the synoptic meteorological stations in Burkina Faso were visited and documented parallel to field study A to C. Meteorological stations in the following cities/villages were visited; Ouagadougou (DMN + aero), Boromo, Dedougou, Ouahigouya, Pô, Bobo-Dioulasso, Dori and Markoye. During the visits, interviews were carried out where the head of the station was asked to describe each measured meteorological parameter in regards to past and present instrumentation, measurement procedure, maintenance and repair possibilities and data handling. Questions were also asked regarding procedure during report of data, exchange of instruments, changes in surroundings and/or location of location, and how general metadata was collected and stored. Finally a question of what improvements would be prioritized if funding would be available was asked.

RESULTS

Atmospheric stability

Weather during the early dry season (October – December, field study A-D) was dominated by high pressure and stable atmospheric conditions with hazy but cloudless skies and no precipitation. Average hourly temperatures, wind speed and stability for extremely, moderately and slightly stable atmospheric conditions are shown in figure 5. Of the 94 days covered with continuous measurements in field study A to D, 80 % were characterized by extremely stable nocturnal atmospheric conditions. The remaining 20 % showed moderately stable nocturnal atmospheric conditions. Daytime wind conditions were neutral to slightly unstable and more turbulent compared to night time. During the transition from dry to wet season, as examined in Field study E, weather was warmer and windier with thunderstorms and precipitation every 2-3 days. In between precipitation, skies were generally clear or hazy. Nocturnal atmospheric stability was lower, with 26 % of nights moderately stable, and 74% slightly stable. Effects of atmospheric stability on spatial and temporal variations in the urban climate and air pollution are examined in Paper II, III and V.

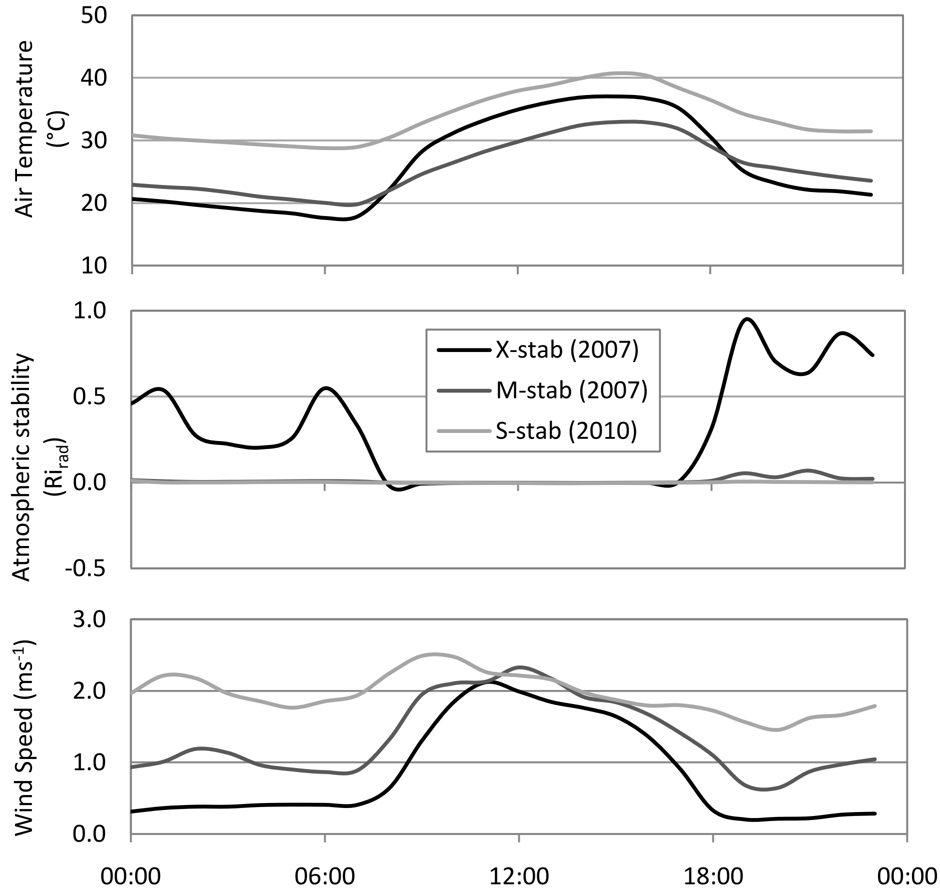

Figure 5. Hourly average temperature, stability and wind speed patterns during extremely (X-stab), moderately (M-stab) and slightly (S-stab) stable nocturnal atmospheric conditions during field study D and E.

The urban climate in relation to land cover

The urban climate of Ouagadougou is characterized during early dry season by considerable spatial and temporal variations, as presented in Paper I to III. The thermal patterns were examined in relation to land cover (Paper I and II) which showed that the most pronounced thermal features in Ouagadougou were nocturnal cool islands in areas with a high vegetation cover, regardless of building structure and urban or rural setting. Temperature differences of on average 5 K were created between vegetated (> 40 % vegetation) and slightly vegetated (< 10 % vegetation) areas shortly after sunset and remained until sunrise. Figure 6 show satellite images with average nocturnal (a) and afternoon (b) temperatures in areas covered by fixed temperature measurements during field study A and B in Ouagadougou. Vegetation is visible as darker areas in the satellite images and it is clear that all cooler areas during night time are located where vegetation is abundant. During daytime, statistical analyses show that the most important land cover parameter was open water which had a cooling effect on temperatures, while impact of vegetation was very limited and instead indicated a slight warming influence (Paper I). This is also visible in figure 6, where the coolest area is located near the reservoir while some of the vegetated areas are among the hottest. The physical processes behind the cooling effects of vegetation are examined in Paper II, where it is shown that the difference between the sites can be explained by a strong evening evaporative cooling (EEC) in the more vegetated areas. The EEC was indicated by a high humidity increase rate in vegetated areas concurrent with cooling. Since soil moisture content was very low the humidity increase rate was likely to be primarily a result of evapotranspiration causing latent heat loss.

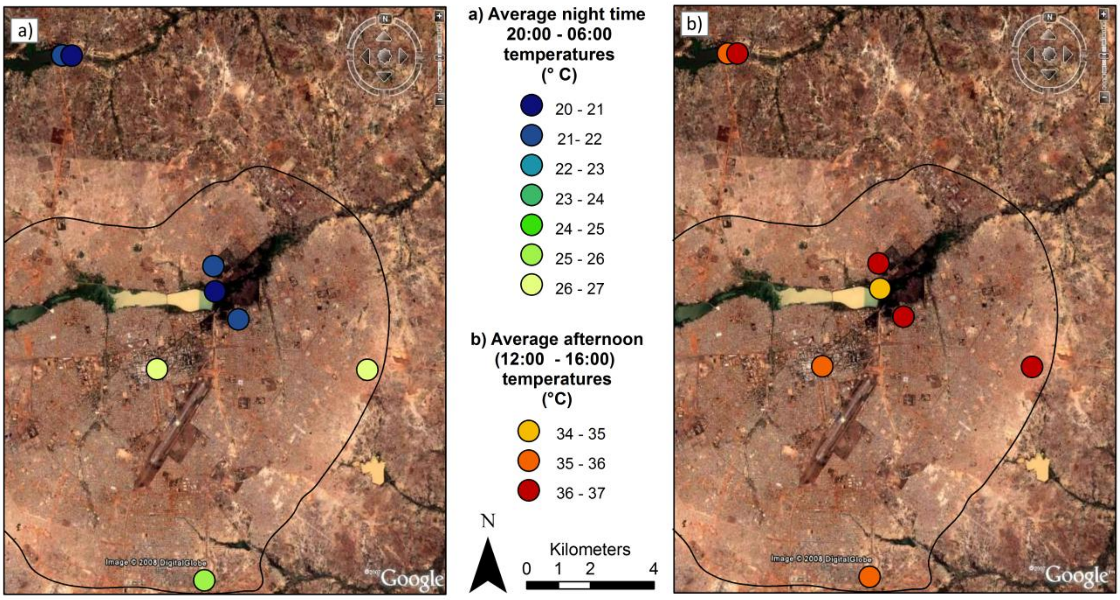

Figure 6. Average a) night time (20 – 06) and b) afternoon (12-16) temperatures from fixed site measurements during field study A and B in Ouagadougou. Note how cooler temperatures night time are all located in areas with abundant vegetation (dark areas in the satellite image) while vegetation have no influence daytime. Also note that nocturnal temperatures are similar in the urban centre (open-set midrise, approx. 2 km south of the reservoir) as in the spontaneous settlements (lightweight low-rise, location to the east).The black line shows the approximate extent of the urban area.

Statistical analyses in Paper I shows that the built up and paved fraction had limited overall impact on temperatures in the different areas both day and night. However, analyses in Paper II shows that if the sites were divided in to vegetated (> 40 % vegetation) and sparsely vegetated sites (< 10 % vegetation), a higher sky view factor (often used as an indication of density of built structure) correlated to a faster cooling rate (Paper II).

The cooling rates at the different sites were also examined in Paper II, which show that cooling could be divided in to two phases; phase I (around sunset), and phase II (after 20:00). During phase 1 cooling rates were site dependent and differed greatly between the sites, where vegetated sites cooled much faster with cooling rates around -5 K/h, compared to slightly vegetated sites where rates were approximately -2 K/h. Cooling rates during phase II were slower (-0.5 to -1 K/h) and homogeneous at the different sites, explained by radiative cooling of the air capping Ouagadougou. Thus the temperature differences developed in Phase 1 were preserved until the morning. Paper I also shows that intra-urban variations exceed urban-rural differences, and that the location of the rural reference would be of great importance for determining the urban-rural differences. The impact of stability on the thermal variations is also analyzed in Paper II. During extremely stable conditions, stronger spatial differences in temperature as well as cooling and humidity rates are found compared to those during moderately stable conditions. Differences between vegetated and sparsely vegetated areas were on average 6 K during extremely stable nocturnal conditions.

Urban wind system

The nature and development of an intra-urban thermal breeze found during extremely stable nights is described in Paper III. During extremely stable nights, a consistent intra urban thermal breeze, generating almost opposite wind directions at two locations within the urban area, with winds from N-NE in the suburban area and winds from SE in the urban centre, was found in Ouagadougou. Wins speed when the thermal wind system was active was around 0.5 ms^{-1} A turn in wind direction were mainly noticed at the urban station when atmospheric stability increased in the evening, but the duration of this deviating wind was irregular, sometimes lasting throughout the night and sometimes only a few hours. 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. The high 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 and thus pressure gradients in Ouagadougou found in Paper I and II.

During moderately stable nights, the thermal wind system was generally not created, though occasional episodes of high stability generated an intra-urban thermal wind system during this period as well.

Spatial and temporal variations in air pollution

Analyses of air pollution measurements in Ouagadougou during field study B to E show large spatial and temporal variations in and around the city (Paper IV and V), with variations most pronounced during extremely stable atmospheric conditions (Paper V). In this introductory part of the thesis, focus will be on new data presented, while results analyzed in Paper IV and V will mainly be summarized. Peak concentrations in PM and CO were found in evenings, when a stabilization of the atmosphere coincided with evening rush hour, and with cooking session for evening meal. During extremely stable conditions, the evening peak lasted for several hours before slowly declining. The higher ventilation during moderately stable atmospheric conditions caused concentrations to decrease shortly after evening rush hour. A smaller peak coinciding with morning rush hour was also visible. However, the daytime atmospheric instability caused a quicker dispersion of the morning rush hour emissions and thus a smaller and shorter peak in pollution levels.

Particulate matter

Background PM_{10} concentrations were consistently high, with daily average levels three times higher compared to WHO recommendations for maximum 24 h exposure during the extremely stable periods. Generally, daily average background concentrations of coarse particles (PM_{10}) were over three times higher during extremely stable compared to moderately stable conditions, while smaller particles (PM_1) over four times higher. The smaller particle size, PM_1, shows a clear diurnal pattern at the heavily trafficked urban site with relatively high concentrations, especially at times of rush hour

(Paper V). Both levels and diurnal variations in PM_1 were considerably lower at the suburban and rural sites. More uniform levels of $PM_{2.5}$ were found in the different areas, which may be caused by a mixture of re-suspended dust with combustion and traffic generated particles (Paper V).

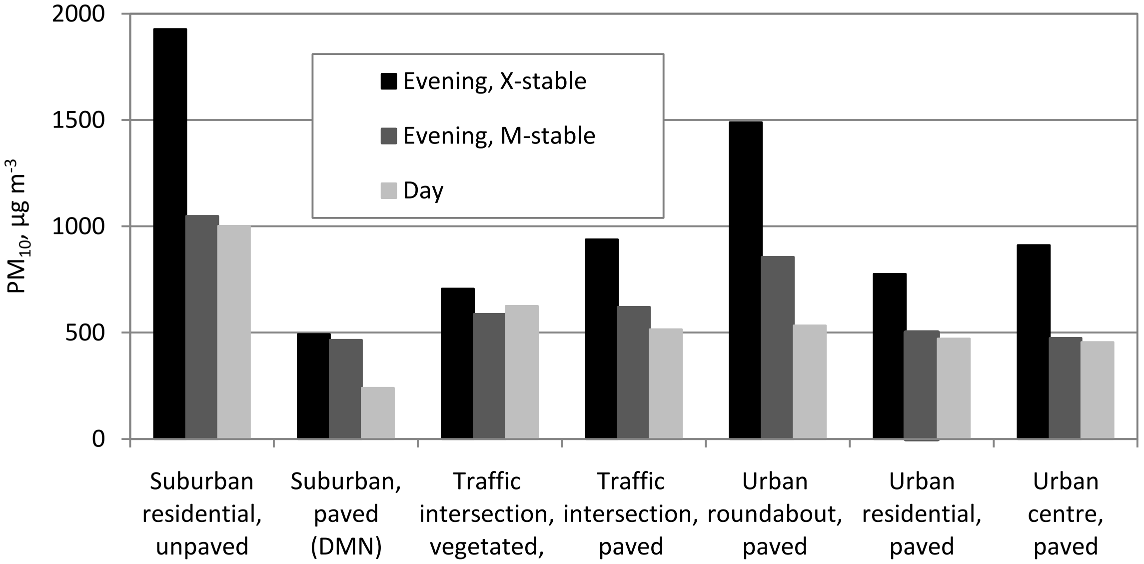

Figure 7. Concentrations in PM_{10} measured at street side stops during car traverses in field study B, C and D. Evening measurements (around 18:00) are separated according to extremely stable (X-stable) and moderately stable (M-stable) nocturnal atmospheric conditions. Daytime levels are measured around 10:00.

Levels of larger particles, PM_{10}, were similar at the urban and rural areas, while between two to seven times higher levels were found in a traditional residential, regardless of stability conditions. This was connected to re-suspension of dust from unpaved roads (Paper V). This is also evident in the new data presented here (figure 7, and table 1), where highest levels of PM were found in the unpaved residential area, and considerably lower levels in the nearby suburban paved area. The paved area also had a higher vegetation cover. These areas are located approximately 600 m apart. An increase in levels of PM_{10} can be seen in figure 7 from the suburban paved location towards the urban centre, with an urban peak by a centrally located highly trafficked roundabout. Lowest values in the central urban area were found in a high-income paved residential area. In the final location of the traverse (to the right in figure 7) lower levels of PM_{10} were found compared to the other non-residential areas, probably due to the longer distance from a traffic intersection, and the location in an urban business district where roads were wide and traffic flow relatively fast. Levels were considerably higher during extremely stable evenings compared to moderately stable, with lowest levels daytime.

Table 2. Relative levels of PM (total suspended particles) in different areas in Ouagadougou during field study C

Location	PM ($\mu g\ cm^{-2}\ month^{-1}$)
Suburban traditional residential, street side (unpaved)	189
Suburban street side (paved)	69
Suburban background, measurement yard	64
Urban central roundabout, street side (paved)	101
Urban central roundabout, middle (paved)	137
Urban background (roof top)	72
Wood fuelled household, inside kitchen	15
Wood fuelled household , outside kitchen	80

Results from passive particle samplers presented in table 1 confirm the high levels found in both the unpaved suburban area and the central, heavily trafficked roundabout. The impact of traffic itself for

PM levels may be indicated by results from passive samplers in one of the paved sites presented in table 3; the urban central roundabout, street side and in the middle (approximately 40 m apart). The differences in PM at these sites indicate that the distance to traffic is also important for PM levels. The much higher levels of PM outside the examined household compared to inside (table 1) are probably a result of the much lesser weight of the smaller particles derived from the biomass burning which, despite extremely high levels inside due to poorly ventilated biomass burning (Paper V), are light compared to the soil derived particles in the unpaved traditional residential area outside.

Combustion related pollutants

CO was measured during Field study B to E, at a number of different locations; background, roadside (at different sides of the road as well as at some meters away from the road), in traffic, and in indoor as well as outdoor wood fuelled kitchens. Background CO levels show similar diurnal patterns at the urban and suburban sites; a shorter peak during morning, and a larger peak in evenings (Paper IV and V). Background levels were generally low, rarely exceeding WHO recommendations for maximum exposure (e.g. 9 ppm for maximum 8 h exposure). However, peak levels near sources are considerably higher, with rapidly decreasing concentrations with distance from source. For example, in-traffic levels were 10–12 times higher than urban background, and 2–3 times higher that street side levels, with differences twice as large during traffic congestions, frequently exceeding WHO recommendations (Paper IV). Measurements at different sides of the street show that distance to source is of greater importance for street side levels compared to wind direction as described in Paper V.

Measurements in wood-fuelled kitchens presented in Paper V show that as a result of high emissions and poor ventilation, CO levels in the indoor household examined during field study C were far above background and roadside levels, with average CO levels during cooking sessions of 33 ppm, and peaks of up to 151 ppm. Compared to in-traffic levels, the duration of episodes with high levels of CO were much longer and peaks slightly higher. Levels were also approximately 10 times higher compared to the outdoor kitchens examined during field study E. The CO monitor is located at approximately the same distance from the source (fireplace) which shows that in this case the impact of ventilation is of great importance. Interviews from the outdoor households show that women are in charge of the cooking and that a younger child is sometimes in charge of maintaining the fire as well as helping with cooking (Paper V).

The impact of biomass burning on background levels may be seen in the similar levels of CO at the background urban and suburban sites despite the much lower traffic density at the suburban site (average 240 versus 3300 passing vehicles/minute, Paper V). As the suburban site is located near traditional residential areas where almost all of the households are wood fuelled, the additional source here is likely to be biomass burning. Measurements of NO_X, benzene and toluene show a rapid concentration decrease from the heavily trafficked urban street level site to the background urban, suburban and rural site, indicating traffic as the main source (Paper V). O_3 showed increasing concentrations from urban to rural areas since it is a secondary pollutant, broken down by reactions with other pollutants in the city.

Documentation of synoptic meteorological stations in Burkina Faso

The documentation of the meteorological stations between 2003 to 2005 show that instrumentation was basically the same at all stations. Measurements at all stations followed a set procedure according to a detailed description. At the end of each month the tables were summarized manually and sent to the main office in Ouagadougou, where data was manually transferred to digital format. A manual (visual) check for erroneous values was done both at the station and in Ouagadougou. Original documents/tables were stored at each station, however not according to any set standards.

With the exception of the meteorological main building in Ouagadougou none of the stations had access to computers, and all instrument readings were done manually. Calculations were done with the aid of a basic calculator if available (status in 2003-2005, current situation now known). The instrument park was generally old and sometimes in poor condition. Malfunctioning instruments often took long to repair or replace due to limited financial resources. Employees at each station were taking care of basic maintenance of the stations, but for technical support and repairs, staff from Ouagadougou was called. While waiting for repairs, temporary solutions were used, for example wind direction was estimated when instrument was malfunctioning. With the exception of air pressure instruments at stations located near airports, exchange of instruments was often done without onsite calibration or comparison.

All observers had two years of training prior to working with data collection at the stations. At fully staffed stations (three or more observers) data was collected every hour for temperature, humidity, wind, precipitation, cloud cover and atmospheric pressure. Evaporation and radiation (where available) was measured once daily, soil temperature four times per day, and barograph, pluviograph, thermograph and heliograph took constant readings. At stations with only two observers, some hours during midday and during midnight were left without taking measurements. All stations followed the same schedule depending on the number of employees

There have been potentially significant changes in the location and surroundings of most stations. Two of the stations (Ouahigouya and Boromo) have been moved due to the growth of surrounding city. The station in Dori was, when started, located outside of the city with only three small buildings within 100m. It is now, due to growth of the city, located near the city centre, and surrounded by buildings (~2 storey) and large trees as opposed to grass/bush savannah, which is the natural environment. At the station in the airport in Ouagadougou, a flight tower has been built and the nearby runway has been paved. The station in Pô has seen little changes in surrounding buildings, but according to the head of the station, the natural surroundings have changed significantly to where more sand and bare soil, and less grass and other vegetation, now covers the area. Metadata about the stations is documented in Paper format at each station. Major changes such as changes in station location or instrument exchanges are documented in Ouagadougou as well. Information about changes in station surroundings was not organized to where the stations describe changes the same way and very limited information of instrumental maintenance and repairs was documented.

The general impression was that staff at the meteorological stations was well educated, interested and precise in their work. They were fully aware of the importance of following set procedures in measurements and reports. However, it was expressed at all stations that funding was a major problem for keeping instruments well-functioning and for assuring that all parameters were continuously measured. For example, when asked to specify what immediate improvements would be done if funding was available, the director of the DMN in Ouaga stated that one primary action would be to exchange instrument sheds as many of them were in poor condition. Meteorological data from Burkina Faso was available free of charge for any noncommercial purposes, through contacts with the meteorological office in Ouagadougou (contact info at www. Meteo-burkina.com).

A fully automatic meteorological station located in Markoye in the north-east corner of Burkina Faso was also visited. This station was obtained through a project sponsored by the World Meteorological Organization in 1995-1996, with the intent to install three identical stations in Burkina Faso. The stations were designed to automatically collect and then transfer data via satellite. However, only the station in Markoye was fully installed, though not functioning at the time of visit (2004) and some years prior to that. The reason given was that the time coordinator for communication with the satellite was not functioning and could not be repaired with the technical skills available in Burkina Faso at the time. There was also no funding available for installing the remaining two stations or for basic maintenance of the station in Markoye if it would be repaired.

DISCUSSION

The spatial and temporal variations of temperature and humidity will be discussed in relation to land cover with special focus on the role of vegetation, followed by the general atmospheric stability situation and its impact on the urban wind field as well as on air pollution. Spatial variations in air pollution concentrations will also be discussed with focus on sources and potential effects on human exposure. Finally a discussion of the future development of Ouagadougou and the region in general will follow, with possible applications of results from this thesis suggested. This part also includes a short discussion of possible climate change and potentials effects of results found during documentation of the synoptic meteorological stations in Burkina Faso.

Urban thermal patterns in relation to land cover

The most distinct feature of the urban thermal climate in Ouagadougou was found to be nocturnal cool islands in areas with a relative dense vegetation cover (> 40 %). Daytime effects of vegetation were very small and possibly warming, in direct opposition to the expected afternoon cooling effect by evapotranspiration (Paper I). This pattern in evaporative cooling was connected to considerable heat stress of the vegetation, causing a mid-day depression in plant photosynthesis during daytime and an increase in evapotranspiration when vapor pressure deficit decreases around sunset, as studied by for example Franco and Luttge (2002). As discussed in Paper I and II, evapotranspiration from vegetation generates a strong EEC, creating exceptional cooling rates of down to -6 Kh^{-1} around sunset (area average) in vegetated areas. This EEC is indicated by an increase in humidity concurrent with strong cooling. The same pattern (cooling and concurrent humidity increase) shortly after sunset was also noticed in vegetated residential areas in the semiarid city of Gaborone and attributed to evaporative cooling as discussed by Jonsson (2004). The effect of built structure was limited in comparison to vegetation, and appeared to have little effect on the EEC. However, as shown in Paper II, if areas are previously divided in to vegetated and slightly vegetated, an increase in temperature with decreasing SVF was found. As often experienced in recent urban settlements in developing countries (Johansson 2006), building structure in the Ouagadougou urban centre lacks the deep canyon structure, preventing a daytime canyon cool island effect by a reduction in the radiation load by shading.

The two-phase cooling with area dependent cooling rates in the first part of the night and relatively uniform cooling rates during the rest of the night have been found in other studies of intra-urban temperatures as well (e.g Erell and Williamson 2007, Holmer et al. 2007). The strongest cooling rates in these studies were found in open areas and attributed to strong radiative cooling. Early night cooling rates due to strong EEC in vegetated areas in Ouagadougou were approximately double compared to those found in the open area (Paper II). This shows the greater importance of cooling by EEC compared to radiative cooling in Ouagadougou during the early night. The strongest cooling rate in the tropical city of Singapore was also found in a vegetated area by Chow and Roth (2006), though no open area was examined in this study. After the initial cooling during early night, rates decrease and become similar at all sites regardless of vegetation, and late night cooling was instead governed by radiative cooling of the air capping Ouagadougou (Paper II).

The apparent great influence of vegetation on the urban climate in this region may generate more pronounced intra-urban compared to urban-rural differences, since urban areas may be more densely vegetated due to irrigation in urban areas. The presented dominant effect of vegetation over built structure is also of critical importance to include when selecting areas to be examined in studies of the urban climate in this region. In order to show an example of how the effect of vegetation cover on the rural area may impact results, a comparison of three different studies presenting dry season UHIs of very different magnitudes - from 1.9 K to 8 K - in Ouagadougou is presented. The studies are presented in table 3 with satellite images of the rural area during dry and wet season in figure 8.

Table 3. Comparison of studies of the UHI in Ouagadougou. Name of rural areas as in this study.

Study	UHI	Rural reference	Land cover in rural reference	Number of days	Time of year
Paper I	1.9 K at 20:00	Rural	Dry ground vegetation and bare soil	17	Early dry season
Jonsson and Lindqvist (2005)	4 K (1 K)	INERA	protected vegetated agricultural research area north of the city	All year	Dry (wet season)
Offerle et al. (2005)	Up to 8 K	DMN	Dry ground vegetation, scattered trees, dense vegetation N-E to S-E, trad. resid. areas in other directions	5	Middle of dry season

Figure 8 presents satellite images of the three areas used as rural representatives during dry (in 2004) and wet (in 2009) season. In the dry season, the denser vegetation cover at DMN and INERA compared to the rural area used in Paper I is apparent, and, given the dominant cooling effects of vegetation on nocturnal temperatures, reflected in the stronger UHI presented in these studies. The vegetation surrounding DMN and INERA is probably more comparable to the original natural vegetation of the region, while current vegetation cover in Ouagadougou rural surroundings is better represented by the rural area used in Paper I due to intense anthropogenic wear such as heavy foraging for firewood, food and grazing. From figure 8 it is also apparent that vegetation cover differs greatly between dry and wet season. The greater differences at the rural area used in this study between dry and wet season might generate larger seasonal variations in the UHI compared to the other rural locations where vegetation cover might be more constant during the year. The location of rural in urban-rural comparison thus calls for a careful consideration as it cannot simply be presented as an area with no urban built structure, but must also carefully consider vegetation cover, including variations over the year. This is likely to be especially true for (semi)arid areas, where vegetation is of more importance compared to temperate areas, but may be important in other climates as well.

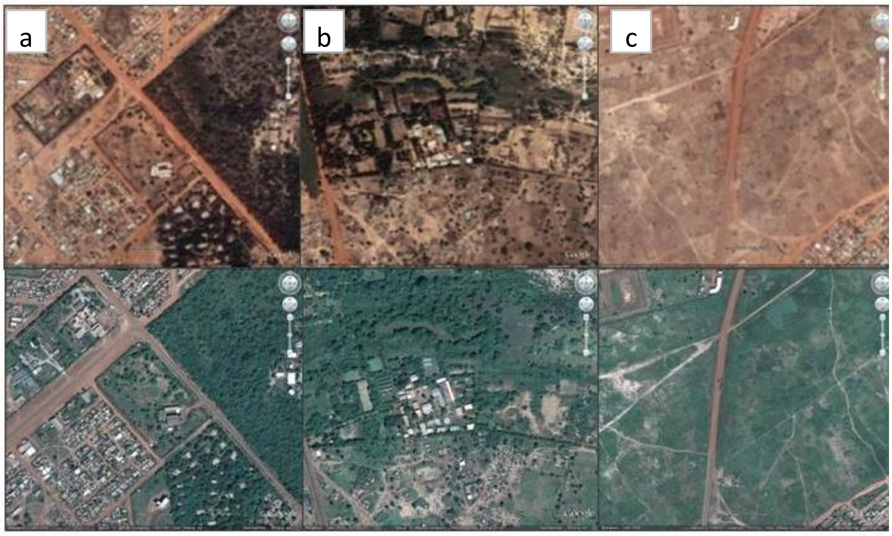

Figure 8. Satellite images of three areas used as rural in three different studies of the thermal climate in Ouagadougou from dry (top) and wet period. a) DMN used by Offerle et al (2005), b) used by Jonsson and Lindqvist (2005), and c) used in Paper I in this thesis.

The importance of the inclusion of vegetation in the descriptions of urban areas for studies in the Sahel region impacts the use of the LCZ classification by Stewart and Oke (2010). The earlier version of the LCZ (Stewart and Oke 2009), where vegetation was included to some extent was applied to Onitsha, Nigeria, a city just south of the Sahel region, in a slightly wetter climate by Nduka and Abdullhamed (2011) with positive outcome, though no actual examination of the urban climate was carried out. Since vegetation is not a variable in the latest version of the LCZ (Stewart and Oke 2010), direct application of the latest version of LCZ classification is not optimal for areas in urban climate studies in (semi) arid areas since this excludes the most important climate affecting parameter and is likely to hide important results. In this study, the earlier version of the LCZ is used with additional information of vegetation cover in each area.

Extreme nocturnal stability - effects on urban climate and air pollution

The urban climate shows large intra-urban differences in air temperature, humidity or wind (Paper I-III). These features require a stable urban atmosphere with low turbulent mixing and ventilation of the urban air. The effect of stability was evident as spatial patterns in temperature and humidity were much stronger during extremely stable compared to moderately stable nocturnal conditions. The considerable influence of EEC, generating strong intra-urban thermal differences, was also linked to the development of a nocturnal intra-urban thermal breeze found in Ouagadougou (Paper III). This consistent thermal wind system was found during all nights with extremely stable atmospheric conditions, and thought to be induced by the strong intra-urban temperature and pressure gradients connected to large intra-urban temperature differences. This wind system studied generated weak winds of almost opposite directions at the two locations studied; urban centre and the suburban background. As discussed by Roth (2000), the extreme heterogeneity of the urban landscape requires a dense monitoring network to obtain an overall understanding of the urban wind field. While the thermal wind found in Ouagadougou was most pronounced in the urban centre, the strongest thermal pattern found was cooler temperatures in vegetated areas in Ouagadougou (Paper I), and the strongest thermal gradient, and thus a thermally induced wind system, is therefore likely to be most pronounced around these areas. Studies with an increased network of wind measurements would be needed to reach a more complete understanding of the thermal wind system in the city

The impact of airflow from vegetated areas has been discussed by Eliasson and Upmanis (2000) and Spronken-Smith and Oke (1999) for example, who suggest that the potential effects of the horizontal flow of cooler air from urban vegetated areas into the warmer surrounding areas could improve air quality and lower temperatures. The low wind speeds during extremely stable nocturnal atmospheric conditions indicate a reduced ventilation of the urban air. Despite the weak winds created, the thermal wind system may therefore still be important for transport of pollutants in Ouagadougou.

The restricted ventilation of the urban air during extreme atmospheric stability caused a considerable increase in pollution levels in Ouagadougou, with for example tripled background concentrations of PM_{10} (Paper V). This confirms earlier presented studies in Ouagadougou by Boman et al. (2009), and Eliasson et al. (2009), and has also been found in other cities in (semi) arid climates (Eliasson et al. 2003, Jonsson 2004, Chan et al. 2005). The relation between stability and increased pollutant concentrations is also evident in duration of the evening rush hour peak, where concentrations stay high considerably longer during extremely stable conditions compared to less stable conditions (Paper V). The higher levels and longer duration of the evening peak increase importance of evening emissions for general pollution levels.

Another feature discussed in Paper III that may affect the urban air quality in Ouagadougou is the occasional disturbances of the stable stratification and the thermal wind system. These disturbances were likely caused by increased wind shear due to a NLLJ above the city breaking up the stable stratification. The intrusion of above air masses would possibly introduce transported pollutants as suggested by De Longueville et al. (2010) and Washington et al. (2006) but, perhaps more important in Ouagadougou, also increase dispersion of urban-derived pollutants during periods with otherwise very reduced urban ventilation.

The regularity of extremely stable nocturnal atmospheric conditions (found during 80% of the nights during early dry season studies) in Ouagadougou is remarkable. It is suggested by Yadav et al 1995 that low wind conditions are more common in the tropics compared to the temperate areas. Studies of nocturnal stability in the Sahel region are scarce, but a study by Bain et al. (2010) show that during the wet season in the small village of Agoufou, Mali, nocturnal surface wind speeds are on occasion low and atmospheric stability high. Direct comparisons with general stability situation in other cities are difficult to make due to for example differences in measurement periods and methods of defining stability. However, as an example it can be mentioned that strong nocturnal stability was found only during two out of 16 calm and cloudless nights in Gothenburg, Sweden (Thorsson and Eliasson 2003), and that only 8 % of the days during an approximately three year period in Salamanca, Spain were defined as stable (Alonso et al. 2003). A city with comparable frequency of nocturnal stability was Beijing, China where 12 out of 15 days during the measurement period were defined as stable (Chan 2005). No differences were made between different strength of stability in Beijing.

The very consistent NLLJ described by Lothon et al (2008) may perhaps be used to indicate the general stability regime in the Sahel region. As the development of a NLLJ requires a stable surface layer (1997), the presence of a NLLJ may in turn be used as an indicator for a stable surface layer. The NLLJ examined by Lothon et al. (2008) is present over the region approximately 80% of the nights during the dry season; the same frequency as nights found to be extremely stable in Ouagadougou in this study. Using this assumption, a similar stability situation could be assumed to apply throughout the dry season since the NLLJ is frequent this whole period. Since the NLLJ was found during 60 % of the nights during wet season, stable surface conditions are likely to exist also during this season. A similar stability situation in the urban nocturnal boundary layer as noted in Ouagadougou, would also apply to the cities examined by Lothon et al. (2008); Niger and Nangatchori, and probably other cities with similar structure and topography in this region.

If extremely stable conditions are likely to be found throughout the dry season, this implies that the thermal wind system may be present in Ouagadougou throughout the dry season as long as horizontal temperature gradients are strong enough to generate winds. The considerably elevated pollution concentrations are also likely to prevail throughout the dry season (or possibly deteriorate as surroundings get drier). Furthermore, as shown in Paper V, levels of PM are also high in an unpaved area in April-May, during slightly/moderately stable atmospheric conditions and recurrent precipitation, with daily PM_{10} levels over double the air quality guideline of WHO (2006) of 50 μg/m^3 as a 24 h average. This suggests that the levels found in this study are not restricted to the dry season, but may exist throughout the year. Due to the influence of atmospheric stability of ventilation of the urban atmosphere, a high frequency of extremely stable night time conditions should be taken in to consideration in predictions and air pollution mitigation strategies for the rapidly growing cities in this region in general.

Spatial variations in air pollution

This study shows that coarse particles dominate the urban air pollution in Ouagadougou, which is in agreement with earlier studies of the urban atmosphere (Boman et al. 2009, Eliasson et al. 2009). According to De Longueville et al. (2010), West Africa is the region most affected by dust transported from the Saharan desert which is reflected in the high background concentrations found in Ouagadougou. The low PM_1 to PM_{10} ratio found in Ouagadougou (Paper V) shows that coarser particles are clearly dominating in Ouagadougou, with ratios around 0.02. Comparable urban measurements in arid areas have been difficult to find, but rates are considerably higher compared to urban sites in other climates, for example the temperate climate of Austria (ratio: 0.58 – 0.62) (Gomiscek et al. 2004), and in the wet tropical climate of Taiwan (ratio: 0.37 – 0.74) (Lin and Lee 2004), confirming the dominance of coarse particles in Ouagadougou. However, while transportation is likely to be an important source of dust, re-suspension of road dust in the unpaved suburban area generated up to four times higher concentrations of PM_{10} compared to the nearby paved area as shown in figure 7 as well as in Paper V. It is also possible that the higher vegetation cover in the paved area may slightly reduce PM as shown by for example Beckett et al. (1998). Re-suspension of road dust have also been suggested to greatly increase levels of PM_{10} in other studies of sub-Saharan cities (Etyemezian et al. 2005, Arku et al. 2008, Boman et al. 2009, Eliasson et al. 2009, Dionisio et al.

2010). However, as seen in figure 7 and table 2, levels of PM_{10} was also high in densely trafficked location such as the paved centrally located roundabout in Ouagadougou, indicating traffic itself as a source of PM_{10}. The old and highly pollution vehicle fleet in sub-Saharan cities have been pointed out as an important source of air pollution in other studies as well (e.g. Etyemezian et al. 2005, Arku et al. 2008, Dionisio et al. 2010)

While background CO concentrations do not exceed the WHO air quality guidelines at any time or location in this study, considerably higher levels of CO were measured in several microenvironments such as in traffic and in wood fuelled kitchens indicating a strong dependence on distance from source. Background levels are comparable with those found in the Lagos, Nigeria (Baumbach et al. 1995). Evening street side concentration was approximately double and morning peak slightly weaker compared to concentrations found in Addis Ababa by Etyemezian et al. (2005). The rapid decrease in CO with distance from source is also shown in a study by Diab et al. (2005) where extreme levels of CO was found in a heavily trafficked location in Durban, South Africa, but a distance of 25 m, CO concentrations dropped to general background levels. The effect of the distance to traffic is also seen in PM levels presented in table 2, where levels decrease from the centre of the densely trafficked roundabout to the nearby roadside and further to the nearby urban background at rooftop level. The impact of traffic can also be seen in the rapid decrease in levels of NO_X, Benzene and Toluene from the urban site towards the rural which is discussed more in Paper V.

While levels of CO show a rapid decrease with distance from traffic, background levels are similar in the heavily trafficked urban centre and the lightly trafficked suburban residential area. This is linked to the additional source of CO from the abundance of biomass burning for household fuel as discussed in IV and V. A principal component analysis of air pollution in Ouagadougou presented by Boman et al. (2009), shows that soil/crust, combustion and biomass burning were the most important sources in the urban center while biomass burning, industry and soil/crust were more important at the suburban site. This confirms the greater importance of traffic in the urban center, and importance of biomass burning at the suburban site. The impact of industry on air quality is not examined further in this thesis due to limited information and data. While industrial emissions found by Boman et al, (2009) was relatively small, the growing, often poorly regulated industry in these regions may be an increasing threat, and should be included in future studies.

The population of Burkina Faso as a whole is likely to suffer from an unhealthy exposure to air pollutants as indicated by the high prevalence of lower respiratory infections, which amounts to 20% of all premature deaths in the country (World Health Organization 2006). However, the large spatial variations found are likely to create considerable differences in exposure depending on socioeconomic situation and gender. This confirms results by Östlin et al. (2006). Unpaved roads and extensive use of biomass as household fuel in middle and low income residential areas is likely to generate considerable increased concentrations of both PM and pollution from incomplete biomass combustion compared to high-income areas, where paved roads and use of cleaner fuels is more common. Exposure differences in gender are explained by the almost exclusivity of women in charge of household chores and cooking in the often poorly ventilated biomass fuelled kitchens in middle and low income areas. They – and their young children – are likely to be exposed to both high levels of pollution from biomass burning and to extreme levels of PM_{10} by spending the majority of the time in the unpaved residential areas. Men who spend time away from home may on the other hand be more exposed to pollutants from traffic.

Perhaps the most alarming effect of indoor air pollution is the connection with acute lower respiratory infections in children, which is the single most important cause death for young children (Bruce et al. 2000). While the majority of children in Ouagadougou attend school from the age of six (UNESCO 2008), girls in this region are often required to continue to help with cooking and household chores during off school hours (Jacquemin 2009). On the other hand, 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

Ouagadougou is expected to experience an extreme urban growth in the near future, increasing from approximately two million today to 3.4 million in 2020 (UN Habitat 2010). As discussed by Pearlmutter et al. (2007), places characterized by harsh thermal extremes present unique opportunities for microclimatic enhancement. The strong evening evaporative cooling of vegetation in the urban thermal climate as shown in this study supports this. Though Burkinabe locals often claim that nocturnal temperatures during the early dry season are too low for comfort, the dominating influence of vegetation shown in this study could, if included in urban planning, create exceptional possibilities for mitigating nocturnal heat stress where this is desired. A relief from daytime heat stress may be preferred in Ouagadougou, and introducing more open water surfaces - the main cooling parameter daytime - would potentially reduce heat stress. However, poverty is high and water scarce, thus greatly limiting possibilities for planning urban growth. The rapid urban growth presented in figure 1 and Paper V show that the informal spontaneous settlements have experienced the proportionally 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 of ventilation of the urban atmosphere, the high frequency of extremely stable night time conditions shown in this study should be taken in to consideration in air pollution mitigation strategies for Ouagadougou, but also for the rapidly growing cities in the Sahel region in general. 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. However, as the pattern was opposite in the east African city Addis-Ababa, with higher morning stability and thus elevated morning pollution levels (Etyemezian et al. 2005), it is important that cities are treated individually.

The rapid economic development in Burkina Faso is likely to bring increased emissions from industry and motor vehicles which generate progressively more serious air quality problems as suggested by Fenger (2007). Fenger also show that as economic development continues, stabilization in pollution levels is likely to occur due to initiation of emission controls. The high levels of pollutants found in general, with alarming levels of PM_{10}, show that air pollution mitigation strategies are greatly needed in Ouagadougou. This is further emphasized by the fact that one of the adverse health effects closely connected to air pollution is lower respiratory infections, which is the most important cause of death in Burkina Faso, amounting to 20% of all deaths (World Health Organization 2006). The increase in levels of PM_{10} caused by re-suspension of road dust specifies this as an area with large potentials for improvement and thus deserved of specific attention to air pollution mitigation strategies. Although work such as paving roads is continuously ongoing in Ouagadougou, large areas, especially traditional residential areas, will most likely remain completely unpaved for many years. To the author’s knowledge, no other type of road dust abatement strategy is currently active in Ouagadougou. Though no air pollution data is available from the informal spontaneous settlements, it is likely that levels of PM_{10} in these areas are similar or worse compared to those measured in the traditional residential areas since all roads are unpaved, vegetation scarce and the population dense. Furthermore, it is also likely that the traffic will increase, and as cleaner fuels such as gas or electricity are expensive it is likely that the proportion of households using biomass fuels will remain high or increase further.

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 (UN Habitat 2010).

Approximately 900 million people lived in informal settlements in 2005, and the number is projected to rise to approximately 1.5 billion in 2020 (UN Millennium Project 2005). Urban traffic is expected to increase with urban growth (Mitric 2008), and the proportion of household depending on biomass is not expected to decline drastically in the near future (Smith and Mehta 2003). Studies from other sub Saharan cities indicate that re-suspension of dust from unpaved roads is a common problem in these regions (Etyemezian et al. 2005, Arku et al. 2008, Eliasson et al. 2009, Dionisio et al. 2010). The air pollution sources will of course vary, but limited financial means available to 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.

Vulnerability to climate change in the Sahel region may create additional threats for the population, due to decreased food and water security for example, more accurate predictions of a future climate scenario would be very valuable. As discussed by Paeth et al. (2011) considerable progress is recently achieved in dynamical and statistical downscaling of data in the Sahel region, but observational networks need to be extended and maintained in order to validate high-resolution regional climate models and to feed downscaling methods.

The documentation of the national meteorological stations show trained observers strictly following set procedures for all stations indicating that data from these station can be regarded as homogenous, following guidelines by Conrad and Pollak (1950). However, risks discussed by Peterson et al. (1998) are potentially significant since several instruments are old and limited funding delays repairs, data sets are likely to be incomplete with gaps sometimes lasting for years for several parameters. A potential risk is also the many manual steps in the data handling and calculations, increasing a risk of error due to the human factor. As the access to metadata is limited, using longer data series and comparing data from different stations becomes unreliable. As noted by Lanzante et al. (2003) variations over time causing temporal inhomogeneity is a large problem in data from African meteorological stations. Changes in location and station surroundings, such as those presented in this study may present an example of this problem.

Relatively limited financial contributions would be needed in order to greatly improve data coverage and minimize the risk for errors, for example investments in new instruments sheds or instruments, or installing computers in each station. The very limited possibilities for national funding for continuous maintenance show the importance of continued financing over a longer time period rather than a one-time contribution. As a reliable prediction of future changes in climate as well as accurate downscaling for in this region would be a great advantage in order to improve for example food security in this region where the threat of famine is constantly present for the population, all possible improvements to available data are of great value.

CONCLUSIONS

The following main conclusions can be drawn from this thesis

- Intra-urban differences in Ouagadougou were more important compared to urban rural, with strong nocturnal cool islands in vegetated areas being the most distinct feature in thermal patterns in Ouagadougou. These cool islands were created by a dominant evening evaporative cooling by the vegetation, indicated by an increase in humidity at the time of cooling. Vegetation did not affect the urban climate during daytime, when instead the presence of open water was the most important cooling parameter. When the sites were previously divided in vegetated and sparsely vegetated sites, those with high building density cooled more slowly. This show that vegetation should be carefully considered in urban climate studies, especially for the choice of rural area where vegetation cover often is dominant. While this is probably especially true for the Sahel and other (semi) arid regions, it should also be taken in to account in urban climate studies in other climates.

- A remarkable frequency of extremely stable nocturnal atmospheric conditions was observed in Ouagadougou. During the extremely stable conditions, spatial patterns in temperature and humidity were more pronounced. An intra-urban thermal breeze generating almost opposite wind directions at the two examined sites was found during all extremely stable nights. The restricted ventilation of the urban air during extreme atmospheric stability was found to cause a considerable increase in pollution levels in Ouagadougou, for example tripled background concentrations of coarse particles.

- Air pollution in Ouagadougou shows strong intra-urban differences with high levels of air pollution in general and extreme levels of coarse particles, commonly exceeding air quality guidelines of WHO in all areas. Though transportation of dust from the Sahara desert was important, re-suspension of road dust generated around four times higher levels of PM_{10} in unpaved compared to paved areas. Other important sources were traffic and biomass burning. The large spatial variations found in pollution levels in the city are likely to create considerable differences in exposure situation depending on both socioeconomic situation and gender.

- Observers at national synoptic meteorological stations in Ouagadougou were well educated and strictly followed set procedures for all stations indicating that data can be regarded as homogenous. However, several risk factors were found, such as the many manual steps in data handling, an old and poorly functioning instrument park and changes in locations and station surroundings. An almost complete lack of funding for maintenance, repairs or investments in new technologies was mentioned as a great restraint on all stations.

FUTURE WORK

To generate a wider understanding of the rarely studied effect of vegetation on nocturnal urban climates, especially in (semi) arid cities, but also in other climates, future studies of the evening and night time effects of vegetation would be necessary.

The rapidly growing cities in the Sahel region would also greatly benefit from studies of the nocturnal stability situation as well as the urban wind field since this is important for ventilation of the often excessively polluted air in these cities.

As a step towards mitigation of the air pollution situation in cities in the Sahel region as well as other cities in developing countries, continuous monitoring system should be set up in these cities in order to evaluate air quality situations and to characterize pollutant components. As air pollution exposure is likely to vary considerably within countries and cities, case studies using personal monitoring methods would be necessary in order to accurately assess pollution exposure for groups of different socioeconomic status and gender, as well as to connect results with health problems of affected inhabitants to examine the effects of this exposure.

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