URBAN MICROCLIMATE AND SURFACE HYDROMETEOROLOGICAL PROCESSES

Christer Jansson

February 2006
PREFACE AND ACKNOWLEDGEMENTS

This work started in 2001, with the focus on water transport below the urban surface, but literally changed direction and settled in the area of energy fluxes between the urban surface and the atmosphere. During my years as a PhD student, there have been several people who have supported my research. My deepest gratitude goes to my main supervisor Per-Erik Jansson for support and guidance throughout this work. I have also been fortunate to have David Gustafsson as a supervisor during the last couple of years. He has been very enthusiastic and given me valuable scientific advice. I also thank Esben Almkvist at the Department of Earth Sciences, Gothenburg University, for collaboration and Michael Bruse at the Department of Geography, Ruhr University, for introducing me to the world of microclimate modelling. My appreciation goes to Klas Hansson for his helpful comments on the first draft of this thesis. I am also grateful to all my friends and colleges at KTH for providing a very enjoyable working environment. Finally, I would like to thank Liv, my family and friends who have encouraged me along the way.

Financial support by FORMAS (Swedish Research Council for Environment, Agricultural Sciences and Spatial Planning) is gratefully acknowledged. The valuable study visit to the Ruhr University was funded by a scholarship provided by Stockholms Byggnadsförening.

Christer Jansson
Stockholm, February 2006
List of Papers

This thesis is a summary of the following papers, which are referred to in the text by their corresponding Roman numerals and reproduced in full in Appendix 1-5.


Articles published or in press are reproduced with the kind permission of the respective journals.
Table of Content

**Preface and acknowledgements** ................................................................. III

**List of papers** .............................................................................................. V

**Abstract** ........................................................................................................ 1

**Introduction** .................................................................................................. 1

  - Climate, scales and urban heterogeneity ....................................................... 2
  - Objectives ........................................................................................................ 3

**Urban climate processes** ............................................................................ 3

  - Local-scale climate processes ..................................................................... 4
  - Micro-scale climate processes .................................................................... 5
  - Urban scale climate processes and influence of vegetation ...................... 6

**Methods** ...................................................................................................... 7

  - Observations ................................................................................................. 7
  - Soil water content ......................................................................................... 7
  - Surface heat fluxes ........................................................................................ 8
  - Microclimate ................................................................................................. 8

**Simulation tools and modelling approaches** ............................................. 8

  - The one-dimensional soil-vegetation-atmosphere system ......................... 9
  - Urban microclimate model .......................................................................... 10

**Results and discussion** .............................................................................. 11

  - Soil water dynamics ..................................................................................... 11
  - Effect of urban climate on evapotranspiration ........................................... 12
  - Heat balance of a paved surface ................................................................. 13
  - Urban microclimate: Observations .............................................................. 14
  - Urban microclimate: Simulations ................................................................. 16

**Summary and concluding remarks** ............................................................ 18

  - Urban surface elements ............................................................................. 19
  - Urban microclimate ..................................................................................... 19
  - Future directions ......................................................................................... 20

**References** .................................................................................................. 21

**Other references** ........................................................................................ 24
ABSTRACT
The urban near surface atmosphere is of great concern since it affects the climate to which an increasing amount of people are immediately exposed. This study investigated the microclimate in central Stockholm in terms of the thermal conditions in the 0-2.5 m air layer and the water and heat exchange processes at different types of surfaces found within the urban environment. The main objective was to improve our understanding of the urban small-scale climate system.

The urban microclimate was measured in terms of vertical air temperature profiles along a horizontal transect running through a vegetated park and its built-up surroundings during three clear and relatively calm summer days. The results showed that the air temperature at 1.2 m height within the park was 0.5 to 1.5 K lower than in the surrounding city blocks, and that the thermal stratification was generally stable (increasing temperature with height) in the park and unstable (decreasing temperature with height) in the built-up areas. In addition, there were a few examples of temperature gradients orientated in different directions within the lowest 2.5 m air layer, indicating horizontal advection between the park and the built-up areas. Climate conditions simulated with a three-dimensional microclimate model agreed well with observations and the model was therefore assumed to provide reasonable representations of important climate processes such as surface-air energy exchange processes. However, there were some discrepancies between observations and simulations that are discussed in terms of differences in real and modelled heat storage processes and wind conditions. Processes that need to be included for a more precise model description of areas such as the Stockholm environment include dynamic heat storage in buildings and dynamic wind forcing during the course of the simulation.

A soil-vegetation-atmosphere transfer model was used to study soil water transport, the surface energy balance of an asphalt surface, and the impact of urban climate on evapotranspiration. Based on model calibration to field measurements of soil water content in a till catchment outside Stockholm, new parameter values were estimated that can be used for water flow modelling of till soils. The heat fluxes of an asphalt surface were reliably simulated without knowledge of site-specific calibration and the model was useful in identifying problems with energy balance closure based on measurements only. Simulations of ‘urban’ modifications to the forcing climate conditions demonstrated that increased air temperature, and thereby increased vapour pressure deficit, had most effect on evapotranspiration from tall vegetation, while increased long-wave radiation raised grass evapotranspiration the most.

Keywords: CoupModel; ENVI-met; roughness sub-layer; surface temperature; urban heat island

INTRODUCTION
Although small in terms of land area, the urban environment affects a considerable portion of the Earth’s population. Forty-seven percent of the Earth’s population lived in urban areas in the year 2005 (Population Reference Bureau, 2006), and predictions show that this figure will increase to about 66% of the population by the year 2025 (World Resources, 1998-1999). Understanding the urban climate is therefore of great interest in the creation of a comfortable and healthy environment to which an increasing amount of urban dwellers are exposed.

Urbanisation has led to distinct changes to the landscape compared to the ‘natural’ conditions. Soil is redistributed, water resources are rerouted, the amount of vegetation is (mainly) reduced, construction materials are added, the topography is changed, and anthropogenic sources of heat and water are introduced. Consequently, urban developments bring about a change in the physical behaviour of the landscape, affecting its hydrological, thermal, radiative and aerodynamic properties, which in turn affects the exchange of heat, mass and
momentum between the surface and the atmosphere. Ultimately these changes result in the development of an ‘urban climate’ that deviates from that of its surroundings (Landsberger, 1981; Oke, 1987). One of the most distinct alterations is the generally warmer urban climate, often referred to as the ‘urban heat island’, which is one of the most well-documented anthropogenic climate modifications (Arnfield, 2003). The urban heat island is an integrated response from the entire city. The small-scale climate within the urban environment deviates from that of the average conditions (Miller, 1980; Bruse & Fleer, 1998) and the variation within the city can be of the same order as the difference represented by the urban heat island (Eliasson & Upmanis, 2000). It has also been demonstrated that the urban areas can affect the outside environment on a planetary scale (Best & Betts, 2002). Therefore, knowledge of the governing processes acting at all scales is necessary in order to understand the urban climate system, which is a prerequisite if we want to predict climate alterations caused by structural changes to the urban environment and to properly formulate policies for urban planners (Chandler, 1976).

**Climate, scales and urban heterogeneity**

In this work, the term *climate* is used referring mainly to air temperature, and its variation in time and space. Air temperature is, together with precipitation, humidity, wind speed and air pressure, one of the most characteristic climatic variables. It is a measure of the thermal energy content of the atmosphere, which within the atmospheric boundary layer (from the surface to 100-3000 m), is significantly influenced by the heat transport between the surface and the air. Hence, air temperature alone can be used as a ‘tracer’ for detecting spatial and temporal variation of the energy exchange between the surface and the air. Furthermore, air temperature is an important property of the urban climate that has implications in areas related to human comfort and health.

The urban landscape has a mosaic-like structure consisting of a variety of surface elements including walls, roofs, roads, ponds, individual trees and patches of grass. Hence, compared to other land uses (e.g. forestry and agriculture), the urban environment has a wider range of surface properties. The individual surfaces can be merged into aggregated surfaces or morphological units. Two opposed building walls and the intervening road and air volume define the *urban canyon*. Several buildings make city blocks, which together with parks, parking lots, railway yards etc. comprise the entire urban environment.

The surface elements have different physical properties as well as different exposure to radiation and turbulence, which affects the way in which the climate near the surfaces develops. For example, the air temperature at two adjacent walls facing in opposite directions can develop differently during the day as a result of their exposure to incoming short-wave radiation (Nakamura & Oke, 1988; Voogt & Oke, 1998; Ali-Toudert, 2005). Hence, within a small distance (<20 m) there can be both temporal and spatial climate differences. At a larger scale, there can be climate variation between different urban canyons as a result of different height-to-width ratios (height of buildings divided by distance between buildings) and canyon orientations (Ali-Toudert & Mayer, 2006), and the climate of an urban park behaves differently than the climate in the surrounding city blocks (e.g. Saito et al., 1990-91; Spronken-Smith & Oke, 1998). At an even larger scale, as mentioned in the introduction, the entire city landscape generates a climate that deviates from that of its rural surroundings. The different scales have different climate responses since they represent different aggregations of the underlying climate processes. Consequently, the climate not only develops differently among the different surfaces, but also develops differently between scales.

The lower part of the urban atmosphere, extending from ground level to the average height of buildings, is often referred to as the *urban canopy layer* (Figure 1) (Oke, 1976; Grimmond & Oke, 2002). Within the urban canopy layer, the climate is influenced by site-
Urban Microclimate and Surface Hydrometeorological Processes

specific characteristics, and spatially there are sharp thermal borders. Above the canopy layer, in the roughness sub-layer, the climate is a response from a mixture of surfaces. The contribution from individual surface elements depends on the ‘source area’ of which the air is influenced, which in turn depends on wind speed, wind direction, surface roughness and atmospheric stability (Schmid, 1994). Hence, within the roughness sub-layer, the atmosphere is not in equilibrium with the surface below, and the turbulent fluxes of heat, mass and momentum change with height (Rotach, 2001). At some height above the canopy layer, the turbulent mixing becomes so extensive that the significance of the individual surface elements is no longer distinguishable, and the state of the atmosphere is influenced by the area average characteristics (Roth, 2000). As a rule-of-thumb, this height begins at 2-5 times the mean height of buildings (Piringer et al., 2002).

The terms micro-scale and microclimate are used in reference to the scale at which the influence of the individual surface elements cannot be ignored. This scale has a vertical extension to the top of the canopy layer in particular, but also includes the roughness sub-layer. The term local-scale is used when referring to the scale that is influenced by the area average characteristics, as e.g. the climate conditions above the roughness sub-layer.

Objectives

This thesis focuses on the urban micro-scale climate and the energy and water processes acting at the surface elements found within the urban environment. The overall aim was to improve our general understanding of the urban microclimate system. This was achieved by examination of measurements of soil water dynamics, surface energy fluxes and climate, which were further evaluated by the use of process-orientated numerical models. More specifically, the following objectives were addressed in the thesis:

- Present estimates of parameter values based on new data on soil water dynamics in glacial till soil that can be used for soil water modelling (Paper I).
- Evaluation of model applicability to estimate the surface energy exchange at an asphalt surface, suggest model developments and identify possible difficulties in measurement (Paper II).
- Examination of the possible impact that the urban environment, in terms of increased load of long-wave radiation and altered air temperature, has on evapotranspiration (Paper III).
- Examination of decoupling between the surface and the atmosphere as an indicator for possible heat advection by new microclimate measurements in an urban vegetated park and its built-up surroundings (Paper IV).
- Evaluation of the ability of a three-dimensional microclimate model to describe the climate of an urban vegetated park and its vicinity (Paper V).

**Urban Climate Processes**

Climatic conditions in the near surface atmosphere, such as air temperature and humidity, are strongly influenced by the energy exchange between land surface elements and the air. These energy exchange processes are already complex to describe for homogeneous land surfaces and are further complicated in urban environments with its characteristic heterogeneous structure. However, basically, the available energy at the land surface elements in terms of radiation and other heat sources at the surface is balanced by heat and vapour fluxes to the air, which are further propagated into the atmosphere through turbulent dispersion and advection. Hence, the climate conditions of an air parcel at one point in the atmosphere will depend on the surface heat fluxes within the ‘source area’ of which the air parcel is influenced. This section reviews some of the important surface energy exchange properties of the urban environment and their influence on the urban climate.
For a single surface element, the energy balance can be given by:

\[ Q = H + E + G \]  (1)

where the net radiation, \( Q \), equals the sum of the turbulent transport of sensible and latent heat between the surface and the atmosphere, \( H \) and \( E \) respectively, and the heat transport between the surface and the material below, \( G \). For a volume representing the local-scale, i.e. extending to the top of the roughness sub-layer, the balance can be described as (similarly to Oke, 1988)

\[ Q_{\text{local}} + F = H_{\text{local}} + E_{\text{local}} + G_{\text{local}} + A \]  (2)

where \( Q_{\text{local}} \) is the area averaged net radiation, \( F \) is energy released or consumed by anthropogenic activities within the volume, \( H_{\text{local}} \) and \( E_{\text{local}} \) are the turbulent fluxes of sensible and latent heat, respectively, across the top of the volume, \( G_{\text{local}} \) is the change in storage within the volume (includes air, structures and ground) and \( A \) is the net advection of heat in the horizontal direction. The bulk of urban surface energy balance budgets have been estimated by measurements of net radiation and sensible and latent heat fluxes above the roughness sub-layer (called the inertial sub-layer or constant flux layer), i.e. the fluxes represent the area average response from an aggregated urban surface as represented by eq. (2). By using this approach, the \( F \) term is included in the measurements of \( Q_{\text{local}} H_{\text{local}} \) and \( E_{\text{local}} \) and for homogeneous areas \( A \) can be assumed to be small. The remaining term in eq. (2), \( G_{\text{local}} \) is usually estimated as a residual. Theoretically it would be possible to further develop the term \( G_{\text{local}} \) in terms of eq. (1) applied for each surface element present in the volume of interest. However, at the micro-scale, representative measurements are complicated to conduct due to the multitude of processes acting in the three-dimensional urban structure and since there is no constant flux layer. Conventional profile flux methods are therefore not valid and energy balance analyses are mainly made by modelling. However, the scales are linked, and e.g. the heat storage at the local-scale is a key processes in the development of the urban heat island, as well as an important factor for the microclimate differences between the urban vegetated park and its built-up surroundings.

Local-scale climate processes

The polluted and warm urban atmosphere affects the radiation balance. Pollutants reduce the incoming radiation while they raise the atmospheric emissivity, which in
combination with the warmer atmosphere increases the amount of incoming long-wave radiation. At the urban surface, the radiation balance is a complex process of shading and reflection of short-wave radiation and absorption and emission of long-wave radiation, all taking place within the urban three-dimensional structures. However, although the urban environment affects all components of the radiation balance, the net effect on the radiation balance as an area average is small, and urban net radiation is generally similar to net radiation observed at rural sites (Arnfield, 1982; Schmid et al., 1991). In contrast, urban heat storage can amount to at least 50% of daily net radiation in densely built-up areas, which is larger than most natural systems (Grimmond & Oke, 1999a). There is a tendency for more energy to be put into storage during the morning, and in city centres heat storage can even be larger than the sensible heat flux during the day. Consequently, there is a large amount of stored energy to be released during the evening and night, which results in upward directed sensible heat flux several hours after sunset and even an upward directed flux throughout the night. During the day, the sensible heat flux is generally the largest term of the energy budget. The latent heat flux is often assumed to be a negligible part of the urban energy balance. However, although smaller than the sensible heat flux, the latent heat flux can constitute 20-40% of daily net radiation (Grimmond & Oke, 1999b) and can also be a significant part of urban water balance (Grimmond & Oke, 1991). Furthermore, Oke & McCaughey (1983) observed suburban latent heat fluxes to be higher than corresponding rural fluxes and explained the increased evapotranspiration rates by micro-scale advection of dry and hot air from the paved areas into the moist vegetated areas. A summary of local-scale energy budgets from 10 sites in 7 cities is provided by Grimmond & Oke (2002).

The urban heat island, the generally warmer city climate, is mainly a nocturnal phenomenon. It has been explained by the differences in cooling rates between the urban and rural environments and one of the important factors is the heat storage in the urban areas, in which energy is stored during the day and released during the night. Associated with the warmer city climate are several negative effects, such as reduced human comfort (Nikolopoulou et al., 2001), increased amount of heat-related diseases (Changnon et al., 1996) and increased energy consumption due to air conditioning (Santamouris et al., 2001). However, the urban impact on the climate is likely to vary depending on location, city structure and weather conditions (Taha, 1997) and does not necessarily have to be negative. For example, for a high latitude city it has been shown that the urban heat island can contribute to a reduction in energy consumption for households (Svensson & Eliasson, 2002).

Micro-scale climate processes

In contrast to the detailed descriptions of important climate processes acting at the local-scale, e.g. those resulting in the urban heat island phenomenon, the climate processes at the micro-scale are not very well documented. However, the microclimate and its underlying processes are important to understand, since they influence the section of the atmosphere to which humans are immediately exposed.

Available energy balance observations at the micro-scale are not very extensive. Spronken-Smith et al. (2000) observed the surface energy balance across an irrigated urban park with emphasis on horizontal heat advection. In Gothenburg, Sweden, flux observations have been conducted at several heights within and above an urban canyon (Eliasson et al., 2006), while Salmond et al. (2003) measured the heat flux from roofs and from the top of urban canyon structures and showed that roof top fluxes dominated during the day and canyon fluxes at night. However, the energy balance processes at the micro-scale are generally analysed by numerical simulations. Energy balance models for canyon structures are perhaps most common and have been used to investigate factors such as the effect of height-to-width ratio, canyon orientation and

5
heat storage (see Arnfield (2003) for a comprehensive review of canyon models). Two and three-dimensional microclimate models that couple the energy exchange of the individual surface elements to the atmosphere have been used to examine the influence of vegetation and the effect of structural changes. Honjo & Takakura (1990-91) used a two-dimensional model to investigate the thermal effects of vegetation on the surrounding areas and suggested that small green areas at sufficient intervals are preferable for efficient cooling of the surroundings. Jesionek & Bruse (2003) used a three-dimensional model to examine the effect of different building structures and vegetation patterns on microclimate and air pollution. For a single surface element, as represented by eq. (1), Aseda & Ca (1993) investigated the surface energy balance of a bare soil, a soil covered by asphalt and a soil covered by concrete. The sealed surfaces had higher surface temperatures during the day and upward directed sensible heat flux during the night. Arnfield (2003) concluded that numerical simulations are methods ‘perfectly suited to deal with the complexities and non-linearities of the urban climate system’, but also pointed out that model validation is to a large extent still lacking.

**Urban microclimate and influence of vegetation**

The thermal difference between the vegetated park and its built-up surroundings has been identified as a possible factor for heat island reduction (e.g. Avisser, 1996; Yo & Hien, 2006), and is therefore the aspect of the urban microclimate that has received most attention. Urban vegetated parks generally act as areas with lower temperatures compared to the rest of the city. Nocturnal air temperature differences between the park and its vicinity are the most well-documented (Upmanis et al., 1998) and have been explained by a faster cooling rate in the park compared to that of its surroundings (Oke, 1989). The important factors in this process have been identified as heat storage dynamics and the long-wave radiation balance (Spronken-Smith & Oke, 1999). An outgoing air flow from the park has been observed during calm nights, which has been explained by a pressure gradient caused by the nocturnal temperature difference between the park and its surroundings (Upmanis, 1999; Honjo et al., 2003). Similarly to during the night, the daytime temperatures are generally cooler in the park than in its vicinity, which has been explained by factors such as albedo, evaporative cooling and canopy shading (Spronken-Smith & Oke, 1998). However, there are also examples showing that a park can be warmer than its surroundings. Jauregui (1990-91) explained the warmer park climate during the morning by faster heating of the park due to smaller thermal inertia compared to the built-up area, while Potchter et al. (2003) reported that a grass-covered park was not only warmer than a park covered by trees, but also warmer than its built up surroundings during daytime.

Micro-scale advection both into and out of the park can be significant from a microclimate perspective. Nocturnal out-flow of cold air from the park has been documented to extend as far as the equivalent of one park width (Jauregui, 1990-91; Eliasson & Upmanis, 2000). For daytime conditions, Yokahari et al. (2001) observed advection of cool air reaching 150-300 m into the built-up areas. Advection in the opposite direction, of warm air from the built-up areas moving into the park, has been shown to enhance evapotranspiration rates (Oke, 1979; Spronken-Smith et al., 2000). However, the urban environment can also possess conditions that suppress evapotranspiration. Energy balance measurements in vegetated areas in Mexico City showed significant seasonal differences in transpiration rates between the ‘dry’ and ‘wet’ seasons (Barrades et al., 1999). The transpiration rates during the dry season were significantly suppressed, probably by low soil water availability and effective stomatal control in relation to high atmospheric evaporative demand caused by the advection of warm dry air from the surroundings (Barrades, 2000). Furthermore, increased interception of long-wave radiation emitted by the warm surrounding surfaces can increase, as well as decrease, the amount
of transpiration depending on stomatal control behaviour (Kjelgren & Montague, 1998; Montague & Kjelgren, 2004).

**METHODS**

The thesis describes the water and heat processes acting at different surface elements (soil, asphalt, grass and tree) and the microclimate (mainly regarding temperatures) within the urban canopy layer. Papers I-III specifically deal with the soil profile, the asphalt surface and the vegetation respectively, while Papers IV and V look at the microclimate of the compound urban environment (Figure 2). The urban microclimate and its underlying processes were investigated by a combination of observations and modelling ranging from the one-dimensional processes of the individual surface elements to the three-dimensional urban small-scale climate. The emphasis on observations or modelling and the way in which they were applied varied between the individual studies. The approach ranged from analysis purely based on measurements (Paper IV) to analysis purely based on simulations (Paper III). In between, observations were used for evaluation of models (Papers II and V) and, conversely, modelling was used to explain observed phenomena (Papers I and II).

**Observations**

**Soil water content**

Glacial till soil covers approximately 95% of Sweden (Lundquist, 1977) and is the predominant soil type in the Stockholm region. Because of practical problems with digging in such a soil, due to the abundance of large boulders and stones, there have been few investigations concerning soil water dynamics of till soils (Espeby, 1989). Furthermore, the role of water movement through preferential pathways, such as cracks...
and old root channels, is not well understood. Rapid responses in terms of elevated groundwater levels and runoff production during snowmelt and intensive rainfall events indicate that preferential water flow occurs as part of the infiltration process in a till soil (Espeby, 1992; Beldering, 2002). However, field-based knowledge is to a large extent still lacking. Paper I examines measurements of soil water content from a till catchment 35 km NW of Stockholm. Soil water dynamics of the upper 60 cm of the soil profile were observed by means of Time Domain Reflectometry (TDR) from mid-June to October 1993. Data were sampled every second hour. Previous analyses of soil samples from the catchment were used for determination of soil hydraulic properties. Analysis was made of the soil water dynamics in general and the role of preferential flow paths in particular.

**Surface heat fluxes**

Surface heat fluxes of a paved surface were measured at a road test site situated at Säve Airport, 10 km north of Gothenburg. The road test site was a 20 x 20 m asphalt surface constructed to be representative of a normal Swedish road. Data obtained from the site included net radiation, surface temperature, road profile temperatures, heat flux below the surface, turbulent sensible heat flux above the surface, and standard meteorological data. Data for the period 2 April to 29 September 2003 were used in the analysis.

**Microclimate**

In Paper IV, the urban microclimate was observed within, and in the surroundings of, a vegetated park in central Stockholm, Sweden. The park, Humlegården, is 15 ha and mainly covered by grass and trees. Tree foliage covers approximately 50% of the park’s surface. Climate observations were made by means of a temperature profile from the surface to approximately 2.5 m height along a route passing through Humlegården and neighbouring city blocks (Figure 3). The measurement equipment consisted of 0.1 mm copper-constantan thermocouples at three different heights (0.19, 1.16 and 2.47 m), an infrared surface temperature sensor, and a two-dimensional sonic anemometer. The equipment was mounted onto the front of a bicycle. A complete traverse, from the start north of Humlegården along the route to the section furthest east of the park and back again, took approximately 40 minutes to complete, during which data were sampled every second. The data were aggregated into 50-150 m sections to represent point values. Measurements of daytime climate were conducted during three days in July 2004 with 3-6 traverses executed each day.

**SIMULATION TOOLS AND MODELLING APPROACHES**

The number of processes contributing to the urban microclimate are numerous and practically impossible to analyse from field data alone. Numerical models describing the urban microclimate are therefore useful tools and offer the possibility of detailed description and analysis of the underlying climate processes. Furthermore, such models can be used to predict climate changes caused by structural changes to the environment. In this thesis two models were used: A one-dimensional model that describes the water and energy fluxes in the soil-vegetation-atmosphere system; and a three-dimensional model simulating the urban microclimate. Most commonly used one-dimensional models for urban areas are the energy transfer models calculating the energy fluxes above the roughness sub-layer (e.g. TEB by Masson (2000); LUMPS by Grimmond & Oke (2002); FMV by Martelli et al. (2002)). There is an increasing interest in such schemes due to the increasing spatial resolution in mesoscale meteorological models, which allows the urban areas to be resolved (Offerle, 2003). However, such models estimate the local-scale fluxes from area-averaged characteristics. In this study, the one-dimensional model used allows for detailed analysis of water and heat transport for the individual surface elements. An advantage of a one-dimensional model is that it is possible to make detailed process descriptions that require relatively little computer time. Furthermore, compared to a
three-dimensional approach, it is easier to isolate the processes of interest without unnecessary feedback. Nevertheless, a three-dimensional approach where the surface elements are coupled to the atmosphere is necessary to realistically treat the urban microclimate dynamics. The major disadvantage is that this type of three-dimensional model requires significantly more computer time and memory.

**The one-dimensional soil-vegetation-atmosphere system**

The CoupModel (Jansson & Moon, 2001) is a physically-based water and heat transport model, i.e. based on the conservation of the water and heat balances. The main part of the model describes the vertical water and heat transport in a layered soil. The model allows for a great deal of flexibility and can be set up to represent a wide range of properties in the soil-vegetation-atmosphere system. Only a brief description of model formulations that are important for the analysis made in this work is given here. More detailed information is available in Papers I-III and a comprehensive description of CoupModel is provided by Jansson & Karlberg (2004).

**Soil water dynamics**

Water transport in the soil profile is calculated by Richard's equation, i.e. the flow is driven by the water potential differences in the soil matrix. The model includes an optional bypass routine where water entering a layer at a higher rate than the sorption capacity is routed to the next underlying layer.

---

**Figure 3.** Photographs from Humlegården and the surrounding built-up areas and a schematic illustration of the measurement equipment used in Paper IV (left). Route of measurements through Humlegården and its neighbouring areas (right).
model layer. This is a simple model representation of the preferential flow system and is used in Paper I to investigate the infiltration process in a glacial till soil. Simulations were made with and without the bypass routine. Hydraulic properties for the soil matrix (water retention and hydraulic conductivity) were given by functions fitted to soil physical data from the till catchment outside Stockholm.

Surface heat fluxes

The upper boundary condition of the soil profile is given by the energy exchange processes at the surface, i.e. eq. (1). The boundary condition is forced by climate data on global radiation, wind speed, air temperature, air humidity and cloud cover. In the model, the terms in eq. (1) are expressed as: the short-wave radiation balance as a function of global radiation and albedo; the long-wave radiation balance as a function of surface temperature, air temperature, air humidity and cloud cover; the turbulent fluxes of sensible and latent heat are calculated from the gradients between the surface and the air of temperature and humidity, respectively, and the turbulent exchange properties of the atmosphere, which are estimated from wind speed and a parameter accounting for roughness of the surface; the storage flux is determined from the temperature gradient between the surface and soil profile and the thermal properties of the soil. All terms are expressed as functions of the surface temperature, which is determined iteratively so that eq. (1) is fulfilled. In Paper II, the model was tested for its ability to simulate the surface heat fluxes of an asphalt-covered road. The soil-road profile was set up based on independent information on road construction and from the literature. Validation data of net radiation, surface temperature, heat flux below the surface, turbulent sensible heat flux and the forcing climate data were taken from the road test site at Säve.

Evapotranspiration

Potential transpiration is estimated by the Penman combination equation as modified by Monteith (1965), in which potential transpiration is expressed as a function of the amount of radiation absorbed by the foliage, the air vapour pressure deficit, the turbulent transport conditions of the atmosphere and the stomatal conductance. In Paper III, the model was used for simulating the impact on evapotranspiration caused by the urban-modified climate. Evapotranspiration is the most poorly understood component of the urban water balance (van de Ven, 1988; Mitchell et al., 2001) but over the long term can be one of the largest outputs from the urban catchment (Grimmond & Oke, 1986). Two basic climate modifications were made to a rural climate series: The nocturnal air temperature was increased to represent the urban heat island effect; and the incoming long-wave radiation was increased to represent radiation emitted from urban structures. The integrated air temperature increase for the year was 1 K, a value that has been reported for Stockholm (Moberg & Bergström, 1997). The long-wave radiation was increased by 10%, which generally corresponded to about 30 W m⁻². Simulations were made for high and low vegetation covers that represented tall deciduous trees and a low grass cover, respectively. Each vegetation cover was given typical characteristics regarding the turbulent transport properties of the atmosphere and stomata conductance. Due to their ‘rough’ structure, trees are in a considerably more turbulent milieu than ‘smooth’ grass surfaces, while grass generally has significantly higher stomatal conductance compared to deciduous trees (Jones, 1992). The urban climate impact was analysed by systematically changing the forcing climate for both vegetation types.

Urban microclimate model

Daily urban microclimate was simulated using ENVI-met, a three-dimensional microclimate model designed for simulating the soil-vegetation-atmosphere interactions within the urban environment at typical grid resolution of 0.5 to 10 m (Bruse & Fleer, 1998; Bruse, 2006). ENVI-met is one of the few models that seeks to describe the major climate processes acting in the urban environment, including turbulence, the turbulent transport of sensible and latent
heat, the radiation fluxes within the urban structures and the influence of vegetation. ENVI-met consists of a three-dimensional core model linked to a one-dimensional border model. In the core model, the urban landscape is constructed from grid cells containing soils, buildings, vegetation and open spaces. The energy balance, eq. (1), is solved at all surfaces using the atmospheric conditions of the grid cells adjacent to the surface (similar procedure as in the CoupModel) assuming no heat storage inside leaves and no evaporation from sealed surfaces (concrete, asphalt, walls and roofs). Heat transport in buildings is calculated from the difference between the surface temperature and a constant interior temperature and a heat transmission coefficient, i.e. heat storage in the buildings is not accounted for. However, dynamic heat storage is estimated for the ground profiles.

Incoming short-wave and long-wave radiation is provided as boundary conditions at the top of the core model. Within the urban canopy layer, the radiation balance is strongly governed by shading, reflection, absorption and emission within and between the urban structures and vegetation. To avoid numerical instabilities, nesting grids are added outside the core model environment to act as a ‘buffer zone’ between the lateral boundary and the main model. The nesting area is open (has neither buildings nor vegetation) and is therefore highly exposed to direct solar radiation, which can result in high surface temperatures that are not representative of the core model environment. An option therefore exists in which the incoming short-wave radiation in the nesting grids is estimated as an average of the global radiation reaching the surface within the core model. The core model generally extends to a height at least double that of the highest obstacle. The one-dimensional border model provides atmospheric boundary conditions at the top of the core model and extends the model to a height of 2500 m.

ENVI-met requires basic climate information, such as wind speed, temperature and humidity, at the start of the simulation. After the initialisation phase, in which wind, temperature and humidity are scaled from the surface to 2500 m, the model uses a constant wind forcing and the temperature and humidity at 2500 m are held constant throughout the simulation.

As mentioned earlier, numerical climate modelling is a promising approach for describing the urban microclimate and its underlying processes. However, model performance is rarely validated against relevant climate data. In Paper V, an ENVI-met simulation was run for, and compared to, the climate conditions that prevailed on one of the days in Paper IV in order to test the ability of the model to simulate the climate conditions of an urban vegetated park and its built-up surroundings. Humlegården and its surroundings were built up in ENVI-met in a 190 x 190 x 20 m grid (in the X, Y and Z directions) with a grid resolution of 5 x 5 x 2 m. To increase the accuracy of the near surface climate, the grid box closest to the ground was further subdivided into five equally thick layers (i.e. $\Delta Z = 0.4$ m). Later boundary conditions were chosen so that downstream conditions were copied to the inflow profile.

RESULTS AND DISCUSSION

Soil water dynamics

The observed response in soil water content after rainfall events was rapid throughout the soil profile, which indicated that preferential flow occurred in the soil. This was further demonstrated by the simulated soil water dynamics. With a strict Darcian modelling approach, in which the water movement was estimated from the vertical water potential gradients in the soil matrix, the response in soil water content was significantly delayed with time and depth (Figure 4). However, when the bypass concept was added to the simulations, i.e. a model representation of the preferential flow processes, the modelled response in soil water content showed similar pattern to the observed. The results show that preferential flow paths can be part of the infiltration process of a till soil throughout the growing season, and not only during snowmelt and intensive rainfall events as has
previously been demonstrated. On the other hand, although the bypass flow concept improved the simulated soil water dynamics during the first few hours after rainfall, it was also demonstrated that the bypass flow did not improve the modelled soil water content on a seasonal basis.

The parameter values presented in Paper I are useful information for water balance-related work on till soils, since the soil water dynamics influence several hydrological processes including groundwater recharge and transit time in the soil. The modelling approach, i.e. whether preferential flow should be taken into consideration or not, must depend on the purpose of the simulation. For example, when studying solute transport, where it is important to know how long the water is retained in the buffering part of the soil, preferential flow paths should be taken into consideration. However, for the seasonal behaviour of e.g. soil water content and groundwater recharge, the water dynamics can be modelled with a strict Darcian approach. In an urban context both approaches can be important, since the urban environment is exposed to more pollutants than its rural counterpart and since many urban structures require a stable groundwater level. In addition, a good description of the soil water dynamics is a prerequisite for obtaining appropriate properties for the energy exchange processes at the surface. For example, the soil thermal properties and the vapour pressure at the surface are closely linked to the water content in the soil profile and their dynamic behaviour will affect all components of eq. (1). Furthermore, the soil water dynamics determine the amount of water available for transpiration in the rootzone.

**Effect of urban climate on evapotranspiration**

The analysis of how the urban-modified climate affected evapotranspiration showed that increased nocturnal air temperature had most effect on evapotranspiration from
surfaces covered by tall vegetation, while elevated incoming long-wave radiation had most effect on grass surfaces (Table 1).

The results reflect the significance of turbulent properties for a ‘typical’ tall deciduous tree cover and a surface covered by low grass. For a ‘rough’ surface, as represented by the trees, the turbulent transport of vapour is efficient. In such a milieu, provided that there is little restriction by stomatal control, an increased air temperature and thereby an increased vapour pressure gradient between leaves and the atmosphere results in greater transpiration. In contrast, the soil surface and the grass cover are ‘smooth’ surfaces representing environments with less efficient turbulent transport, and an increased vapour pressure gradient is therefore less significant for evapotranspiration. For such environments, the increase in radiation is the dominant factor for increased evapotranspiration.

The analysis showed that a simple change in the meteorological forcing of a process-orientated soil-vegetation-transfer model was useful in understanding the effect that the urban-modified climate could have on evapotranspiration. In reality, the urban effect on evapotranspiration depends on the thermal conditions and the turbulent nature of the surrounding built-up area. These are site-specific and, as mentioned earlier, may vary significantly from the conditions represented by the urban heat island. The effect will therefore vary within the urban environment and can be both higher and lower than demonstrated by the simulations. The size and structure of the vegetated area is also important and the urban effect tends to decrease with increasing size of the vegetated area due to 1) attenuation of the long-wave radiation emitted by the built-up structures; and 2) feedback between the vegetation and the atmosphere in which the climate surrounding the vegetation becomes more influenced by its own properties and to a lesser extent by those of the built-up surroundings.

To properly consider the effect on evapotranspiration of the urban climate in terms of radiation from buildings and microscale advection of (mainly) dry and warm air, the surrounding microclimate has to be treated adequately. This ultimately depends on the local energy exchange between the built-up structures and the atmosphere.

### Heat balance of a paved surface

Model performance was compared to data observed between April and September at the road test site. Simulated net radiation, ground heat flux and surface temperature agreed well with the measurements and the coefficients of determination ($r^2$) were 0.94, 0.93, and 0.97, respectively, all with slopes close to unity. However, there were large discrepancies between the modelled and the observed sensible heat flux (Figure 5). A probable explanation for the differences was that the measured flux was underestimated due to 1) the eddy-correlation instrument possibly not capturing the small turbulent eddies close to the surface due to a too long

| Table 1. One year of accumulated evaporation terms simulated with: (i) a non-modified climate (rural climate), (ii) increased air temperature, and (iii) increased long-wave radiation. Absolute values (mm) are in bold, followed by the relative difference (mm) compared to (i) |

<table>
<thead>
<tr>
<th></th>
<th>Soil evaporation</th>
<th>Transpiration</th>
<th>Interception</th>
<th>Evapotranspiration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grass</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Non-modified climate</td>
<td>132</td>
<td>199</td>
<td>44</td>
<td>375</td>
</tr>
<tr>
<td>Increased air temperature</td>
<td>141</td>
<td>9</td>
<td>210</td>
<td>11</td>
</tr>
<tr>
<td>Increased long-wave radiation</td>
<td>179</td>
<td>47</td>
<td>240</td>
<td>41</td>
</tr>
<tr>
<td>Trees</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Non-modified climate</td>
<td>81</td>
<td>431</td>
<td>82</td>
<td>594</td>
</tr>
<tr>
<td>Increased air temperature</td>
<td>89</td>
<td>8</td>
<td>462</td>
<td>31</td>
</tr>
<tr>
<td>Increased long-wave radiation</td>
<td>134</td>
<td>53</td>
<td>469</td>
<td>38</td>
</tr>
</tbody>
</table>
path length or a too slow sampling rate; and 2) air originating from the vegetated surroundings probably mixing with air originating from the asphalt surface, i.e. the instrument did not measure completely within the internal boundary layer of the asphalt surface. Problems were also identified with the model formulation whereby the model had a tendency to underestimate net radiation round midday. A probable explanation was that the model overestimated the albedo at large solar zenith angles and therefore underestimated the amount of absorbed short-wave radiation.

The comparison of observed and simulated heat fluxes for the 20 x 20 m asphalt surface illustrated the difficulties in obtaining reliable turbulent heat flux measurements in a non-homogeneous environment. In addition, the results demonstrated that surface energy balance modelling could be a useful method in quantifying the surface fluxes and explaining measurements. Within the urban canopy layer, measurement of turbulent heat fluxes becomes even more complicated since the urban canyon geometry affects the turbulent exchange processes. From that point of view, numerical modelling provides a very attractive method for quantifying the surface heat fluxes. However, it becomes difficult to validate model performance based on flux observations. It is therefore more practical to compare model performance to more easily obtained state variables that are related to the energy exchange processes, e.g. air temperature.

**Urban microclimate: Observations**

The climate measurements from the park Humlegården and its surroundings in central Stockholm showed the common pattern of cool temperatures inside the vegetated park and warmer temperatures in the adjacent built-up area. The air temperature in the park was generally 0.5-0.8 K cooler than in the surrounding city blocks during the day but the difference increased in the afternoon, reaching a maximum of 2 K at sunset (Figure 8b). There were also distinct differences in the way in which the temperature changed with height within the 0-2.5 m air layer. Inside the park, the air was mainly stable.

![Image](image-url)

*Figure 5. Observed and simulated variables for the asphalted road test site outside at Säve.*
(increasing temperature with height), while the air in the built-up area was unstable (decreasing temperature with height).

The heat storage dynamic in the urban structures was expected to be an important process underlying the increased air temperature difference between the park and its vicinity in the evening, as well as the unstable air in the built-up area during the late evening and early morning. Energy stored in the urban fabric during the day was probably released during the evening and night. This provided heat to the surface, enabling an upward directed sensible heat flux and hence, an unstable thermal stratification. Furthermore, the heat released slowed cooling of the built-up areas compared to the park, which resulted in an increased temperature difference between the park and the built-up areas during the evening. The observed unstable air in the built-up areas during the early morning indicated that there could have been an upward directed sensible heat flux throughout the night.

Variation in the thermal stratification within the park and the built-up area respectively (Figure 6) could to a large extent be explained by the site-specific characteristics and their effect on the local radiation budgets. The thermal stratification below the tree canopies did not vary significantly during the day, probably because of a moderated radiation balance due to tree canopies reducing incoming radiation during the day and re-emitting parts of the outgoing long-wave radiation during the night. In contrast, the open grass areas were exposed to incoming radiation during the day and to long-wave radiation losses during the night. Hence, the
surface temperature at the grass sites varied more compared to the tree-covered areas and the air stability at the grass sites was stable in the morning and in the evening but became close to neutral at midday. In the built-up area, the canyon orientation had an influence on the vertical air temperature profiles. The air stability varied most in the canyons running in the north-south direction, which, when compared to the east-west canyons, had more unstable thermal stratification during the day but were closer to neutral in the morning and evening. This probably reflects the effect of canyon orientation on the radiation balance, in which the canyons running in the north-south direction received more direct short-wave radiation around midday but less in the morning and afternoon compared to the east-west canyons.

Generally, the thermal condition of the surface appeared to be coupled to the thermal conditions in the air, which was indicated by the continuously increasing temperature with height in the park, and the opposite in the built-up area, a continuously decreasing temperature with height. However, deviations from this pattern were observed on a few occasions, which was interpreted as an indication of small-scale advection between the park and the built-up area. For example, at 13:00 an unstable air layer at P4-6 and P12-13 lay above the stable park air, which indicated that warm air from the built-up surroundings was advected into the park (Figure 6). The opposite was demonstrated at 22:00 as stable air lay above the unstable air in the built-up area at F5-6, E1 and E12, which indicated that cool air from the park advected into the built-up area.

**Urban microclimate: Simulations**

ENVI-met simulated the spatial air temperature variation that was expected to exist in the urban environment, such as the warmest and most unstable air in the sections of the built-up area that were most exposed to direct short-wave radiation (Figure 7). The model also reproduced the observed air stability patterns within the park, i.e. the air layer was more stable below the tree canopies than above the open grass surfaces during daytime. To compare the simulations with the observations, a selection of the simulated data were made that corresponded to the route taken through Humlegården and the surrounding city blocks during the observations (Figure 3). The selected data were then aggregated similarly as the aggregation made to the measured data.

The amplitude of the daily air temperature cycle was not well represented in the simulations (Figure 8a). The model was probably sensitive to the way in which the radiation was handled in the nesting area, i.e. in the area between the lateral border and the core model. The simulations used the ‘area average’ approach for the estimation of direct short-wave radiation in the nesting area, which probably resulted in an underestimated temperature amplitude of the air entering the lateral boundary of the core model. An ‘open’ approach, in which the short-wave radiation reached the surface of the nesting area without reduction, would have increased the air temperature amplitude and thereby reduced the gap between observation and simulation. However, the modelled temperature difference between the park and its surroundings and the thermal stratification in the 0-2.5 m air layer were both of the same magnitude as the observed (Figure 8b and c). This was an indication that important physical properties governing the climate difference between the park and the city blocks were well represented in the core model.

Simulated air temperature difference between the park and its surroundings and the vertical thermal stratification deviated from the observations significantly during the morning and midday, as well as late in the evening. This could to some extent be explained in terms of heat storage dynamics. As mentioned earlier, energy is generally stored into the urban structures during the day and released during the evening and night, and there is a tendency for more energy to be put into storage during the morning phase of the day. In the model, dynamic heat storage was accounted for in the ground profiles but not in the buildings. This could have resulted in...
Figure 7. Simulated air temperature at 1.2 m height (upper figure) and the vertical air temperature difference between 0.2 and 2.5 m heights (lower figure) at 13:00.
too little energy being transported into the urban structures during the morning, and too little heat being released during the evening. As a result, the modelled sensible heat flux could have been overestimated in the built-up area during the morning to midday phase of the day, resulting in overestimation of the instability of the air. Furthermore, too little heat released from the modelled urban structures would result in too fast cooling rate in the evening, and hence an underestimated temperature difference between the park and the built-up areas. The constant wind forcing used throughout the course of the simulation was probably another important factor for the underestimated air temperature difference between the park and the built-up areas. The park might have cooled too slowly in the simulations due to too high wind speed, resulting in overestimation of the turbulent mixing that reduced the development of a cool air layer inside the park.

**SUMMARY AND CONCLUDING REMARKS**

In the beginning of the 1980s, the state of knowledge regarding the urban heat island was summarised as ‘well described but rather poorly understood’ (Oke, 1982). However, during recent decades there has been a considerable increase in the understanding of the processes underlying the urban heat island, which to a large extent has been achieved by local-scale heat flux measurements and process-based modelling. Hence, the climate of the aggregated urban environment has developed from a long tradition with observations describing the phenomenon, towards an increased knowledge of some of the important underlying physical processes. Urban microclimate studies seem to have developed...
from the opposite direction, with detailed process descriptions and sophisticated numerical models but with limited connection to empirical data. This is no surprise, however, since the difficulty in obtaining good measurements is one of the reasons for the creation of numerical models. Furthermore, the development of computer resources has made detailed microclimate analysis of the urban environment highly available since models can be run on ‘standard’ computers. Nonetheless, the possible use of such models will be restricted if their performance is not compared to real data.

This thesis has to a large extent used process-orientated numerical models, in combination with available and new measurements, to analyse the surface energy balance processes and climate within the urban canopy layer. Individual surface elements found within the urban environment were analysed using a one-dimensional soil-vegetation-atmosphere transfer model, while a three-dimensional model, in which the surface elements were coupled to the atmosphere, was used for describing the urban microclimate.

**Urban surface elements**

The soil-vegetation-atmosphere transfer model provided a good basis for appropriate description of soil water transport, surface heat fluxes and evapotranspiration for the individual surface elements. These are important processes influencing the climate and are therefore included, to differing extents, in atmospheric models. Hence, the model was useful and provided suggestions for surface parameterisation and for some possible improvements of surface schemes that can be implemented in atmospheric models. For example, the results from Paper I demonstrated that a ‘simple’ Darcian modelling approach would be adequate for the estimation of available soil water content for transpiration and that considerations of preferential flow paths may not be necessary if the seasonality of soil moisture is the focus of study. In Paper III, the one-dimensional modelling approach made it possible to study the urban effect on evapotranspiration. By making changes to the meteorological forcing, it was possible to estimate the impact on evapotranspiration caused by radiation and temperature changes, respectively.

Paper II illustrated the difficulties in making turbulent flux measurements in a heterogeneous environment, but at the same time demonstrated that the heat fluxes of a paved surface were relatively simple to model. A reliable estimation of the surface heat fluxes was obtained without site-specific calibration. Based on this, it should be straightforward to describe similar elements of the urban built-up structures, including roads, walls and roofs, and the challenge may be to make reliable descriptions of the urban environment so that important physical conditions such as radiation and wind are represented adequately at the surface elements.

**Urban microclimate**

It was shown in Paper IV that relatively simple measurements could illustrate the spatial and temporal variation in the urban climate. The micro-scale observations were useful in identifying differences in air temperature and atmospheric stability within the urban environment, and were also an indicator of advection between the contrasting park and built-up areas. Furthermore, the measurements provided sufficient information to be used for testing the performance of a three-dimensional microclimate model. Hence, it was demonstrated that simple climate measurements were useful for the evaluation of a sophisticated and detailed climate model.

The climate conditions modelled using ENVI-met in Paper V were of the same magnitude as the observed. Hence, the model seemed to make an adequate description of the urban environment that enabled the surface-air energy exchange processes from the surface elements to be accurately estimated. However, there were some observation-simulation discrepancies. Based on these differences, it was suggested that development of model representation of heat storage dynamics and allowing the wind conditions to vary within the simulation
period could improve model performance. On the other hand, it should be noted that including dynamic heat storage in buildings would increase the demand for reliable parameter values, and the thermal properties of buildings are expected to vary significantly both between and within cities. For example, the thermal properties of an old stone building (such as the city blocks surrounding Humlebäcken) are very different from the thermal properties of a modern well-insulated building, and these differences will ultimately affect the climate.

**Future directions**

Due to the heterogeneity of the urban environment and the wide range of city compositions regarding size, shape and materials, the urban microclimate cannot be generalised, which emphasises the importance of making reliable descriptions of the physical processes underlying the climate. This has become possible by three-dimensional numerical models that provide the possibility to integrate descriptions of urban environments and important climate processes. However, relevant microclimate data, and hence relevant model assessment, are to large extent still lacking, and to obtain a comprehensive picture of the urban microclimate, knowledge is needed from a variety of urban structures and climate conditions. In such a context, the methods and results presented in this thesis are promising and provide a good basis and guidance for further studies towards an increased understanding of the urban microclimate. It was demonstrated that relevant data on urban microclimate conditions could be efficiently obtained during short measurement campaigns at a low cost. This was possible since the area of interest was relatively small (100 m$^2$ to few km$^2$), the time span short (hours to few days) and the measurement equipment basic but well designed for the specific purpose. Some key areas of the urban small-scale climate were carefully investigated and in addition it was demonstrated how different types of data can be used for the assessment of a sophisticated model. Already today, microclimate models such as the ENVI-met are useful and give reasonable results. In development work, when these models are further refined and carefully evaluated for a wide range of conditions and environments, such tools will provide the possibility for urban planners to model scenarios that can help them in optimising planning decisions.

Some events are less well-known and we can expect that models are less precise on these issues. Examples that need to be addressed are the climate conditions after rainfall events and winter conditions including ice and snow. Furthermore, diurnal cycles should be considered, since daytime and nighttime climate are not isolated from each other, although the underlying processes are different. It would also be interesting to investigate the effects that soil water content and type of vegetation cover have on evapotranspiration and shading, and thereby on the temperature difference between the park and its surroundings. In addition, evapotranspiration is a significant part of the urban water balance and therefore important for both urban meteorologists and urban hydrologists. A holistic approach, considering both water and heat balances, would close the gap between the two fields and could provide more reliable hydrological and meteorological estimates.

Ultimately we need to know the significance of the urban microclimate in a broader perspective. For example, if a planned structural change to the urban environment is estimated to change the air temperature by 1 K, what would the effect be in terms of energy consumption, human comfort and health? To be able to answer such a question we have to develop knowledge by combining disciplines.
REFERENCES


Miller, D. 1980. The two-dimensional energy budget of a forest edge with field measurements at a forest-parking lot interface. Agricultural Meteorology: 22 53-78.


Potchter, O., Cohen, P., Yaakov, Y. & Bitan, A. 2003. The climatic behavior of various types of urban parks in a coastal Mediterranean city during the summer – the case of Tel Aviv, Israel. Fifth International Conference on Urban Climate, 1-5 September 2003, Lodz, Poland.


OTHER REFERENCES

24