climate changes spatial planning

Communication

Modelling and observing urban climate in the Netherlands

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KvR 020/11

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KvR report number: KvR 020/11
ISBN/EAN 978-90-8815-020-3

This project (COM29; Climate in The Urban Environment) was carried out in the framework of the Dutch National Research Programme Climate *changes* Spatial Planning. This research programme is co-financed by the Ministry of Infrastructure and the Environment.

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Summary

Summary in Dutch

Volgens de klimaatscenario's van het KNMI uit 2006 zal de gemiddelde temperatuur in Nederland in de komende decennia verder stijgen. Hittegolven zullen naar verwachting vaker voorkomen en de intensiteit van met name zomerse buien kan toenemen.

In steden zijn de gevolgen van de opwarming extra voelbaar, omdat de temperaturen er door het zogenoemde *Urban Heat Island* (UHI) effect veel hoger kunnen zijn dan in het omliggende gebied. Zulke periodes met hoge temperaturen gaan veelal gepaard met verslechterde luchtkwaliteit en droogte. Dit alles kan grote gevolgen hebben voor de leefbaarheid en de gezondheid van de bevolking in stedelijke gebieden. Veranderingen in de buienintensiteit beïnvloeden de waterhuishouding van de stad.

In de nabije toekomst zal de verstedelijking verder toenemen. Adaptatiemaatregelen zijn dan ook noodzakelijk om mogelijke nadelige gevolgen van veranderingen in weer en klimaat te verzachten. Het ontwikkelen van effectieve adaptatiestrategieën vereist kwantificering van (1) de effecten van een toekomstig klimaat en (2) de effecten van beoogde adaptatiemaatregelen op het stedelijk klimaat.

De resolutie van de huidige generatie modellen voor het stadsklimaat maakt deze kwantificering in principe mogelijk. De laatste jaren zijn zulke modellen vooral in landen buiten Nederland in snel tempo verder ontwikkeld. In het huidige project is de bruikbaarheid van twee veelgebruikte modellen voor de Nederlandse situatie (klimaat, typen gebouwen, stadsmorfologie) onderzocht. Beide modellen zijn in staat het UHI te simuleren, maar onderschatten dat effect enigszins. De simulaties laten een duidelijk invloed van de stad op haar omgeving zien. Speciale simulaties van een van de modellen hebben aangetoond dat het mogelijk is om effecten van veranderingen in de stadsconfiguratie op het UHI te kwantificeren.

In de laatste 30 jaar zijn er in Nederland geen systematische meteorologische waarnemingen in steden uitgevoerd. Datasets die analyses van het UHI en parameterisatie en validatie van modellen voor de Nederlandse situatie mogelijk maken ontbreken dan ook. In deze studie is een meetstrategie ontwikkeld om bruikbare gegevens hiervoor te krijgen, via nieuwe metingen of ontsluiten van bestaande datasets. Amateurmeteorologen blijken over een waardevolle, betrouwbare bron van informatie over het weer in de urbane omgeving te beschikken. Een eerste voorlopige analyse van de resultaten van hun waarnemingen voor 20 Nederlandse steden laat zien dat het UHI ook in Nederland waarneembaar is en uiteenloopt van ongeveer 3 tot 10°C. In 7 van de 20 steden lijkt momenteel op ongeveer 7 dagen per jaar sprake te zijn van duidelijk verhoogde warmtestress.

Systematische waarnemingen aan het stadsklimaat voor analyses van het UHI en zijn werking, en voor modelparameterisatie en –validatie kunnen het beste gebaseerd worden op een combinatie van meetmethodes. Daarbij is het van belang rekening te houden met de grote ruimtelijke verschillen binnen een stad. Een combinatie van langdurige waarnemingen op vaste punten met gedetailleerde waarnemingen aan de ruimtelijke structuur is aan te bevelen. Daarbij zijn gespecialiseerde waarnemingen, zoals waarnemingen aan de warmtestromen en de stralingshuishouding, gewenst voor interpretatie van de gevonden patronen en voor parametrisatie, calibratie en validatie van modellen.

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Project website	www.klimaatindestad.nl		
Startdatum	Juni 2008	Einddatum	December 2009

Extended Summary

Facing the phenomena of climate change, city planners and architects have to develop adaptation strategies to mitigate the impacts of extreme weather conditions on citizens to ensure human well-being outdoors and indoors. To assess the effectiveness of proposed adaptation measures, quantitative information is needed. Models designed to simulate the urban climate can serve as valuable tools to provide this information.

During the last decade, substantial progress in both mesoscale numerical weather prediction (NWP) and the description of urban atmospheric processes has been achieved. With increasing computer capacity, NWP models are now approaching the required horizontal and vertical resolution to provide high quality urban meteorological data.

The partners in the present project, MAQ and ESS-CC, have a large expertise with respect to the mesoscale models WRF[1] and RAMS[2], respectively. Recently, these models have been equipped with a so-called Urban Canopy Model (UCM) embedded within a land surface scheme, WRF has been coupled to the NOAH land surface model-single-layer Urban Canopy model (NSLUCM) and RAMS to the Town Energy Balance model (TEB) (Kusaka et al. 2001; Chen et al., 2004; Dandou et al. 2005; Masson, 2000; Masson et al., 2002; Lemonsu et al. 2004). In the present study currently available models for the Urban Canopy have been reviewed and the performance of the aforementioned specific models was evaluated.

The theoretical basis of all present-day models is the Surface Energy Balance (SEB) for the urban area:

$$Q^* + Q_F = Q_H + Q_E + \Delta Q_S$$

Where Q^* is net all wave radiation, Q_F heat arising from anthropogenic activities, Q_H is the turbulent sensible heat flux, Q_E is the turbulent latent heat flux, and ΔQ_S is the net heat storage flux of buildings. A large number of urban surface schemes exists. These vary in complexity from simple schemes that represent the city as a concrete slab to multi-layer models that model energy exchanges at multiple levels within the urban canopy, thereby allowing for varying building heights. All models forecast the SEB fluxes representative of the local (or neighbourhood) scale.

1 Weather Research and Forecasting Model (mesoscale numerical weather prediction system, Boulder Colorado)
2 Regional Atmospheric Modeling System (NOAA)

Many of the models are also capable of calculating additional terms, typically air and surface temperatures and wind speed at street level, and providing more detailed flux information, for example by facet[3].

We participated with WRF in the Urban Surface Energy Balance: Land Surface Scheme Comparison project (PILPS[4] URBAN) which started in March (2008) and was coordinated by the Department of Geography, King's College London. By participating, we were able to assess the offline performance of the model as compared to other available models. Since the analysis of latter phases in not complete yet, this report covers only the first phase of the project. It appears that the models have best overall capability to model net radiation (Q*) and least capability to model latent heat flux (Q_E). None of the models performs best or worst for all fluxes. Generally speaking, the simple models in each of the classifications perform as well, if not better, than the more complex models for the daytime fluxes. For Q*, Q_H and ΔQ_S, NSLUCM-WRF performs better than the other models. However, the model has a relatively low capability to model QE during day time, but this holds for most of the participating models.

Online simulations with NSLUCM-WRF and TEB-RAMS have been carried out for the city of Rotterdam. Because characteristics of the built environment are not known yet, the default settings of each model were applied for these simulations. The main aim was to get a first impression of the model performance and capabilities under Dutch climatic conditions. Although both models differ in their results for the diurnal variation and maximum value for UHI intensity, they show a clear overall Urban Heat Island effect ranging from 1 to 5 K. Both modelling studies show a significant influence of urban areas on their neighbouring rural areas (the effect of the urban plume). The capability to quantify with mesoscale models the effect of changes in city configuration on the UHI has been demonstrated.

At present, no systematic meteorological data records for towns and cities in the Netherlands are available. Therefore, an inventory has been made of internationally available data sources. In addition, the possibility to utilize datasets provided by hobby meteorologists has been explored. We collected meteorological observations for 20 urban sites in the Netherlands including air temperature and humidity, wind speed, and for some stations also incoming solar radiation. With these data a first assessment of the UHI intensity for the Netherlands could be made. To assess the effect on thermal comfort, wet-bulb-globe-temperature (WBGT) was estimated. The preliminary analysis shows that the UHI is clearly present in the Netherlands as well. The UHI ranges from 3 to 10 °C. Seven out of the 20 cities investigated experience extreme heat stress for ~7 days a year under the present climatic conditions.

Detailed observations are required for process understanding, and to support model development and evaluation, to ensure realistic simulations. To obtain meaningful observations, it is essential to clearly establish the objectives of the observations (measurement rationale). In connection with this, it is necessary to pay careful attention to urban scale and related issues. Recognition of scale differences in cities is a central key to the design of meaningful field observations. A distinction can be made between: (1) Observations in the Urban Canopy Layer (UCL) and (2) observations in the Urban Boundary Layer (UBL).

3 Surface of the urban geometry (roof, wall, road) that can be characterized by a single temperature and surface energy balance, and that can interact thermodynamically with other facets (for example, a wall facet exchanging long-wave radiation with the road facet).

4 Project for Inter-comparison of Land-Surface Parameterization Schemes

The observations in the UCL provide insight into the dependence of the microclimate on street and city quarter characteristics. With the observations in the UBL, valuable information on the urban surface energy balance (SEB) can be obtained. It can be concluded that systematic observations of the urban meteorological and climatological conditions should be based on a set of complementary observations, covering detection of temporal as well as spatial variations of the meteorological conditions in the urban canopy. For model parameterization and validation more specialized observations are required as well. Satellite imagery and other remote sensing techniques can give valuable additional information that can also be used to determine optimal locations for observations within the urban canopy.

As an illustration experiences obtained with measurements that have been conducted in the framework of the 'Heat stress in the city of Rotterdam' project are discussed.

1. Introduction

1.1 Background

Observations indicate that extreme weather events like heat waves and excessive rainfall (downpours) have increased in North-West Europe (Klein Tank et al., 2002). Climate projections show that the frequency and severity of these extreme weather events will probably continue to increase (IPCC, 2007). In addition, coastal areas may be subject to rising sea levels combined with storm surges (FitzGerald et al., 2008; Cazenave and Llovel, 2010).

It is now widely recognized that mankind needs to prepare for the consequences of climate change. This is particularly true for the urban environment. Urban characteristics induce localised climatic effects that interact with climate change and may aggravate its consequences (McCarthy et al., 2010). Much of the infrastructure is designed and built for long periods of time. Thus, buildings, infrastructure and open space need to be adequately 'climate proofed' for future conditions, in particular regarding extreme events.

The projected trends could have significant consequences for the liveability in cities in North-west Europe (IPCC 2007). For instance, the summer heat wave of 2003 combined with the Urban Heat Island (UHI) effect has shown to trigger major public-health crises in largely urbanized populations (Haines et al., 2006). Moreover, heat waves often coincide with summer smog (ozone) and increased levels of particulate matter. According to an analysis by Stedman (2006) adverse health effects of smog and particulate matter during the 2003 heat wave caused between 21 and 38 percent of the casualties in several cities in the UK.

The growth of cities is expected to continue in the near future. Worldwide, between 2007 and 2050, the number of citizens living in urban areas is projected to increase from 3.1 billion (49%) in 2007 to 6.4 billion (70%) in 2050. In Europe, in the same period, the number of urban dwellers is projected to increase from 528 million (72%) to 557 million (84%) (United Nations, 2008). Facing the phenomena of climate change, urban planning must cover adaptation strategies to mitigate the impacts of extreme conditions on citizens in order to ensure human well-being outdoors as well as indoors, even during extreme weather events.

Urban climatology has been studied in a large number of European countries and in countries like the USA, Japan, China and Australia. By contrast, until recently, urban climate was not an issue in the Netherlands. Participation in the existing scientific networks only started recently. As a result, in this area expertise in the Netherlands is largely lacking.

Although foreign studies on urban climate contain valuable information, their results cannot be easily extrapolated to the Dutch situation. The differences in climatic conditions, air quality, urban landscape and geometry, and in building styles and materials render such extrapolation extremely difficult. Furthermore, the focus in most of the foreign studies has been on the UHI effect. Consequently, less knowledge is available on the direct and indirect effects of air pollutants in the urban atmosphere and on the water budget of urban areas, which are considered important issues in the Netherlands.

It can be concluded that tools to assess the effect of climate change on urban climate in the Netherlands have to be tailored specifically to the Dutch situation and needs. Such tools, developed in support of designing planning strategies, then ensure that proper adaptation measures will be taken for the Dutch situation. It is important that integrated assessments can be made that include heat stress, water stress (excess and shortage) and air pollution.

Numerical weather prediction (NWP) models coupled to a so-called urban canopy model (UCM) may become useful tools to evaluate urban landscape design options and tailor-made applications under differing climate scenarios. During the last decade, substantial progress in both mesoscale NWP and UC models has been achieved. With increasing computer capacity, NWP models are now approaching the required horizontal and vertical resolution to provide high-quality urban meteorological data. For instance, state-of–the-art nested NWP models can use land-use databases down to a resolution of 1 km or even finer.

To ensure realistic model results, the models have to be verified against observations, preferably obtained in the region of interest. Because urban environments are often very heterogeneous, obtaining meteorological observations suitable for model validation and development of parameterizations is a challenging task and requires a proper measurement strategy.

1.2 Objectives and research questions

The main aims of the present study are:

1) to evaluate the performance of two well-known mesoscale NWP models coupled to a UCM
2) to develop a proper measurement strategy for obtaining meteorological data that can be used in model evaluation studies

We choose the mesoscale models WRF[5] and RAMS[6], respectively, because the partners in the present project, MAQ and ESS-CC, have a large expertise with respect to these models. In addition WRF and RAMS have been successfully used in the meteorology and climate research communities for various purposes, including weather prediction and land-atmosphere interaction research. Recently, state-of-the-art UCM's were embedded within the land surface scheme of the respective models, in order to better represent the exchange of heat, momentum, and water vapour in the urban environment.

5 Weather Research and Forecasting Model (mesoscale numerical weather prediction system, Boulder Colorado)
6 Regional Atmospheric Modeling System (NOAA)

Key questions addressed here are:
- What is the general model performance with respect to the urban environment?
- How can useful and observational data be obtained that allow sensible validation and further parameterization of the models?
- Can the models be easily modified to simulate the urban climate under Dutch climatic conditions, urban configuration and morphology?

1.3 Outline of the report

Chapter 2 reviews the available Urban Canopy Models; we discuss their theoretical basis, the different representations of the urban environment, the required input and the output. Much of the information was obtained from the *Urban Surface Energy Balance: Land Surface Scheme Comparison project* (PILPS[7] URBAN). This project started in March 2008 and was coordinated by the Department of Geography, King's College London.

In order to test the performance of our models we participated in this project. Chapter 3 discusses the main results of the first phase of PILPS URBAN.

A first impression of the model performance under Dutch climatic conditions is obtained from a number of online simulations with the non- calibrated versions of NSLUCM-WRF and TEB-RAMS. These simulations have been carried out for the city of Rotterdam and their results are discussed in Chapter 4.

Chapter 5 gives an inventory of the available datasets for model validation and parameterization. Also, the possibility to use data from hobby meteorologists will be discussed.

Chapter 6 deals with the 'measuring strategy' that will be illustrated by the measurements carried out as part of the Hotspot Heat Stress Rotterdam project (HSRR05, 1st phase KfC, 2009-2010).

Finally, in chapter 7, conclusions and recommendations are presented.

7 Project for Inter-comparison of Land-Surface Parameterization Schemes.
www.kcl,ac.uk/ip/suegrimmond/model_comparison.htm

2. Characteristics of the urban canopy models

2.1 Urban Surface Energy Balance

The Surface Energy Balance (SEB) is an essential component of mesoscale models, being the driver for the near-surface weather patterns simulated by these models. The SEB describes all exchanges of energy between the land surface and the atmosphere. These include solar and thermal radiation fluxes, turbulent heat fluxes, and energy stored in the soil - canopy system.
The SEB for an urban area can be described by (Oke, 1988):

$$Q^* + Q_F = Q_H + Q_E + \Delta Q_S \qquad (1)$$

Where Q^* is net all-wave radiation, Q_F the heat flux arising from anthropogenic activities, Q_H the turbulent sensible heat flux, Q_E the turbulent latent heat flux, and ΔQ_S is the net heat storage flux associated with heating and cooling of urban mass that is composed of gas, liquids, and solids.

Relative to the vegetated surfaces of natural or agro-ecosystems, each energy balance term will be altered in urban areas. Furthermore, contrary to rural surfaces, the heat release from anthropogenic activities (QF) can play a significant role. Often, these differences in the energy balance terms cause the urban areas to be warmer than their rural surroundings. This is the Urban Heat Island effect (UHI) (Oke, 1987). The temperature difference between a city and its surroundings is usually most pronounced during night-time hours.

2.2 Representation of the urban environment

Many different Urban Canopy Models (UCM) describing the SEB have been developed (see Appendix 1 for a broad list). These models vary in complexity from simple schemes that represent the city as a concrete slab, to those which incorporate detailed representations of momentum and energy fluxes distributed within the atmospheric boundary layer.

Table 2.1 provides a summary of the features of the urban surface that are actually solved by the UCM. The table shows that a wide variety of complexities exists among the UCM. Next, we briefly discuss the most important differences between the model classes. More details on the differences between the model categories are given by Grimmond *et al*. (2010).

Vegetation

Some models take vegetation into account, others do not. Two differing methods to incorporate the vegetation exist: (1) vegetation is treated as a separate surface (referred to as “tiles”) that does not interact with other surface types up to the first layer of the meso-scale model, or (2) it is embedded into the urban area so that it affects, and is affected by, the built environment (referred to as integrated).

Anthropogenic heat flux

Quantification of the anthropogenic heat flux Q_F is very difficult and is subject of ongoing research (Kpro et al., 2010). Not all models consider Q_F and models that include Q_F may apply very different methods. For example, in some models Q_F is specified to be a fixed amount, while in others it depends on the assumed internal temperature in buildings. Only few models consider diurnal and seasonal variations of Q_F.

Urban morphology

With respect to the representation of the urban morphology, the models can be classified into three types. First, in slab models the urban area is represented in terms of a surface (e.g. concrete) with appropriate thermal characteristics. Second, single-layer models treat the urban area as a layer of buildings with the overall surface heat exchange being the sum of exchange of individual surfaces. Third, in multi-layer models the energy exchanges are computed at multiple levels within the urban canopy, thereby allowing for varying building heights. Another important characteristic is the way how street canyons are dealt with in terms of, orientation and intersections, in connection with the number of facets.

Radiative fluxes

The modelled reflection of solar radiation depends on the complexity of the urban morphology. The single reflection is the least computationally intense and is used in both slab and single layer models, whereas models which simulate multiple reflections include both single layer and multilayer models. The albedo that these reflections are based on may either be a single value, by facet, or may consist of combinations of various facets, for example, of canyon and roof.

Heat storage

The storage heat flux is sometimes simply determined as the residual of the energy balance equation (1). Other models compute the storage flux explicitly from the energy exchange trough a number of facet layers. Yet other models compute the storage as a function of net all wave radiation and the surface characteristics.

2.3 Model inputs

The inputs required to run the models consist of three general types:

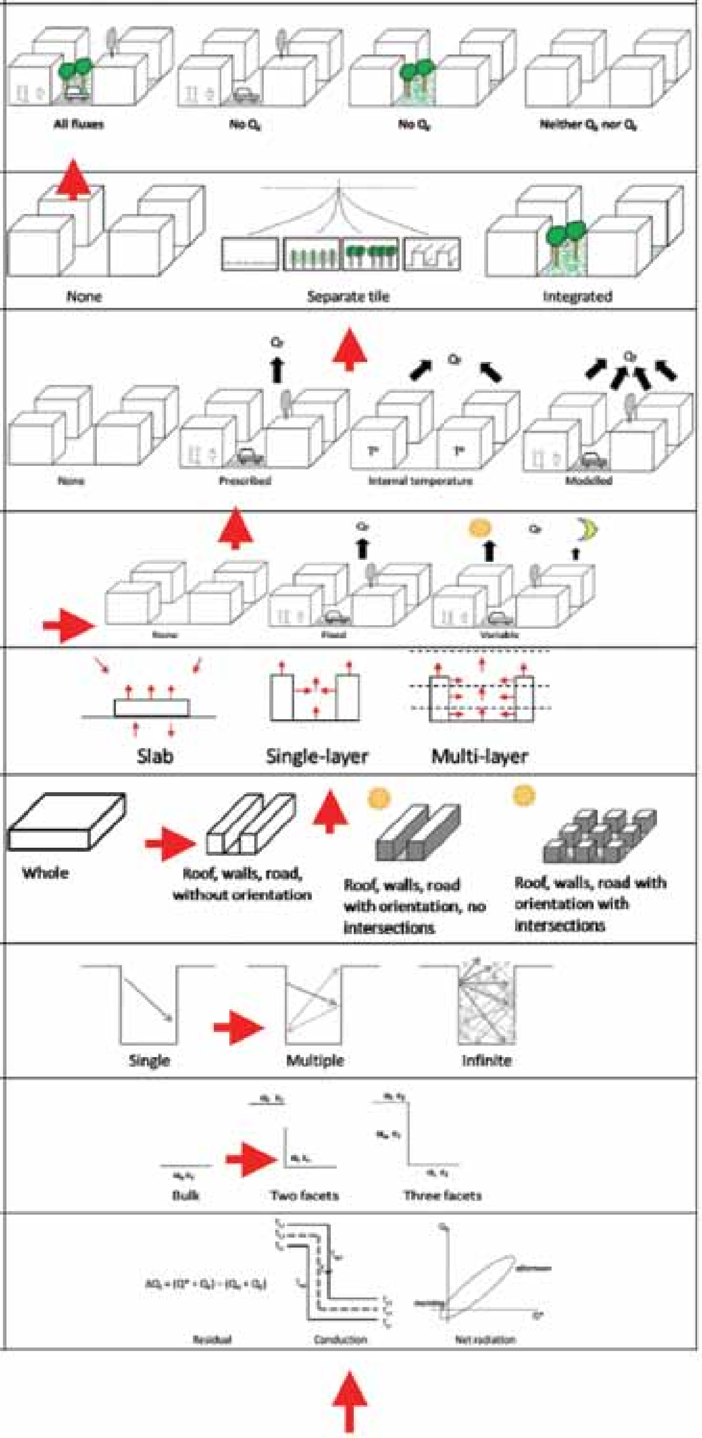
- Site-specific parameters to describe the surface morphology and materials;
- Time series of atmospheric or forcing variables as boundary conditions;
- Initial conditions required to initiate the model runs (spin-up).

The first set of information is needed in any type of model run, so there is no difference between a typical run and an offline model run. The second set of data are used in a normal online run; they consist of meso- (or larger-) scale model output that are used to drive the urban SEB models. These relate to wind, temperature, humidity, down welling radiation, and precipitation. The data are updated at each time step. The third set of inputs are explicitly related to the surface scheme. Most of input parameters needed for (3) are similar to the input variables of (1). For example, many of the models require temperatures (e.g. facet temperatures) as initial state conditions, and for some models soil moisture characteristics are important. Sometimes these data are difficult to obtain with as consequence a long initialization period (spin-up) time needed to ensure that the temperature profiles are stable and representative of conditions.

Table 2.1

Classification of Urban Canopy Models. Class number (column 1), letter codes (column 2) and number of models (model capability, cap column 3; used in VL92, column 4) are shown. Classes with small numbers, indicated by *, have been amalgamated with another class in results plots. Red arrow: NSLUCM-WRF and TEB-RAMS (Grimmond et al. 2010)

		Cap	VL92
	Fluxes included (F)		
	All fluxes (a)	13	8
	No Q_E (e)	2	2
	No Q_F (f)	10	14
	Neither Q_E nor Q_F (g)	2	3
1	**Vegetation (V)**		
	Not included (n)	7	12
	Separate tile (s)	16	11
	Integrated (i)	4	4
2	**Q_F (AN)**		
	Negligible or ignored (n)	11	21
	Prescribed (p)*	5	1
	Internal Temp. (i)*	3	3
	Modelled (m)*	6	1
	i,p*	2	1
3	**Temporal Q_F variation (T)**		
	None (n)	11	21
	Fixed (f)	3	2
	Variable (v)	13	4
4	**Urban Morphology (L)**		
	Slab(s)	9	9
	Single layer(1)	11	11
	Multiple layer (m)	7	7
5	**Facets & orientation (FO)**		
	Whole (w)	4	4
	No orientation (n)	14	14
	Orientation (o) no intersections	5	5
	Orientation (w) with intersections	4	4
6	**Reflection (R)**		
	Single (s)	8	9
	Multiple (m)	12	11
	Infinite (i)	7	7
7	**Albedo, Emissivity (AE)**		
	Bulk (b)	4	5
	Two facets (2)	4	4
	Three or more facets (f)	19	18
8	**ΔQ_S (S)**		
	Residual (r)*	5	6
	Conduction (c)	20	19
	Net radiation based (n)*	2	2



2.4 The urban canopy models of WRF and RAMS

In WRF, the NOAH land surface model/Single-layer Urban Canopy model (NSLUCM-WRF) is used to better describe all exchanges in energy between the atmosphere and urban areas; the Town Energy Balance model (TEB) is used in RAMS (Kusaka et al. 2001; Chen et al., 2004; Dandou et al. 2005; Masson, 2000; Masson et al., 2002; Lemonsu et al. 2004). Both models can be classified as single-layer urban canopy models. The major features of the urban canopy models used in WRF and RAMS, NSLUCM-WRF and TEB-RAMS respectively, are indicated by means of the red arrows in Table 2.1.
The models simulate the surface temperature of roof, wall and road surfaces as well as the fluxes from these surfaces. A separate vegetation tile is included. The urban canopy is assumed to be an isotropic array of infinite street canyons. Some of the modelled features include shadowing from buildings, multiple reflection of short and long wave radiation and a wind profile in the canopy layer (Kusaka and Kimura, 2004). The description of radiative fluxes takes into account the canyon orientation and the diurnal variation of azimuth angle. The definition of the albedo and emissivity follows from a distinction of two facets. Heat transfer by conduction is computed through several layers of materials.

In WRF anthropogenic heat releases from traffic, buildings and industries can be prescribed. In TEB, heat releases from the building for space heating are parameterized using a simplified model of the building energy budget.

3 The PILPS Urban Project

We participated with WRF in the *Urban Surface Energy Balance: Land Surface Scheme Comparison project* (PILPS[8] URBAN). This project started in March (2008) and was coordinated by the Department of Geography, King's College London. By participating, we were able to assess the offline performance of the model as compared to other available models. Also, important insights into the physics of the urban environment could be obtained in this way.
PILPS URBAN consists of two phases, of which only the first one has been completed to date. Therefore, this report only covers the first phase of the project. Analyses and papers presenting the results of phase 2 (ALPHA) are in preparation. For more details on PILPS URBAN the reader is referred to Grimmond *et al*. (2010a,b).

3.1 Methodology

Twenty-three groups participated in the PILPS Urban project with 27 urban canopy models. The models were run offline, which means that the forcing data are provided on 'top' of the model without feedback between the surface and the atmosphere. The methodology therefore also excludes interactions with larger scale conditions within the modelling domain.

8 Project for Inter-comparison of Land-Surface Parameterization Schemes

The methodology adopted in PILPS URBAN follows the one that was successfully applied in earlier intercomparison studies on models for vegetated surfaces (e.g., Chen et al., 1997). The procedure is briefly outlined below. For more detailed information, the reader is referred to Grimmond et al. (2010a).

In all simulations, the land surface scheme was forced using observations of down welling short- and long-wave radiation, precipitation, wind speed, and temperature. Next, the urban single layer scheme provided turbulent fluxes of sensible and latent heat, the anthropogenic flux, and the storage flux of heat in the soil and buildings. The modelled fluxes were then independently compared with observed fluxes after submission to Kings College. The observed fluxes as well as information of the city that was simulated were unknown to the individual modellers. As such, PILPS URBAN provided a blind model evaluation.

PILPS URBAN was set up in a number of phases (Table 3.1). First, a test phase (called VL92) was organized in which each modeller was asked to submit results for a short times series only. The purpose of this phase was to test whether the requested fluxes could be handed in by the participating modelling group. Subsequently, the experiment was repeated for a different anonymous city in 4 different stages. In each stage additional information regarding the geometry and morphology of the city under investigation was provided. In the final stage the participating modellers were asked to optimize their model and observational fluxes were provided.

Table 3.1
Structure of the PILPS URBAN model intercomparison project.

	Dataset/duration	Stage	
Phase 1	VL92; 14 days	0	Test phase
Phase 2	ALPHA; 12 months of 15 months dataset	1	Forcing data only
		1.5	As stage 1 + vegetation fraction information
		2	As stage 1a + basic morphology information about the site
		3	As stage 2 + detailed information about the site
		4	As stage 3 + all site data released for validation (re-run of VL92 dataset)

3.2 General results from phase 1

Fig. 3.1 shows the scatter plots of modelled (27 models) versus observed fluxes for the VL92 dataset. It can be seen that, generally speaking, the models have best overall capability to model net radiation (Q^*) and the least overall capability to model the latent heat flux (Q_E) of urban surfaces. None of the models performs best or worst for all fluxes. In particular, it seems to be difficult to minimize both the Q^* and the Q_H errors. There is some evidence that some model classes perform better for individual fluxes but not overall. Based on the statistical measures applied by Grimmond et al. (2010a) it can also be concluded that simpler models perform as well as more complicated ones.

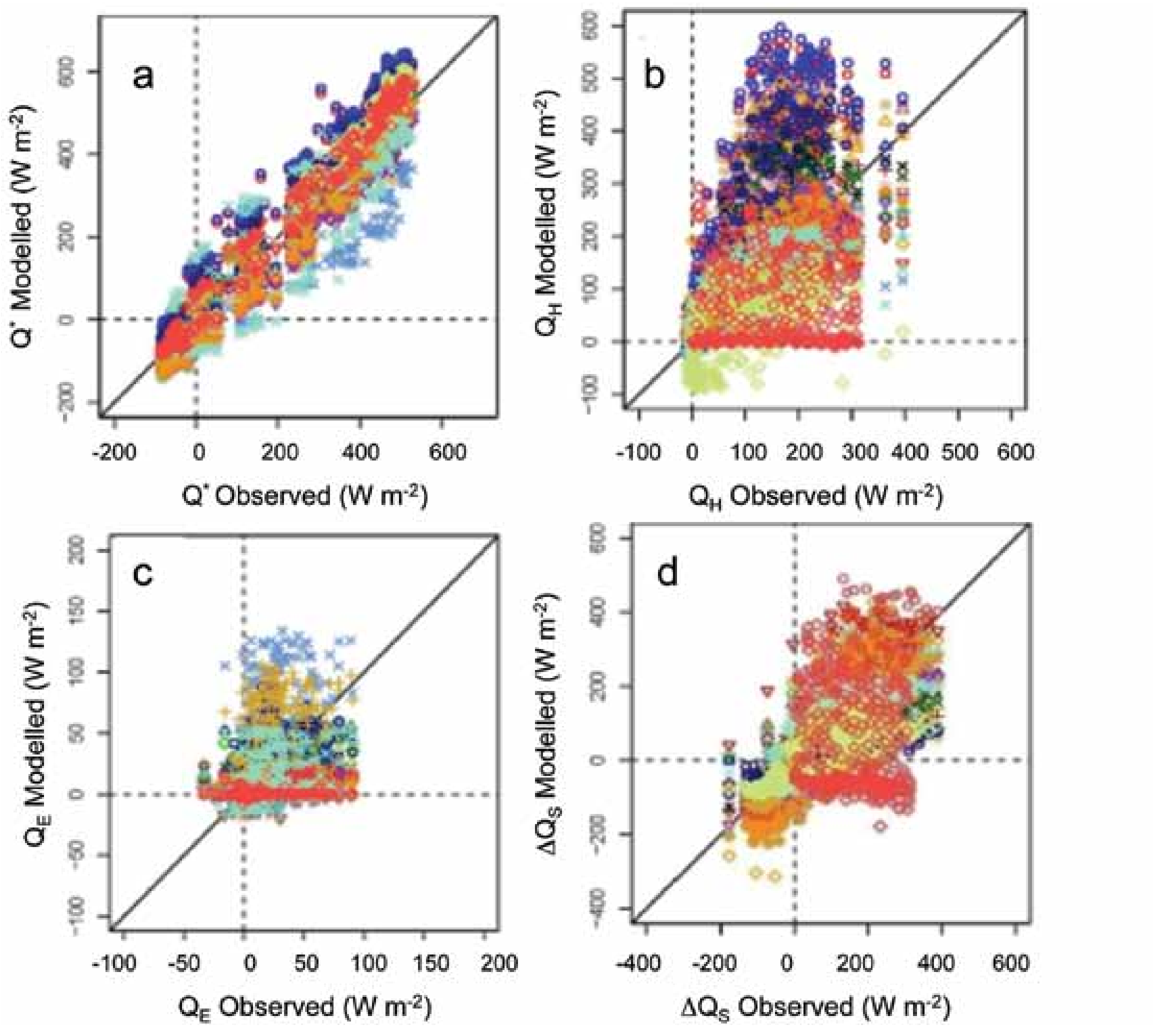


Figure 3.1
Scatter plots of modelled (27 models) against observed fluxes for the VL92 dataset. a. Net all wave radiation, b. turbulent sensible heat flux, c. turbulent latent heat flux, and d. net storage heat flux (Newsletter June 2008, PILPS urban project).

All models were ranked based on the root mean square error[9] (RMSE). The result is shown in Figure 3.2. For Q^* and Q_H there is a step change in the performance. This step change in the model performance is not so obvious for the latent heat flux or the heat storage flux. The models that perform least well for one of the fluxes are not necessarily those that perform the least well for the other fluxes. The models with the greatest errors in Q^* use multiple reflections (but not infinite) and facet albedos. However, it is not clear whether or not that is the reason for their poor performance because other models with these classifications have much better performances.

9 The root mean square error is a frequently-used measure of the differences between values predicted by the model and the values actually being observed. The smaller the root mean square error, the better the model performance.

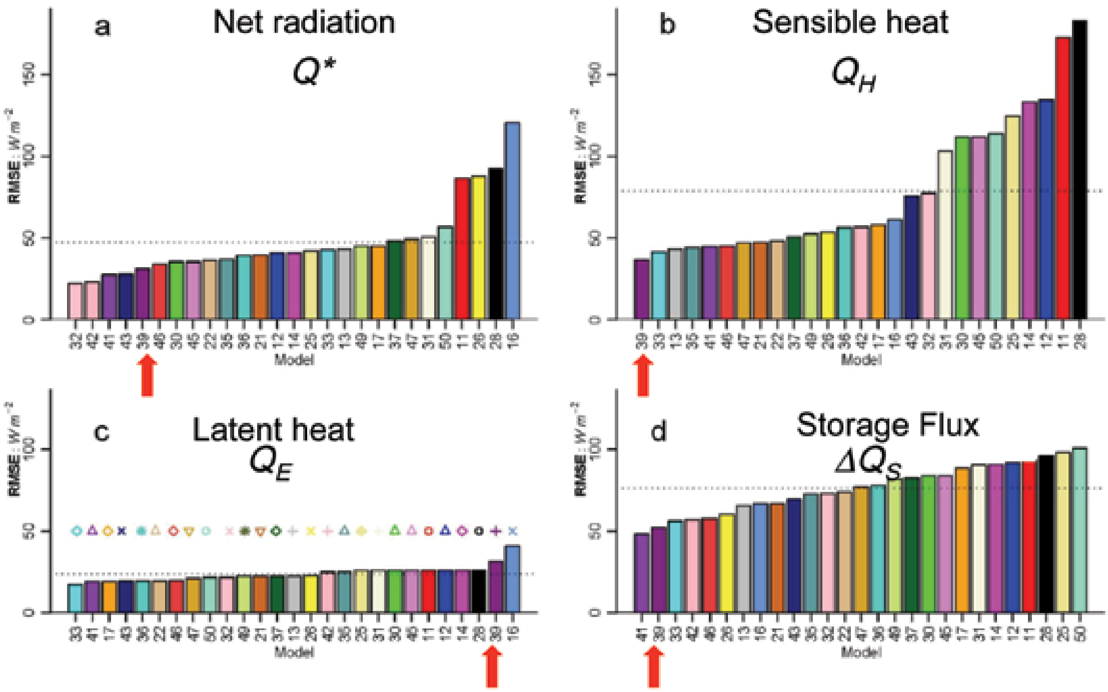


Figure 3.2
Root mean square error of the participating (anonymized) models in stage VL92 for net radiation (a), sensible (b), and latent heat flux (c) and heat storage flux (d). Note the model participating on behalf of COM29 is no. 39 (single layer model as implemented in WRF, designed by Kusaka et al, 2001).

There is no clear set of categories that explain the performance for the poorest models with respect to QH. It is likely that such performances are due to a combination of many factors. In general the models have a high correlation with both observed Q^* and Q_H, although the RMSE and standard deviation errors for Q_H have far more spread than for Q^*. This is expected because the radiation is the main driver for the surface energy balance.

In general, all types of models have consistent mean bias errors (MBE). The daytime MBEs are larger than the night-time MBEs, due to the larger absolute fluxes during daytime. Furthermore, Q_H has a positive bias for both daytime and night-time fluxes. In all cases, ΔQ_S opposes this with a negative bias in both daytime and night-time fluxes. Finally, Q^* is the closest to having no bias during the day, but has a negative bias during the night. In other words, all models tend to overestimate Q_H, which is balanced by underestimating ΔQ_S at all times of the day.

The simple models in each of the classifications do as well, if not better, than the more complex models for the daytime fluxes. However, no clear winner in terms of the level of complexity required was found for night time fluxes. This implies that for this limited dataset, including more complexity into the surface energy balance is not a priori beneficial for modelling the surface fluxes. This may be due to the reduced parameter requirements from the simpler schemes. In addition, this result suggests that the simpler schemes are capturing the dominant physical processes, at least in the PILPS URBAN test simulations.

The exception to the aforementioned general finding is that excluding vegetation gives larger MBEs and RMSE for both daytime and night-time periods than including vegetation. This is true even for this site with minimal evaporation and vegetation cover. Including vegetation appeared to be more important than the precise method that is used to model the vegetation in the urban environment.

Using an internal building temperature to represent the anthropogenic heat flux gives the largest MBEs and RMSEs for the daytime fluxes, and even larger than neglecting the anthropogenic heat flux all together. However, for the night-time fluxes, the internal building temperature method gives the smallest MBEs and RMSEs. But even in this situation, not including the anthropogenic heat flux leads to equally good performances as the other methods.

For the daytime results, the basic slab models tend to have the smallest errors, with the single layer models having the largest errors. For the night time fluxes, the performance of all methods is about the same.

3.3 The performance of the UCMs of WRF and RAMS

The (offline) performance of NSLUCM-WRF (no. 39) is indicated with red arrows in Figure 3.2. For Q^*, Q_H and ΔQ_S its mean RMSE is lower than the median values calculated for all models. However, for Q_E the RMSE of NSLUCM-WRF is higher than the median value. This is probably due to the fact that in the analysed PILPS URBAN phase vegetation was not yet accounted for in NSLUCM-WRF. This leads to a relatively low capability to model Q_E during daytime in particular, whereas the model has a relatively high reliability during night-time. This result regarding NSLUCM-WRF is consistent with the conclusion that it is important to include vegetation in the description of the urban SEB.

4 Simulations of WRF and RAMS for Rotterdam

In addition to the offline model evaluation in PILPS, a number of online model simulations has been performed in order to obtain a first impression of capabilities of NSLUCM-WRF and TEB-RAMS to simulate the urban environment in the Netherlands. Since parameters such as those related to characteristics of the built environment and anthropogenic sources are not known yet, the default settings of the models were used. The simulations were performed for the domain of Rotterdam, for the heat wave periods of 2003 and 2006.

4.1 Model simulations with WRF

The model simulations with WRF (version 3.0) has been carried out in a nested grid configuration (Fig. 4.1, A-C), consisting of three domains, zooming in from 25 km via an intermediate grid of 5 km to the finest resolution of 1 km. The simulations were carried out for 120 hrs time periods (time steps 180 sec) during the heat waves of 2003 and 2006. The selected periods were 4-9 August 2003 and 15-20 July 2006.

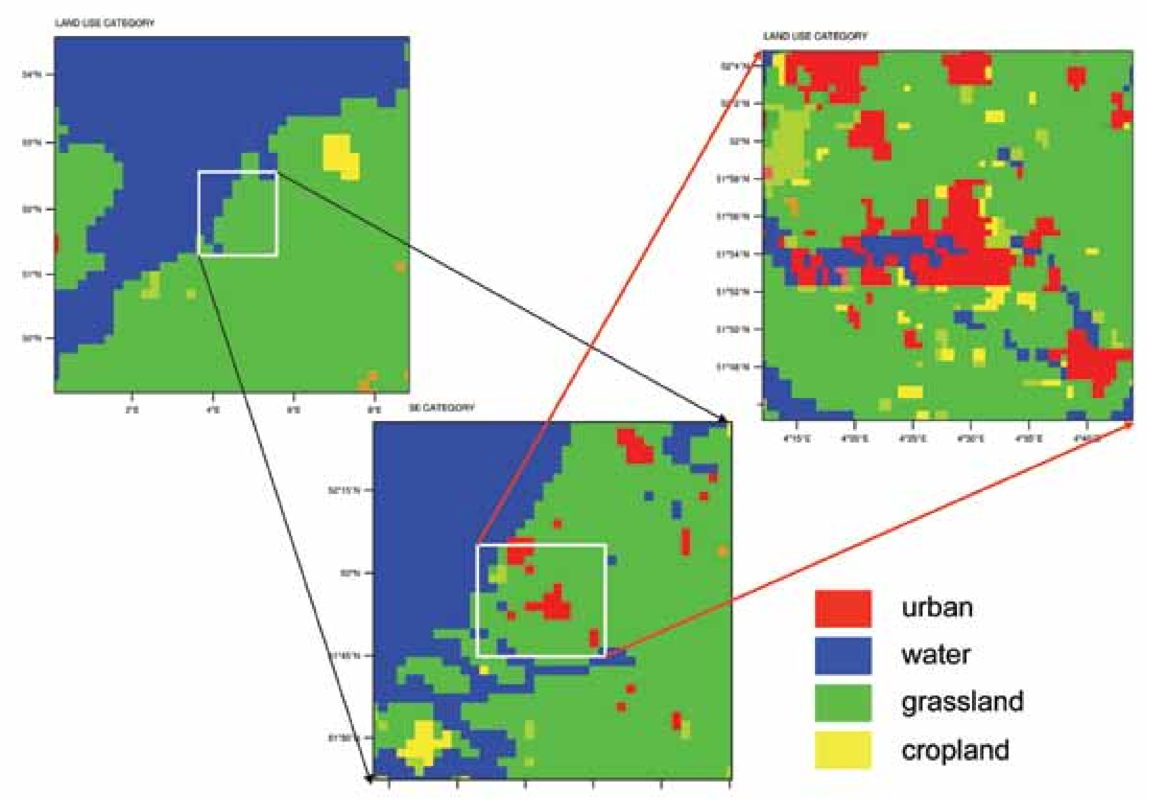


Figure. 4.1
The three domains used for the land use configurations, with the city of Rotterdam in the centre (51,9167 N; 4.4667 E). Resolution domain 1: 25 x 25 km (41 x 41 grid cells). Resolution domain 2: 5 x 5 km (41 x 41 grid cells). Resolution domain 3: 1 x 1 km (61 x 61 grid cells).

Heat wave 2003

Fig. 4.2 shows the simulated spatial distribution of air temperature for 5 August 2003. During day time the simulated air temperatures are only slightly higher (ca. 1 K) higher than in the rural area which is in accordance with meteorological observations. The simulated maximum air temperature (30 °C) is 0.2 °C lower than the observed maximum air temperature reported by airport Rotterdam suggesting that the model generates realistic results. The largest differences are found during the evening hours due to a slower cooling down of the urban areas.
Remarkably, figure 4.2 shows a cold plume on the leeward side of the urban areas at 19:00 UTC (e.g. Delft, Zoetermeer, Gouda). An explanation may be that the lower wind velocity causes a faster cooling down at the surface during sunset.

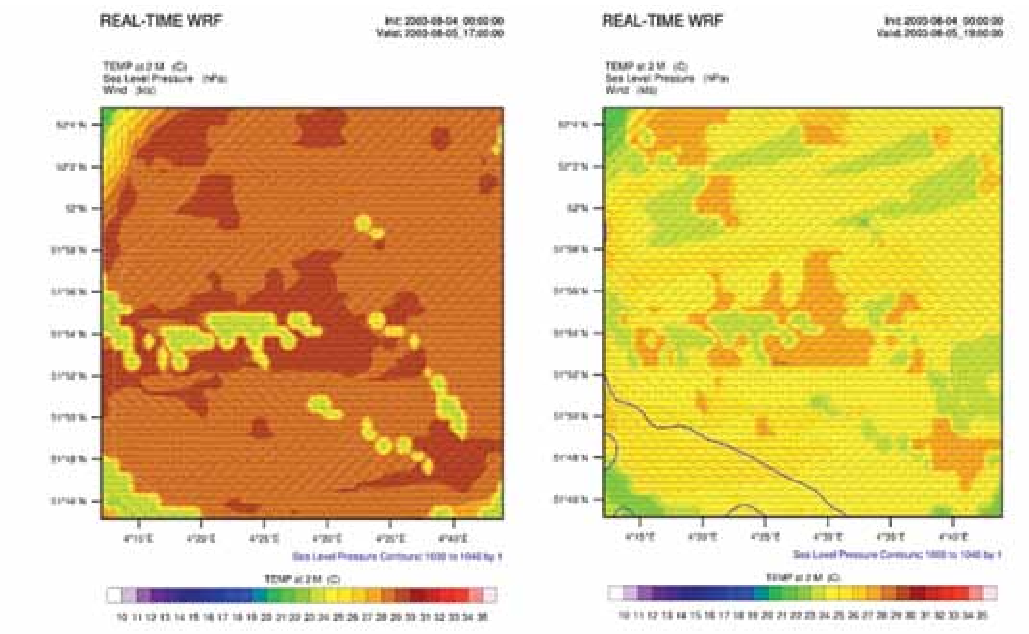


Figure 4.2
Modelled spatial distributions of air temperature at 2m, Sea Level Pressure (hPa), and wind velocity at 10 m for 5 August 2003, 17:00 (left panel) and 19:00 UTC (right panel).

Heat wave 2006

The river Maas intersects the city of Rotterdam. For a grid point north and a grid point south of the river, air temperature and relative humidity at 2 m, and wind velocity at 10 m height have been calculated. The result is shown in Figure 4.3. In addition, the calculated differences between the urban and rural area are shown (Fig. 4.3d-f). The model results for the heat wave period in 2006 are consistent with the ones for 2003. Again, the simulated air temperatures during daytime in the urban area are only slightly higher than in the rural area. The largest differences are found during night-time as result of a slower cooling of the urban area. Differences between the urban and rural area vary between 2 and 6 K, whereby the cooling of northern urban area is faster than that of southern one (Fig. 4.4 a and d). This result was confirmed by observations with the measuring network and mobile traverse measurements (see Chapter 6).

The simulation shows a very low relative humidity during daytime. The calculated relative humidity in the urban area is 10 to 30% lower than in the rural area, both during day and night-time. The modelling result suggests that the relative humidity in northern Rotterdam is higher than in southern Rotterdam. Wind velocities in the urban area are 1 1.5 m s^{-1} lower than in the rural area. The differences remain intact during night time, when wind speeds are lower. No differences in wind speed between north and south are found. The peak in the wind velocity during the night of 17 – 18 July (after 68 hours) can be explained by the passage of a sea wind front.

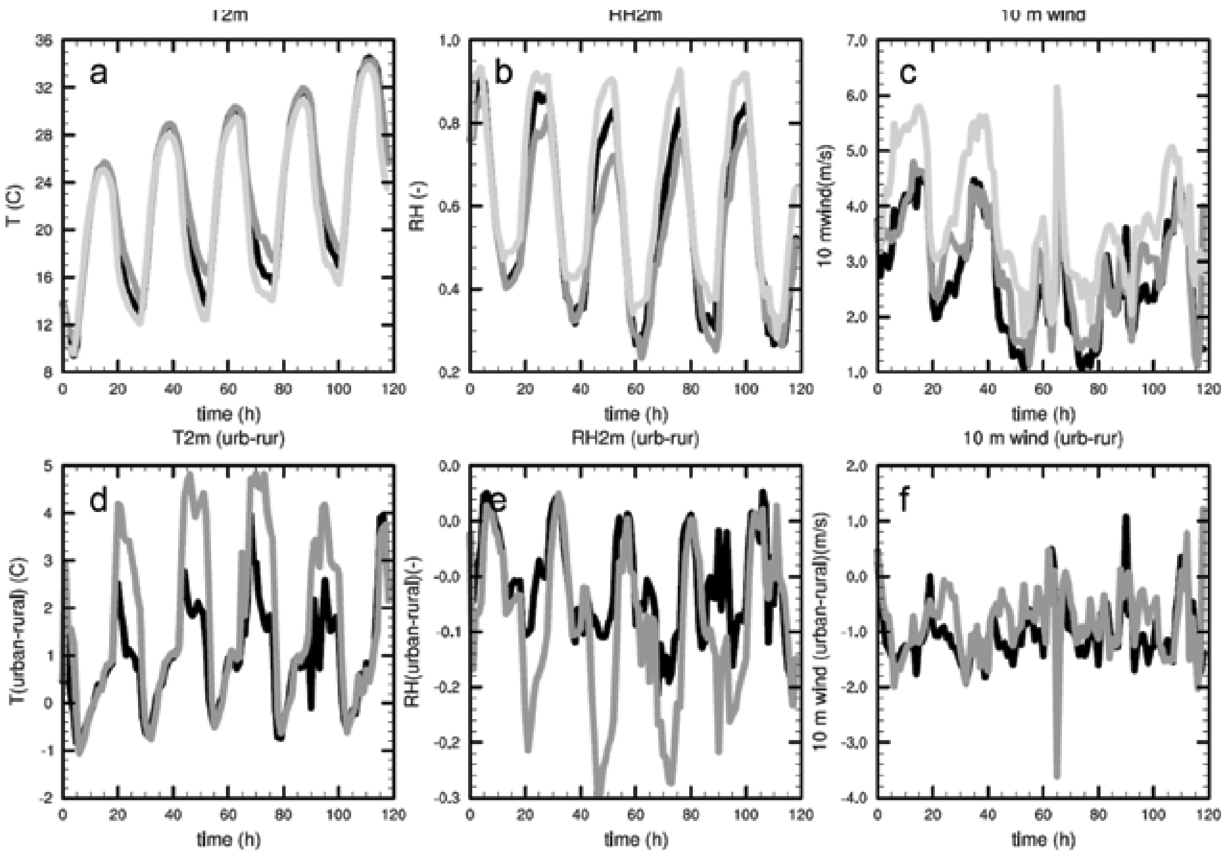


Figure 4.3
Modelled air temperature (a) and relative humidity (b) at a height of 2 m, wind speed at a height of 10 m (c), differences in air temperature (d), relative humidity (e) and wind velocity (f) between the urban and rural area, 15-20 July (start model simulation: 15 July 00:00 UTC). Black line: Rotterdam north (51 °56'; 4 °30'). Dark grey line: Rotterdam south (51 °53'; 4 °31'). Light grey line: rural area (51 °58'; 4 °40').

The spatial distributions of air temperature, sea level pressure and wind velocity are shown for two contrasting days. Fig. 4.4 depicts the results for 17 July, a day with a cooling sea-breeze circulation, while Fig. 4.5 shows the results for 19 July, when such a breeze was absent.

The large water bodies in the surroundings of Rotterdam are easily identifiable in Figure 4.4, because of their much lower temperatures (up to 8 K). The passage of a sea-breeze front (thick blue line in figure 4.4a) has a strong cooling effect (4-5K). Behind this front differences in air temperature between the urban and rural area vanish. At 19:00 hrs the area of Rotterdam is 2K warmer than the surrounding area.

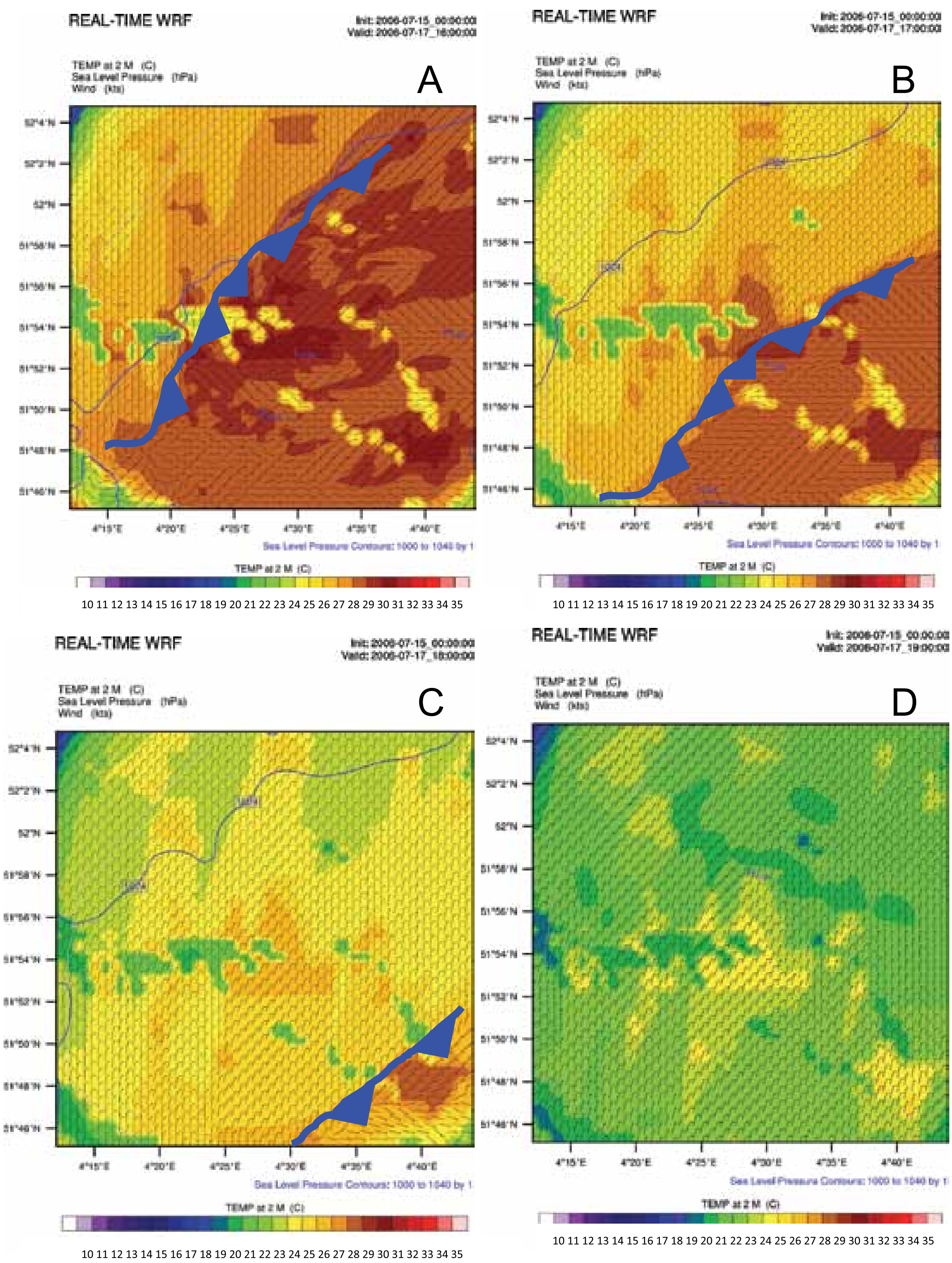


Figure 4.4
Modelled spatial distributions of air temperature at 2m, Sea Level Pressure (hPa), and wind velocity for 17 July 2006 at 16:00 (a), 17:00 (b), 18:00 (c), and 19:00 UTC (d). The thick blue line shows the position of the sea-breeze front.

The 19th of July was the hottest day during the heat wave of 2006. The calculated average air temperature in the urban area was 35 °C. During daytime differences in air temperature between the urban and rural area remain limited to several degrees. After sunset, a fast cooling of the rural area occurs whereas the urban area remains relatively warm. As a result, the difference in air temperature between the urban and rural area becomes 5 K.

At the downwind side of urban areas warm plumes can be seen at 21:00 UTC (fig. 4.5 right panel). It can be derived from this figure that the effect range of an urban area on its neighbouring rural area may be up to 10 km.

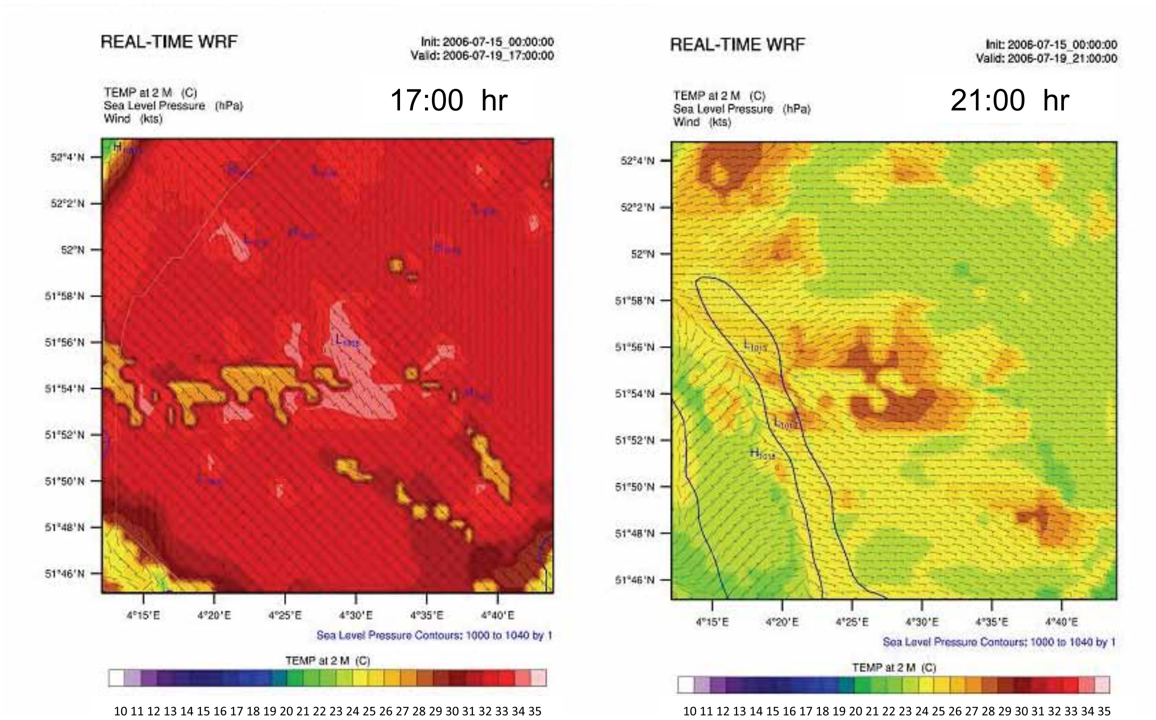


Figure 4.5
Modelled spatial distributions of air temperature at 2m, Sea Level Pressure (hPa), and wind velocity for 19 July 2006 at 17:00 (*left panel*) and 21:00 UTC (*right panel*).

4.2 Model simulations with RAMS

The model simulations with RAMS were performed with the most recent version of RAMS (v6.1a3, not yet released officially). The model system has been set up in a nested grid configuration zooming in from 18 km via an intermediate grid of 6 km to the finest resolution of 2 km.

The model has been run for two contrasting city configurations (City A vs. City B) describing the urban area of Rotterdam. Table 4.1 shows the parameters used for the simulations. City A is the default city in RAMS; it represents a high-rise concrete city with building heights up to 50 m. City B resembles the Canadian city of Vancouver; the parameters for TEB were derived from Masson et al. (2002).

Table 4.1
parameters for the two different cities used in the simulations.

Parameter	Value – City A	Value – City B
Geometric parameters		
• Building fraction	0.5	0.51
• Building height (m)	50	5.80
• Wall/plane aspect ratio	1.2	0.39
• Roughness length (m)	3.0	0.35
Radiative parameters		
• Roof albedo	0.15	0.12
• Wall albedo	0.25	0.50
• Road albedo	0.10	0.08
• Roof emissivity	0.90	0.92
• Wall emissivity	0.85	0.90
• Road emissivity	0.90	0.95

Simulations with the default city configuration

RAMS was run for the heat wave period between 15 and 20 July 2006, which corresponds to the second set of simulations with WRF. A first test has been performed to see whether RAMS is able to simulate an UHI effect. The 2m air temperature in a rural area in the neighbourhood of Rotterdam has been compared with the air temperature within the city limits of Rotterdam. This test has been performed with the default settings of the model (city A).

Relatively small differences between urban and rural air temperatures are obtained with this model (Fig. 4.6). The differences are smaller than those modelled with WRF. The maximum UHI intensity is found in the early afternoon (ca. 15:00 GMT), after which it declines and becomes even negative after sunset. This is in contradiction with meteorological observations, showing small differences between urban and rural air temperatures during day time, whereas large differences are observed after sunset. So, both the magnitude of the UHI intensity and the diurnal UHI cycle generated by RAMS are not in line with observations. The reason for this is not clear yet and needs further analysis.

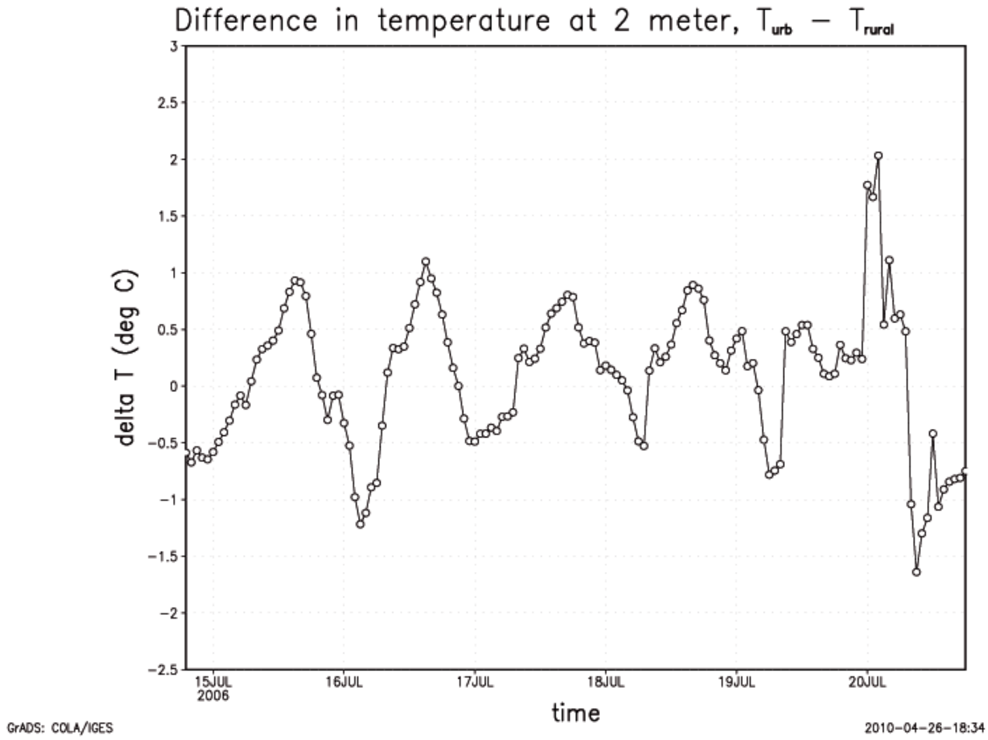


Figure 4.6
The calculated differences in simulated air temperature at 2 m between a grid cell in the city of Rotterdam and a grid cell 30 km northwest of Rotterdam .

Simulations with different city configurations

It was also examined whether the city configuration has an impact on the simulated spatial distribution of air temperature. If so, different city configurations can be tested for evaluation of adaptation measures, provided the aforementioned problem is solved. The comparison was made for the area around Rotterdam, depicted in Figure 4.7. The 'cooling'-effect of the city B configuration can be clearly seen in the panel showing the difference between city B temperature and city A temperature (dark blue areas). This effect is not only limited to the city area, but extends into the areas around the cities (light blue areas). Because the wind is from the east-southeast, this is to the north-northwest of the city.

So, simulations with both WRF and RAMS show a significant influence of urban areas on their neighbouring rural areas. This can be ascribed to an effect of the 'urban plume.' With RAMS it has been demonstrated that it is also possible to quantify the effect of a change in city configuration on both the magnitude of the UHI intensity and its influence on the neighbouring rural area.

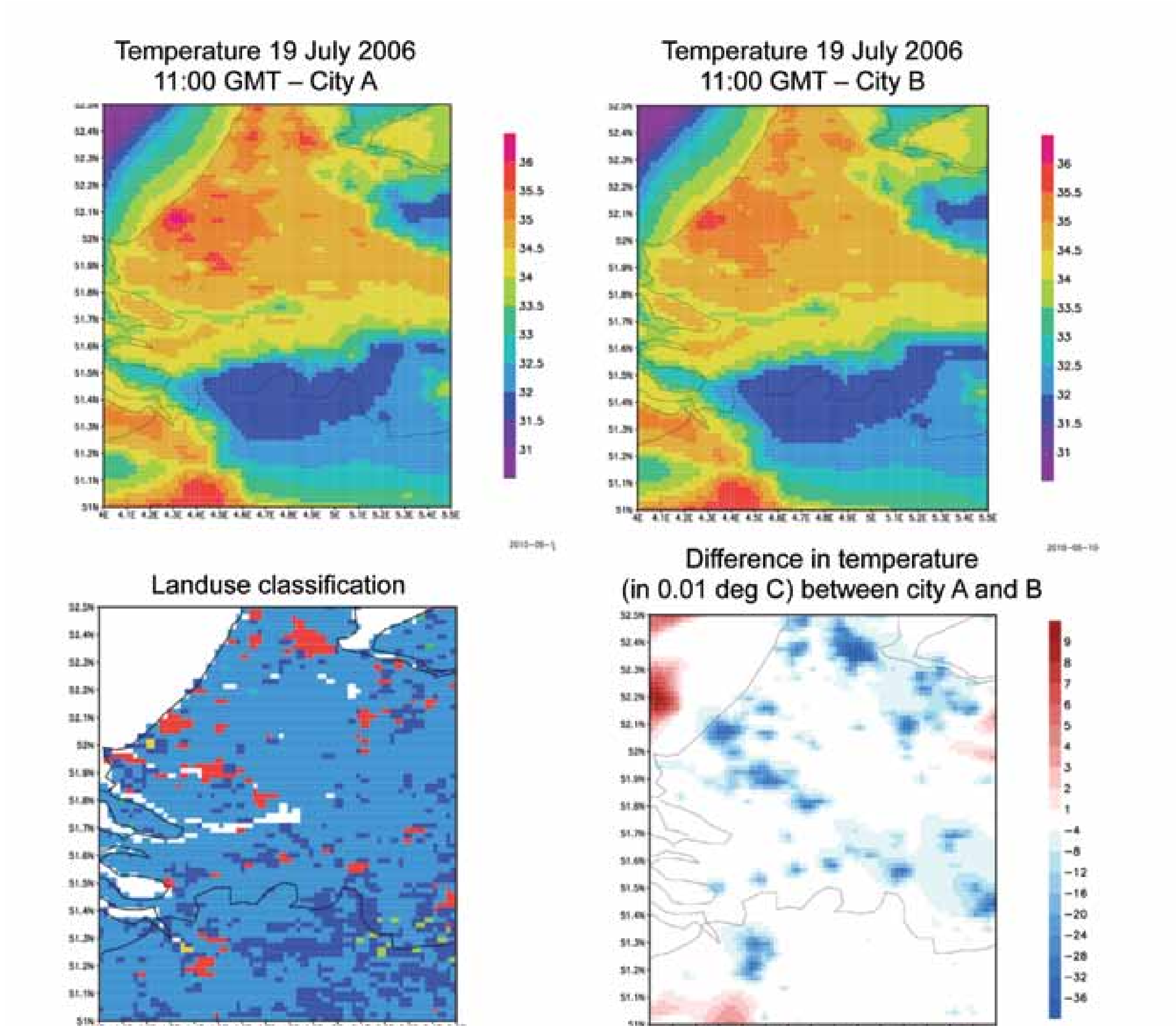


Figure 4.7
Upper panels: Modelled air temperature at 23 m high for the city A (left) and B configuration (right). Lower panels: Land use classification of the dominant land use type for the Rotterdam and surrounding area (left). Red: urban area, dark blue: grassland, light blue: irrigated arable land, white: inland waters & sea. Difference between City B temperature and City A temperature (=TB- TA). This is a snapshot taken at 19 July 2006 11:00 UTC.

5. Available data sets for model evaluation

With the exception of a study carried out in 1969-1970 on the UHI effect of the city Utrecht (Conrads, 1975), a study to assess the long-term validity of KNMI (Royal Netherlands Meteorological Institute) temperature time series (Brandsma et al. 2003), and some general heat wave mortality studies (Huynen *et al*., 2001), the urban climate has not been studied in the Netherlands. At present, no systematic meteorological data records for towns and cities are available yet. The weather forecasts issued for the Netherlands do not specifically address the weather in towns and cities. Therefore, an inventory was made of internationally available data sources. In addition, the possibility was examined to make use of alternative data sources in the Netherlands.

5.1 Internationally available datasets

Table 5.1 gives an overview of available observational datasets from measuring campaigns in cities in Europe and North America. The datasets not only contain information from standard meteorological observations, such as temperature, humidity and wind speed, but also from highly specialized observations, such as heat exchange. This combination makes these datasets quite useful as 'bench-mark' datasets in future research including model evaluation. Access to the datasets is usually obtained via close cooperation with the investigators.

5.2 Alternative data sources in the Netherlands

Dutch institutions like 'Rijkswaterstaat' (Directorate-General for Public Works and Water Management) and large municipalities are conducting meteorological observations that could be used in studies on the urban climate. Another interesting data source may be the meteorological observations by hobby meteorologists. The society of weather amateurs has about 800 members, of which a large number lives in urban areas. These amateurs have often been performing careful meteorological observations for several years, with quite advanced equipment that gives reliable results. This would imply that an enormous amount of data is ready to be exploited. The potential of these datasets are now being examined in the Region specific climate information project (HSHL05/HSRR04, KvK 1st phase).

Table 5.1
Examples of recent, large campaign-style urban climate studies

Location	Study	Characteristics	Reference	When
Basel, Switzerland	Basel Urban Boundary Layer experiment (BUBBLE), SARAH	ES, AP, S1, S2, S3, S4, RS2, RS3	Rotach et al. (2004)	2001-02
Marseille, France	ESCOMPTE/CLU-UBL	AP, S1, S2, S3, S4, S5, RS1, RS2, RS3	Cros et al. (2004) Mestayer et al. (2005)	2001
Mexico City, Mexico	IMADA-AVER Boundary layer experiment	NP, ES, AP, RS3, S4, S5	Doran et al. (1998)	1997
Nashville, USA	Southern Oxidant Study	AP, S4, S5, RS1, RS3	Cowling et al. (1998; 2000) Meagher et al. (1998)	1995, 1999
Oklahoma City, USA	Joint Urban 2003	NP, AP, S1, S2, S4, RS1, RS3	Allwine (2004)	2003
Paris, France	Atmospheric pollution over the Paris area (ESQUIF) field campaign	NP, AP, S3, S4, S5, RS1, RS3	Menut et al. (2000)	1998-99
Phoenix, USA	1998 Ozone field study	NP, ES, AP	Fast et al. (2000) Gaffney et al. (2002)	1998
Phoenix, USA	CAP-LTER	NP, ES, S1, S2, S3, S4, S5	Brazel et al. (2000)	1998
Phoenix, USA	2001 Phoenix Sunrise Experiment	ES, AP, S1, S5, RS1, RS3	Doran et al. (2003	2001
Salt Lake City, USA	VTMX/Urban 2000	AP, S1, S2, S4, S5, RS1, RS3	Allwine et al. (2002) Doran et al. (2002)	2000
Vancouver, Canada	Pacific '93	ES, AP, S4, S5, RS1, RS3	Steyn et al. (1997)	1993

NP – Network Present, ES – Earlier studies in the city, AP – Air pollution focus
S1 – Indoor or building or canyon scale, S2 – Neighborhood or local scale, S3 – multiple neighborhoods, S4 – urban area, S5 – Region
RS1 – aircraft, RS2 – satellite, RS3 – lidar and/or sodar and/or radar

As part of this project we investigated the potential of the data from hobby meteorologists for 19 urban sites in the Netherlands. The urban stations have been selected based on the available record length and on city size, with the intention to cover the range of large cities (10^6 inhabitants) to small villages (103 inhabitants). The urban cover ranges from 35-90%. The available data sets contain air temperature, humidity and wind speed. For some stations incoming solar radiation is available as well Most instruments are located in gardens and are well ventilated and shielded. (Steeneveld et al. 2010).

Fig. 5.1 displays the location were reliable long-term datasets from hobby meteorologists could be obtained so far. It can be seen that the observations cover the northern part of the country rather well, but long-term observations are lacking in the south. On the other hand the majority of the largest cities in the western part (i.e. Rotterdam, Delft, The Hague and its suburbs, Leiden and Haarlem) are represented in the datasets.

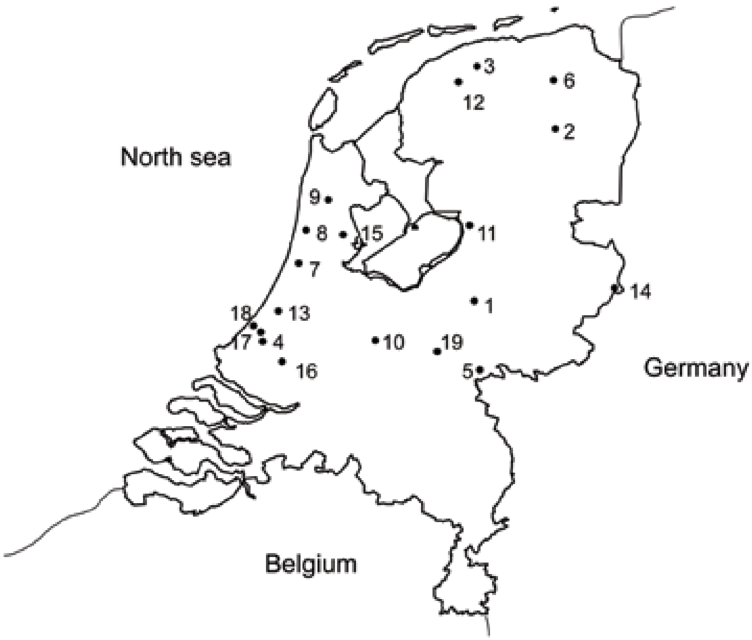


Figure 5.1
Locations with available observations

We analysed the data focusing on the determination of the largest UHI effect during a diurnal cycle (UHI_{max}), and the statistical distribution of this maximum daily UHI value. In order to detect the UHI, each urban station has been coupled to meteorological observations at the closest KNMI weather station. The UHI has been determined as the city air temperature minus the rural air temperature at screen level, and has been recorded based on hourly data (Steeneveld et al., 2010).

Table 5.2 shows the median values and the 95 percentile values of the UHImax in a diurnal cycle for the settlements. Large median and 95 percentile UHI_{max} values are obtained for Rotterdam despite its location close to the coast. However, it should be noted that also for a small, more inland located settlement as Losser, relatively large median and 95P UHI_{max} values are obtained.

Table 5.2
Median and 95 percentile (95P) values for the maximum urban heat island intensity (UHImax) in a diurnal cycle.

	City	Number of inhabitants (x1000)	UCZ[1]	UHI_{max}	
				median	95P
1	Apeldoorn	160	5	2.9	6.2
2	Assen	65	3	1.8	4.0
3	Damwoude	5.5	5-7	1.3	3.2
4	Delft	97	2-3	1.7	4.8
5	Doornenburg	2.7	5	2.6	5.7
6	Groningen	198	3	1.5	3.1
7	Haarlem	149	3	2.5	5.7
8	Heemskerk	39	3	2.8	5.9
9	Heerhugowaard	50	3-5	2.4	6.2
10	Houten	47	3	1.2	3.0
11	Ijsselmuiden	12	3	3.1	6.8
12	Leeuwarden	94	3-5	1.1	3.0
13	Leiden	117	3	3.2	5.6
14	Losser	23	3-5	2.9	6.8
15	Purmerend	79	3	2.5	4.6
16	Rotterdam	588	2-3	3.4	9.8
17	The Hague	483	3-5	2.2	5.3
18	Voorburg	40	2	2.4	5.6
19	Wageningen	35	3-5	2.4	5.6

UCZ – Urban Climate Zone (Oke, 2006): 2: intensely developed high density urban with 2 – 5 storey, 3: highly developed, medium density, 5: medium developed, low density, 7: semi-rural development with scattered houses

Note that the UHI_{max} values observed for Rotterdam are larger than the modelled differences with WRF. However, this may be partly due to the fact that the modelled temperatures were no single point results, but grid average values.

In addition, we estimated the wet bulb globe temperature (WBGT) that is used as a thermal comfort or heat stress index (Budd, 2008). For the general public, a WBGT < 27.7 represent conditions without heat stress. For 27.7 <WBGT < 32.2 the heat stress increases, and once WBGT > 32.2 the heat stress can become dangerous. WBGT>31 usually results in cancellation of major public events. Physical training is not advised for WBGT > 29.4.

Table 5.3 shows that in 7 out of the 18 cities the threshold for extreme heat stress is exceeded for the 98 percentile. In other words: 39% of the cities under investigation experiences extreme heat stress for ~7 days a year (Steeneveld et al., 2010).

Table 5.3
Median, 95 and 98 percentile values for the Wet Bulb Globe Temperature (WBGT) as an indicator of heat stress. Bold, exceeding the threshold WBGT value of 27.7 °C.

	City	Number of inhabitants (x1000)	UCZ	WBGT		
				median	95P	98P
1	Apeldoorn	160	5	14.5	24.4	25.1
2	Assen	65	3	15.8	25.0	26.4
3	Damwoude	5.5	5-7	16.0	25.2	26.9
4	Delft	97	2-3	16.6	25.2	27.5
5	Doornenburg	2.7	5	10.5	14.3	15.2
6	Groningen	198	3	16.2	26.4	**28.7**
7	Haarlem	149	3	-	-	-
8	Heemskerk	39	3	13.7	21.3	24.1
9	Heerhugowaard	50	3-5	16.6	25.6	**27.8**
10	Houten	47	3	12.8	20.8	23.0
11	Ijsselmuiden	12	3	16.6	25.4	**27.8**
12	Leeuwarden	94	3-5	15.8	24.1	26.0
13	Leiden	117	3	18.5	26.6	**28.2**
14	Losser	23	3-5	16.3	26.2	**28.0**
15	Purmerend	79	3	14.0	23.2	24.8
16	Rotterdam	588	2-3	15.1	29.7	**32.3**
17	The Hague	483	3-5	16.0	25.3	26.9
18	Voorburg	40	2	17.5	25.8	**28.5**
19	Wageningen	35	3-5	17.6	25.6	27.6

6. Observing the urban climate system

Detailed observations are required in order to unravel the complex interactions between meteorological processes, urban configurations and geometries, and anthropogenic activities. Moreover, such data are essential to support model development and evaluation, to ensure realistic simulations. However, because of the large heterogeneity of the urban landscape and the influence of waste heat and water vapour from human activities, it will be a challenging task to obtain representative observations. Therefore, much attention has been paid to the development of a measurement strategy. As an illustration, our experiences with measurements in the framework of the 'Heat stress in the city of Rotterdam' project are discussed.

6.1 Urban scales

Urban climate phenomena play on various spatial scales, from mesoscale to human scale. Three horizontal scales and related vertical scales can be distinguished (Fig. 6.1):

1. *Microscale or street canyon scale*
   Typical scales of urban microclimates relate to the dimensions of individual buildings, trees, roads, streets, courtyards, gardens, etc.
   The dimensions extend from less than one meters to hundreds of meters.
2. *Local scale or neighbourhood scale*
   It includes landscape features such as topography but excludes microscale effects. In urban areas this translates to a mean climate of neighbourhoods with similar types of urban development (surface cover, size and spacing of buildings, activity).
3. *Mesoscale or city scale*
   The city elements in the microscale are affected by phenomena at the local scale. In their turn, the phenomena at the local scale or neighbourhood scale are affected by the conditions and interactions the mesoscale.

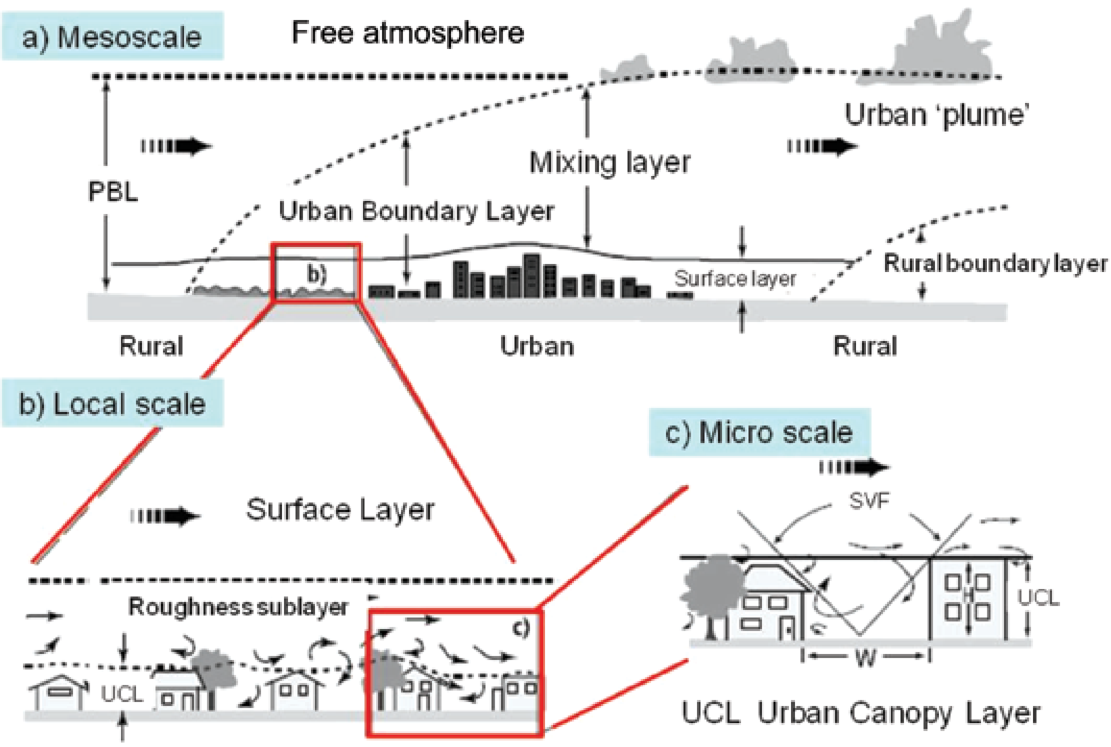


Figure 6.1
Three scales used to distinguish atmospheric processes in urban area and the atmospheric layers which are typically identified at each scale. PBL the planetary boundary layer, UBL the urban boundary layer, UCL urban canopy layer. The bold arrow in each of the sub-figures going towards the right indicates the mean wind direction. The smaller arrows shown in (b) and (c) indicate the nature of the mean and turbulent flow (figure modified after Oke 1997).

So, roughly speaking, atmospheric urban heat islands can be divided into two types of heat islands:

- Urban canopy layer (UCL) heat island, i.e. in the layer of air where people live, from the ground to below the tops of trees and roofs
- Urban Boundary Layer (UBL) heat island, that start from the rooftop and treetop level and extend up to the point where urban landscapes no longer influence the atmosphere. This region typically extends to a maximum of 1.5 km from the surface.

The UCL heat islands are the most commonly observed of the two types and are often referred to in discussions of UHIs.

6.2 Measurement strategy

To obtain meaningful observations, it is essential to clearly establish the objectives of the observations (measurement rationale). In connection with this, it is necessary to pay careful attention to urban scale and related issues. Recognition of scale differences and their regimes is a central key to the design of meaningful field observations. Table 6.1 presents the issues and the observational approaches related to these scales.

A distinction can be made between:

1. Observations in the Urban Canopy Layer (UCL)
2. Observations in the Urban Boundary Layer (UBL)

The observations in the UCL provide insight into the dependence of the microclimate on street and city quarter characteristics. The observations can be related to the orientation of buildings, building density and height, properties of materials used for building facades and pavements (emissivity, albedo), and the presence of open water and vegetation, including green roofs. Also the results may be related to indoor climate of buildings, and to indicators for thermal comfort and heat stress (PET, WBG, PMV[10]). In addition, the observations in the UCL can be used as reference for verification of results obtained with remote sensing techniques (e.g. satellite and airborne observations) and models for the microscale environment. These techniques are increasingly being used to characterize the Urban Heat Island (UHI), as well as the urban surface and its influences on the UBL (e.g. precipitation).

With the observations in the UBL, valuable information on the urban surface energy balance (SEB) can be obtained (see Chapter 2). It is important to know the magnitude and behaviour of the individual components of the SEB for urban areas. This information is required to get a proper description and analysis of the behaviour of the urban heat island. This behaviour differs greatly between cities. However, measurements of the SEB components are also important for validation of mesoscale as well as microscale models. Output of the mesoscale model can be used to constrain the boundary conditions of a micro climate model. In addition, the SEB measurements give valuable information with respect to the urban water balance, since the water balance is connected to the SEB by the evaporation flux.

10 PET – Physiologically Effective Temperature; WBGT – Wet Bulb Globe Temperature; PMV - Predicted Mean Vote

Table 6.1
Issues and observations at the different urban scales

Administration level	Planning level	Issues	Scale	Approaches
City (+ surrounding) 1 : 25,000	Urban development	• Heterogeneity UHI intensity • Interaction urban area-region • Interactions between city quarters (internal circulation patterns) • City typology and morphology • Urban Surface Energy Balance (SEB) and water balance • Vertical structure UBL • Regional weather prediction	Meso UBL	• Satellite • Airborne
Neighbourhood/ city quarter 1 : 5,000	Urban fabric system	• Impact built environment • Impact urban green and open water • Air pollution • Urban SEB and water balance	Meso UCL + USL	• Satellite • Airborne • Meteorological tower • Scintillometers, sodar, lidar • Mobile traverse measurements
Building blocks and streets 1 : 2,000	Open space design	• Micro climate • Thermal comfort • Human health	Micro UCL	• Continuous *in situ* measurements • Mobile traverse measurements
Building 1 : 500	Building design	• Outdoor ↔ indoor climate • Building envelope • Exchanges of energy between interior of buildings and outdoor atmosphere	Micro UCL	• Indoor measurements in combination with outdoor measurements

It can be concluded that systematic observations of the urban meteorological and climatic conditions should comprise a set of complementary observations. The observations should enable detection of temporal as well as spatial variations of the meteorological conditions in the urban canopy. To that end, long-term meteorological observations at fixed positions can be combined with campaign-based observations at high spatial resolution. For model parameterisation and validation, not only routine measurements should be performed, but also specialized observations of, for example, heat and radiation fluxes in and above the UCL as well as observations of the structure of the UBL. Satellite imagery and other remote sensing techniques can give valuable additional information with high spatial resolution. Such information can also be used to determine optimal locations for observations within the UCL.

6.3 The ‘case study’ Rotterdam

The above measurement strategy has been applied for the first time in the Hotspot Heat Stress Rotterdam project[11] of the Knowledge for Climate Programme. The main objectives of the project are to:

1. assess the extent and possible consequences of the actual and future heat stress (1st phase of the project);
2. explore the possibilities to reduce the heat stress (2nd phase)

To cover detection of temporal as well as spatial variations of the meteorological conditions in the urban canopy, both long-term meteorological observations at fixed positions and campaign-based observations at high spatial resolution are carried out. Furthermore, satellite imagery and airborne measurements have been used to make a first, preliminary assessment of the spatial extent of the UHI. From thermal infrared images, urban surface temperatures have been retrieved and the Surface Heat Island (SHI) intensity as well as the urban areas most vulnerable to heat have been identified. The results were used to find the locations for the *in situ* measurements and to plan the routes for the mobile traverse measurements through the city (Fig. 6.2).
In reverse, the *in-situ* observations and mobile traverse measurements can be used as ground truth for satellite-derived surface temperatures and to rate the value of thermal infrared imagery as an indicator for the UHI effect.

Because the results are also used for model parameterisation and validation, numerical modellers are involved throughout the duration of the project.

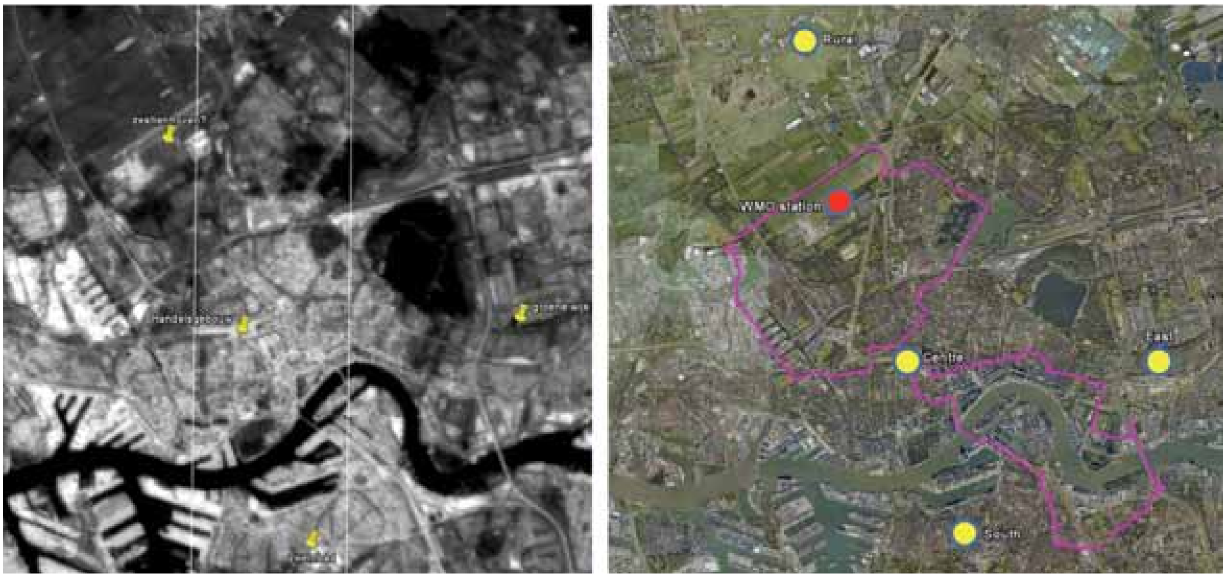


Figure 6.2
Landsat thermal image during daytime (left panel), location of the WMO station Rotterdam-Haaglanden Airport (red point), locations of the automatic weather stations (AWS) of the measuring network (yellow points), and routes of the mobile traverse measurements in the city of Rotterdam (right panel). The mobile traverse observations were carried out during four 2 h time intervals. It is assumed that during 2h time interval the weather conditions are constant. Starting in the city centre, the north and south route (each with a length of ca. 20 km) were measured simultaneously, using two cargo bicycles as a mobile platform (see also Fig. 6.3 and 6.4). During the resting hours comparison and calibration measurements were carried out.

11 Project HSRR05, 1st phase Knowledge for Climate, 2009-2010. Consortium partners in the project are: the municipality of Rotterdam (leading partner), TNO, WUR (MAQ, ESS-CC), Deltares, WaterWatch and Stichting Bouw Research (SBR).

The *in situ* measurements[12] are performed for a long-term period (> 1 year), for different locations. This allows sampling during a variety of weather conditions, that is, a high temporal resolution and coverage can be obtained. In addition, the influence of the surrounding built environment can be assessed. To be able to assess the impact on thermal comfort and heat stress, we measure air temperature and humidity, black globe temperature, wind velocity and direction, radiation (all components), and precipitation.
Furthermore, temperatures in and above open water are measured by the institute Deltares using the fiber optic Distributed Temperature Sensing (DTS) method.

Figure 6.3
Reference automatic weather station in the rural area north of Rotterdam (left) and in the city centre (right).

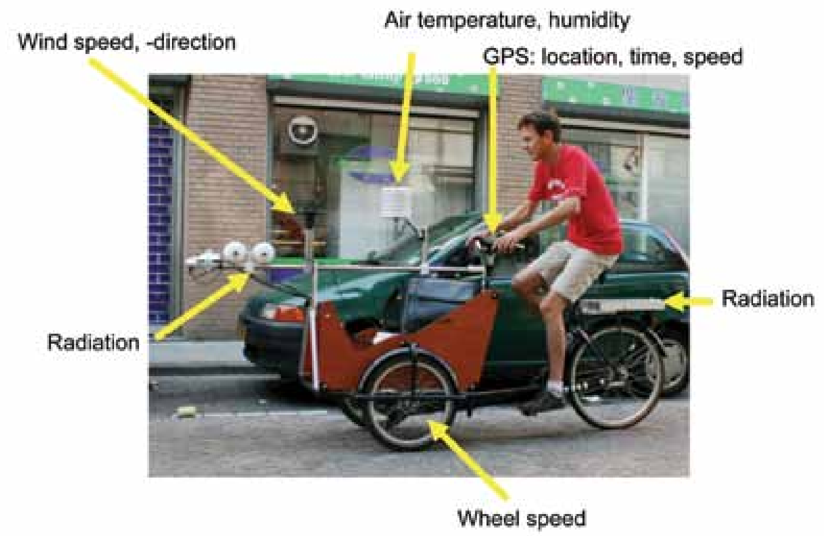


Figure 6.4
Traverse measurements were performed in the city using two cargo bicycles as a mobile platform, equipped specifically for urban meteorology measurements. The cargo bicycles allow manoeuvring easily through the narrow streets in the city. They are equipped with a thermometer, a humidity sensor, a 2-dimensional sonic anemometer and a set of radiation sensors to measure solar radiation and infrared radiation exchange from six directions. The data are recorded at 1 Hz, and connected with concurrent readings from a GPS device. The instruments are powered by a solar panel mounted on the baggage carrier (photo: Bert Heusinkveld).

12 The observations are available on line (http://www.climatexchange.nl/sites/rotterdam/index.htm)

With the traverse mobile measurements, a higher spatial resolution can be obtained. The magnitude and range of effect (footprint) of typical street and city quarter characteristics on meteorological conditions in the UC, can be assessed, notably of:

a. Sky View Factor, Aspect Ratio (building-height-to-street-width ratio), orientation of streets and buildings, and properties of facades and pavements (albedo, emissivity);
b. Open water (ponds, canals, fountains) and vegetation (parks, tree shelters and green roofs).

The observations in the UBL are performed by combining large aperture scintillometry, and airborne measurements. Scintillometry has been shown to be an effective new tool for the measurement of spatially averaged turbulent fluxes over both homogenous and heterogeneous surfaces. With the airborne measurements, the spatial heterogeneity of surface fluxes can be assessed. These measurements also give information about the structure of the UBL from which the surface exchange of momentum, heat, water vapour, CO2 and reactive species in the urban environment can be studied in support of model development. Also characteristics of the urban districts can be determined, such as urban surface temperatures, land cover fractions and overall albedo.

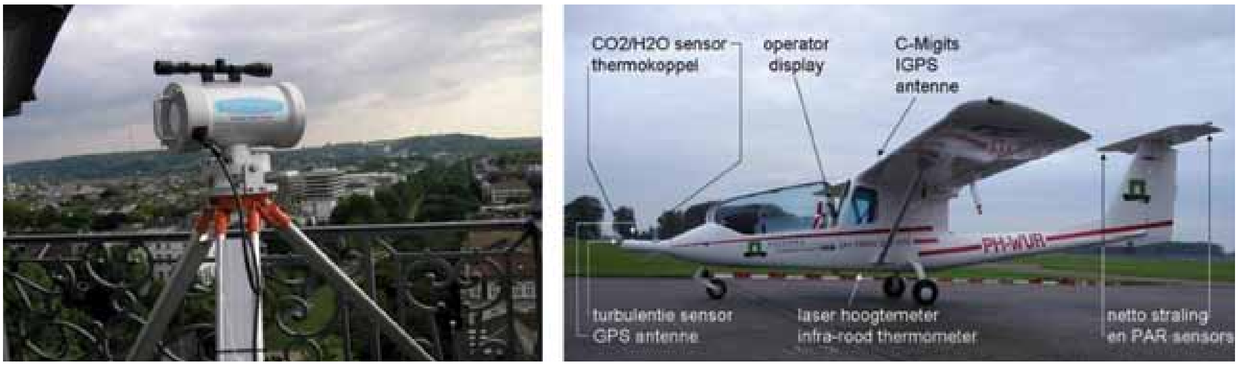


Figure 6.5
Scintillometry and air borne measurements for observations in the UBL

7. Conclusions and recommendations

Conclusions:

- Many different urban canopy models have been developed. These models vary in complexity from simple schemes that represent the city as a concrete slab, to those which incorporate detailed representations of momentum and energy fluxes distributed within the atmospheric boundary layer.
- Results from the international PILPS project shows that generally the models perform well with respect to net radiation and worse with respect to evapotranspiration (order net radiation, storage in the UCL, sensible heat flux, latent heat flux). No model performs best or worst for all fluxes. Relatively simple models may perform equally well or better as very detailed models.
- Different results for the diurnal variation and maximum value for UHI intensity are obtained with the non calibrated UCM versions of WRF and RAMS. Comparison of the grid-box-averaged temperatures with local observations suggests that both models tend to underestimate the actual average UHI effect. In the case of RAMS the timing of the UHI clearly needs improvement.
- Both modelling studies show a significant influence of urban areas on their neighbouring rural areas (the effect of the urban plume). With RAMS it has been demonstrated that it is possible to quantify the effect of a change in city configuration on both the magnitude of the UHI intensity and its influence on the neighbouring rural area.
- At present, no systematic meteorological data records for towns and cities in the Netherlands are available yet. Datasets provided by hobby meteorologists may be a valuable alternative data source.
- A preliminary analysis of the data from hobby meteorologists obtained in 19 towns and cities in the Netherlands shows that the UHI is clearly present in the Netherlands as well. The UHImax ranges from 3 to 10 °C. Seven of the examined cities experience strong heat stress for ~7 days a year under the present climatic conditions.
- Because of the large heterogeneity of the urban landscape and the influence of anthropogenic heat, it will be a challenging task to obtain meaningful observations. Recognition of scale differences in cities and related issues is a central key to the design of meaningful field observations.

Recommendations:

- An important step which has to be considered is what parameter values represent the city configuration. Next to that the question has to be answered how the various city areas should be represented in the model: high-rise buildings in the city centre versus greener areas in the suburbs. One suggestion is to split the urban areas in separate classes if the configuration and structure of a city is known.
- Systematic observations of the urban meteorological and climatological conditions should be based on a set of complementary observations, covering detection of temporal as well as spatial variations of the meteorological conditions in the urban canopy.
- Special attention should be paid to improve model performance with respect to the latent heat flux.
- For model parameterisation and validation, not only routine measurements should be performed, but also specialized observations of, for example, heat and radiative fluxes in and above the UCL as well as observations of the structure of the UBL.

8. References

1. Allwine, K.J, M.J. Leach, L.W. Stockham, J.S. Shinn, R.P. Hosker, J.F.Bowers & J.C. Pace, 2004: Overview of Joint Urban 2003 — an atmospheric dispersion study in Oklahoma City, *Symposium on planning, Nowcasting and Forecasting in the Urban Zone*, Amer. Meteor. Soc.,Seattle. http://ams.confex.com/ams/84Annual/techprogram/paper_74349.htm

2. Basara, J., P.K. Hall, A. Schroeder, B.G. Illston, and K. L. Nemunaitis, 2008: Diurnal cycle of the Oklahoma urban heat island. *J. Geophys*. Res., **113**, D20109.

3. Best M.J. 2005. Representing urban areas within operational numerical weather prediction models. *Bound-Layer Meteor.* **114**, 91-109.

4. Biltoft, C.A., E. Yee & C.D. Jones, 2003: Overview of the mock urban setting test (MUST). http://ams.confex.com/ams/pdfpapers/36654.pdf

5. Brandsma, T., Können, G.P., Wessels, H.R.A. (2003). Empirical estimation of the effect of urban heat advection on the temperature series of De Bilt (The Netherlands), *Int. J. Clim*., **23**, 829-845.

6. Brazel A, Selover N, Vose R, Heisler G (2000) The tale of two climates – Baltimore and Phoenix urban LTER sites. *Climate Research* **15**, 23–135.

7. Budd, G.M., 2008. Wet-bulf globe temperature (WBGT) – its history and its limitations. *Journal of Science and Medicine in Sport*, **11**, 20-32.

8. Cazenave, A., & Llovel, W. (2010). Contemporary Sea Level Rise. *Annu. Rev. Mar. Sci*. 2: 145-173.

9. Chen, T.H., A. Henderson-Sellers, P.C.D. Milly, A.J. Pitman, A.C.M. Beljaars, J. Polcher, F. Abramopoulos, A. Boone, S. Chang, F. Chen, Y. Dai, C.E. Desborough, R.E. Dickinson, L. Dümenil, M. Ek, J.R. Garratt, N.Gedney, Y.M. Gusev, J. Kim, R. Koster, E.A. Kowalczyk, K. Laval, J. Lean, D. Lettenmaier, X. Liang, J.-F. Mahfouf, H.-T. Mengelkamp, K. Mitchell, O.N. Nasonova, J. Noilhan, A. Robock, C. Rosenzweig, J. Schaake, C.A. Schlosser, J.-P. Schulz, Y. Shao, A.B. Shmakin, D.L. Verseghy, P. Wetzel, E.F. Wood, Y. Xue, Z.-L. Yang, Q. Zeng (1997). Cabauw Experimental Results from the Project for Intercomparison of Land-Surface Parameterization Schemes. *J. Clim*, **10**, 1194–1215.

10. Chen, F., Y. Liu, H. Kusaka, M. Tewari, J.W. Bao, C.F. Lo, & K.H. Lau,2004: Challenge of forecasting urban weather with NWP models.*14th MM5 users' workshop NCAR*, June 22-25.

11. Conrads, L.A. (1975). Observations of meteorological urban effects. The heat island of Utrecht. PhD thesis University Utrecht. 84 pp.

12. Cotton, W. R., Pielke, R. A., Walko, R. L., Liston, G. E., Tremback, C. J., Jiang, H., McAnelly, R. L., Harrington, J. Y., Nicholls, M. E., Carrio, G. G., and McFadden, J. P.: RAMS 2001: Current status and future directions, *Meteor Atmos Phys*, **82**, 5-29.

13. Cowling EB, Chameides WL, Kiang CS, Fehsenfeld FC, Meagher JF (1998) Introduction to special section: Southern Oxidants Study Nashville=Middle Tennessee Ozone Study. *J Geophys Res-Atmospheres* **103**: 22209–22212

14. Cowling EB, Chameides WL, Kiang CS, Fehsenfeld FC, Meagher JF (2000) Introduction to special section: Southern Oxidants Study Nashville=Middle Tennessee Ozone Study, Part 2. *J Geophys Res-Atmospheres* **105**: 9075–9078

15. Cros, B., P. Durand, H. Cachier, Ph. Drobinski, E. Fréjafon, C. Kottmeier, P. E. Perros, V. -H. Peuch, J. -L. Ponche, D. Robin, F. Saïd, G. Toupance, & H. Wortham, 2004: The ESCOMPTE program: an overview. *Atmos. Res*. **69** (3-4), 241-279.

16. Dandou, A., M. Tombrou, E. Akylas, N. Soulakellis, & E. Bossioli, 2005. Development and evaluation of an urban parameterization scheme in the Penn State/NCAR Mesoscale Model (MM5), *J. Geophys. Res*., **110**, D10102, doi:10.1029/2004JD005192.

17. Doran J.C., S. Abbott , J.Archuleta , X. Bian, J.Chow , R.L. Coulter , S.F. J. de Wekker, S. Edgerton,S. Elliott , A. Fernandez, J.D. Fast, J.M. Hubbe, C. King, D. Langley, J. Leach, J.T.Lee , T.J. Martin, D. Martinez , J.L. Martinez, G. Mercado, V. Mora, M. Mulhearn, J.L. Pena , R. Petty, W. Porch, C. Russell, R. Salas, J.D. Shannon, W.J. Shaw, G. Sosa, L. Tellier, B. Templeman , J.G. Watson, R. White, C.D. Whiteman, D. Wolfe D (1998) The IMADA-AVER boundary layer experiment in the Mexico City area. *Bull Amer Meteor Soc* **79**: 2497–2508.

18. Ek, M.B., K.E. Mitchell, Y. Lin, E. Rogers, P. Grunmann, V. Koren, G. Gayno & J.D. Tarpley, 2003, Implementation of the Noah land surface model advances in the National Centers for Environmental Prediction operational mesoscale Eta model, *J. Geophys. Res*., **108** (D22), 8851, doi:10.1029/2002JD003296, 2003.

19. Fast JD, Doran JC, Shaw WJ, Coulter RL, Martin TJ (2000). The evolution of the boundary layer and its effect on air chemistry in the Phoenix area. *J Geophys Res-Atmospheres* **105**: 22833–22848.

20. FitzGerald, D.M., M.S. Fenster, B.A. Argow and I.V. Buynevich (2008). Coastal Impacts Due to Sea-Level Rise. *Ann. Rev. Earth Planet. Sci.* 36: 601-647.

21. Gaffney JS, Marley NA, Drayton PJ, Doskey PV, Kotamarthi VR, Cunningham MM, Baird JC, Dintaman J, Hart HL (2002). Field observations of regional and urban impacts on NO2, ozone, UVB, and nitrate radical production rates in the Phoenix air basin. *Atmos Environ* 36: 825–833

22. Grimmond, C.S.B., H.A. Cleugh, & T.R. Oke, 1991: An objective urban heat storage model and its comparison with other schemes. *Atmos.Environ*., **25B**, 311-326.

23. Grimmond, S, M Blackett, M Best, with Baik J, Bohnenstengel S, Calmet I, Chemel C, Chen F, Dandou A, Fortuniak K, Gouvea M, Hamdi R, Kondo H, Krayenhoff S, Lee S, Loridan T, Martilli A, Masson V, Miao S, Oleson K, Pigeon G, Porson A, Salamanca F, Shashua-Bar L, Steeneveld G, Sugar L, Trombou M, Voogt J, Zhang N, 2009: The international urban energy balance comparison project: initial results from phase 2., 29 Jun-3 July 2009, 7th *International Conference on Urban Climate*, Yokohama, Japan.

24. Grimmond, C.S.B., M. Blackett, M. Best, J. Barlow, J.-J. Baik, S. Belcher, S.I. Bohnenstengel, I. Calmet, F. Chen, A. Dandou , K.Fortuniak, M. Gouvea, R. Hamdi, M. Hendry, H. Kondo, S. Krayenhoff, S.-H. Lee , T. Loridan, A. Martilli, V. Masson, S. Miao, K. Oleson, G. Pigeon, A. Porson, F. Salamanca, L. Shashua-Bar, G.J. Steeneveld, M. Tombrou, J. Voogt, N. Zhang, 2010a: The International Urban Energy Balance Models Comparison Project: First results from Phase 1, J. *Appl. Meteor. Clim*., 49, 1268-1292.

25. CSB Grimmond, M Blackett, MJ Best, J-J Baik, SE Belcher, J Beringer, SI Bohnenstengel,I Calmet, F Chen, A Coutts, A Dandou, K Fortuniak, ML Gouvea, R Hamdi, M Hendry, M Kanda, T Kawai, Y Kawamoto, H Kondo, ES Krayenhoff, S-H Lee, T Loridan, A Martilli,V Masson, S Miao, K Oleson, R Ooka, G Pigeon, A Porson, Y-H Ryu, F Salamanca, G.J. Steeneveld, M Tombrou, JA Voogt, D Young, N Zhang, 2010b: Initial Results from Phase 2 of the International Urban Energy Balance Comparison Project, *Int. J. Climatol.*,31,244-272.

26. Haines, A., Kovats, R.S., Campbell-Lendrum, D. & Corvalan, C. (2006) Climate change and human health: impacts, vulnerability, and public health. *Lancet*, **367**, pp. 2101–2109.

27. Hidalgo J., G. Pigeon, & V. Masson, 2008: Urban-Breeze Circulation during the CAPITOUL Experiment: Experimental Data Analysis Approach. *Meteor. Atmos. Phys*. **102**, 223-241.

28. Huynen, M.M.T.E., P. Martens, D. Schram, M.P. Weijenberg and A.E. Kunst, 2001. The Impact of Heat Waves and Cold Spells on Mortality Rates in the Dutch Population. *Environmental Health Perspectives*, **109**, 463-470.

29. IPCC, 2007, Climate Change 2007, Impacts, Adaptation and Vulnerability, Working Group 2 contribution to the IPCC Fourth assessment report.

30. Kanda, M., 2007: Progress in Urban Meteorology, *J. Met. Soc. Japan*, **85B**, 363-383.

31. Krpo, A., F. Salamanca, A. Martilli and A. Clappier, 2010: On the Impact of Anthropogenic Heat Fluxes on the Urban Boundary Layer: A Two-Dimensional Numerical Study. *Bound.-Layer Meteorol*. DOI: 10.1007/s10546-010-9491-2

32. Kusaka, H., H. Kondo, Y. Kikegawa, & F. Kimura, 2001: A Simple Single-Layer Urban Canopy model for Atmospheric Models: Comparison with Multi-Layer and Slab Models, *Bound.-Layer Meteor.*, **101**, 329-359.

33. Lemonsu, A, Grimmond, CSB, Masson, V (2004) "Modelling the surface energy balance of an old Mediterranean city core." *J Appl Meteor* **43**: 312-327.

34. Louis, J. F. (1979). Parametric Model of Vertical Eddy Fluxes in the Atmosphere, *Bound-Layer Meteorol*, **17**, 187-202.

35. Martilli, A., 2002: Numerical study of urban impact on boundary layer structure: sensitivity to wind speed, urban morphology, and rural soil moisture. *J. Appl. Meteor.*, **41**, 1247-1266.

36. Martilli, A., 2007: Current research and future challenges in urban mesoscale modeling. *Int. J. Clim.*, **27**, 1909-1918.

37. Masson, V. 2000: A Physically based scheme for the urban energy budget in atmospheric models. *Bound.-Layer Meteor.*, **94**, 357-397.

38. Masson, V., C.S.B. Grimmond & T.R. Oke, 2002: Evaluation of the Town Energy Balance (TEB) scheme with direct measurements from dry districts in two cities. *J Appl Meteor* **41**,1011-1026

39. Meagher, JF, E.B. Cowling, Fehsenfeld FC, Parkhurst WJ (1998) Ozone formation and transport in southeastern United States: Overview of the SOS Nashville/Middle Tennessee Ozone Study. *J Geophys Res-Atmospheres* **103**: 22213–22224

40. Menut L, Flamant C, Pelon J, Flamant PH (1999) Urban boundary-layer height determination from lidar measurements over the Paris area. *Appl Opt* **38**: 945–954.

41. Mestayer P, Durand P, Augustin P, Bastin S, Bonnefond J-M, B_enech B, Campistron B, Coppalle A, Delbarre H, Dousset B, Drobinski P, Druilhet A, Fr_ejafon E, Grimmond S, Groleau D, Irvine M, Kergomard C, Kermadi S, Lagouarde J-P, Lemonsu A, Lohou F, Long N, Masson V, Moppert C, Noilhan J, Offerle B, Oke T, Pigeon G, Puygrenier V, Roberts S, Rosant J-M, Saïd F, Salmond J, Talbaut M, Voogt J (2005) The Urban Boundary Layer Field Experiment over Marseille UBL/CLU-ESCOMPTE: Experimental Set-up and First Results. *Bound-Layer Meteor* **114**: 315–365.

42. Oke, T.R., 1988: The urban energy balance. *Prog. Phys. Geog.*, **12**, 471-508.

43. Oke, T.R., 1997: Urban environments. In *Surface Climates of Canada*, Bailey, W.G., T.R. Oke and W.R. Rouse, eds., McGill-Queen's University Press, Montréal, pp.303-327.

44. Oke, T.R., 2006: Initial guidance to obtain representative meteorological observations at urban sites. Instruments and observing methods, no. 81. Canada. World Meteorological Organization.

45. Pielke, R. A., Cotton, W. R., Walko, R. L., Tremback, C. J., Lyons, W. A., Grasso, L. D., Nicholls, M. E., Moran, M. D., Wesley, D. A., Lee, T. J., and Copeland, J. H., 1992: A Comprehensive Meteorological Modeling System - Rams, *Meteor Atmos Phys*, **49**, 69-91.

46. Rotach, M.W., S-E. Gryning, E. Batchvarova, A. Christen, & R. Vogt, 2004: Pollutant dispersion close to an urban surface- the BUBBLE tracer experiment. *Meteorol. Atmos. Phys.*, **87**, 39-56.

47. Stedman, J.R. (2004) The predicted number of air pollution related deaths in the UK during the August 2003 heatwave. *Atmospheric Environment*,**38**, pp. 1083–1085.

48. Steeneveld, G.J, S. Koopmans, B.G. Heusinkveld, L.W.A. van Hove, and A.A.M. Holtslag, 2010: Urban Heat Island Effects and Human Comfort in a Mild Cfb Climate: Exploring Long Term Observations by Hobby Meteorologists in The Netherlands., 9th Symp. on the Urban Environment, 2-6 Aug 2010,Keystone, USA. Online available via http://ams.confex.com/ams/pdfpapers/172498.pdf

49. Steyn DG, Hay JE, Watson ID, Johnson GT (1986) The determination of sky view-factors in urban environments using video imagery. *J Atmos Oceanic Technol* **3**: 759–764

50. United Nations (2008): World Urbanization Prospects: The 2007 Revision, Dep. of Econ. and Soc. Affairs, U. N., New York. (http://www.un.org/esa/population/publications/wup2007/2007wup.htm)

51. Walko, R. L., Band, L. E., Baron, J., Kittel, T. G. F., Lammers, R., Lee, T. J., Ojima, D., Pielke, R. A., Taylor, C., Tague, C., Tremback, C. J., and Vidale, P. L., 2000: Coupled atmosphere-biophysics-hydrology models for environmental modeling, *J Appl Meteor,* **39**, 931-944.

Appendix A: Scientific papers and other contributions

1. Döpp, Sonja, Ronald Albers, Bert van Hove, Chris Geurts en Tejo Spit. Klimaatverandering in de stad. Paper voor oploopdebat klimaat in de stad (12-2-2009).

2. Grimmond, S, M Blackett, M Best, with Baik J, Bohnenstengel S, Calmet I, Chemel C, Chen F, Dandou A, Fortuniak K, Gouvea M, Hamdi R, Kondo H, Krayenhoff S, Lee S, Loridan T, Martilli A, Masson V, Miao S, Oleson K, Pigeon G, Porson A, Salamanca F, Shashua-Bar L, Steeneveld G, Sugar L, Trombou M, Voogt J, Zhang N, 2009: The international urban energy balance comparison project: initial results from phase 2., 29 Jun-3 July 2009, 7th *International Conference on Urban Climate*, Yokohama, Japan.

3. Grimmond, S, M Blackett, M Best, with Baik J, Bohnenstengel S, Calmet I, Chemel C, Chen F, Dandou A, Fortuniak K, Gouvea M, Hamdi R, Kondo H, Krayenhoff S, Lee S, Loridan T, Martilli A, Masson V, Miao S, Oleson K, Pigeon G, Porson A, Salamanca F, Shashua-Bar L, Steeneveld G, Sugar L, Trombou M, Voogt J, Zhang N, 2009: An international urban surface energy balance model comparison study: first results, 11-15 Jan. 2009, *AMS 89th Annual Meeting/ Eighth Symposium on the Urban Environment*, Phoenix, USA.

4. Grimmond, S, M Blackett, M Best, with Baik J, Bohnenstengel S, Calmet I, Chemel C, Chen F, Dandou A, Fortuniak K, Gouvea M, Hamdi R, Kondo H, Krayenhoff S, Lee S, Loridan T, Martilli A, Masson V, Miao S, Oleson K, Pigeon G, Porson A, Salamanca F, Shashua-Bar L, Steeneveld G, Sugar L, Trombou M, Voogt J, Zhang N, 2009: First Results from the International Urban Energy Balance Model Comparison: Model Complexity., *Newsletter of the FP7 EC MEGAPOLI Project* 2009 (2009)3. - p. 8.

5. Grimmond, C.S.B., M. Blackett, M. Best, M.J. Barlow, J.-J. Baik, S.E. Belcher, S.I. Bohnenstengel, I. Calmet, F. Chen, A. Dandou , K. Fortuniak, M.L. Gouvea, R. Hamdi, M. Hendry, M. Kawai, Y. Kawamoto, H. Kondo, E.S. Krayenhoff, S-H. Lee , T. Loridan, A. Martilli, V. Masson, S. Miao, K. Oleson, G. Pigeon, A. Porson, Y,-H Ryu, F. Salamanca, L. Shashua-Bar, G-J. Steeneveld, M. Tombrou, J. Voogt, . Young and N. Zhang, 2010: The International Urban Energy Balance Models Comparison Project: first results from Phase 1. *J. Appl. Meteor. Clim*. 49: 1268-1292, DOI:10.1175/2010JAMC2354.1.

6. Grimmond, C.S.B., M. Blackett, M. Best, J.-J. Baik, S.E. Belcher, J. Beringer, S.I. Bohnenstengel, I. Calmet, F. Chen, A. Coutts, A. Dandou , K. Fortuniak, M.L. Gouvea, R. Hamdi, M. Hendry, M. Kanda, T. Kawai, Y. Kawamoto, H. Kondo, E.S. Krayenhoff, S.-H. Lee , T. Loridan, A. Martilli, V. Masson, S. Miao, K. Oleson, R. Ooka, G. Pigeon, A. Porson, Y.-H. Ryu, F. Salamanca, G.J. Steeneveld, M. Tombrou, J.A. Voogt, D.T. Young and N. Zhang, 2010: Initial results from Phase 2 of the International Urban Energy Balance Model Comparison. Int. J. Climatol. (pre-publication) DOI:10.1002/joc.2227

7. Heusinkveld, B.G., L.W.A. van Hove, C.M.J. Jacobs, G.J. Steeneveld, J.A. Elbers, E.J. Moors, A.A.M. Holtslag 2010. Use of a mobile platform for assessing urban heat stress in Rotterdam. Proceedings of the 7the Conference on Biometeorology. Albert-Ludwigs-University of Freiburg, Germany, 12-14 April 2010. 433-438.
http://www.meteo.uni-freiburg.de/forschung/publikatione/berichte/index.html

8. Jacobs, C.M.J., , L.W.A. van Hove, B.G. Heusinkveld, G.J. Steeneveld, C.C. van Heerwaarden and J.A. Elbers. Explorative Observations of the Urban Climate System in the Rotterdam Metropolis. Abstract AGU Fall Meeting 14-18 December, San Francisco, California, USA.

9. Steeneveld, G.J., L.W.A. van Hove, H. ter Maat, C. Jacobs, E. J. Moors, A.A.M. Holtslag (2008). Urban meteorology in The Netherlands: Evaluation of Models and Observations. *Kennis voor Klimaat congres Rotterdam*, November 2008.

10. Steeneveld, G.J., S. Koopmans, S., L.W.A. van Hove (2009): Quantification of the urban heat island effect in the Netherlands: exploring long term observations by hobby meteorologists, 1 Dec 2009, *SENSE Symposium Climate Proofing Cities*, Amsterdam, Netherlands.

11. Van Hove, L.W.A., B.J. Heusinkveld , C.M.J. Jacobs, J.A. Elbers, G.-J. Steeneveld, E.J. Moors, P. Kabat, A.A.M. Holtslag. Observing the urban climate system. *SENSE Symposium Climate Proofing Cities*, Amsterdam, Netherlands. Abstract Sense symposium 1 December 2009.

Appendix B: Media attention and lectures

Television attention	
6 August 2009, Cargo bike measurement Urban Heat Island Rotterdam. Opening news item	NOS, RTL, NU, TV-Rijnmond

Radio attention	
• 6 August 2009, Cargo bike measurement UHI Rotterdam, Vroege vogels, Radio 1 • 6 August 2009, Cargo bike measurement UHI Rotterdam, De Praktijk, Radio 1 • 19 August 2009, Cargo bike measurements UHI Arnhem	VARA AVRO Radio Gelderland

Publication in newspaper
In 2009, articles in more than 20 national and regional daily journals including the largest national daily news papers

Publication in popular magazine	
Warme stad (Popular scientific journal)	Quest July 2010

Publication on the internet
• Website World Landscape Architects • www. Sciencedaily.com • Newsletter Issue 33, 12 September 2009 International Association for Urban Climate (www.urban-climate.org)

Presentations for professionals/education

- Presentations for architects, urban developers and policy makers
- 'Urban climate' has become a part of the course on Governance for Sustainable Cities (MSc) of Wageningen University. In addition, subjects related to urban climate can be chosen as thesis subject in the BSc Soil, Water and Atmosphere, the MSc Earth and Environment , and in the MSc Climate Studies.

Appendix C: Following projects

As a follow-up of the COM29 project, WUR-MAQ and WUR-ESS-CC participate in the following projects:

	Project		Objectives	Period
1	Heat stress in the city of Rotterdam	HSRR05 1stphase Knowledge for Climate	Explorative study to the UHI intensity in Rotterdam and impact on thermal comfort	2009-2010
2	Regional specific information Haaglanden/ Region Rotterdam	HSHL05-HSRR04 1st phase KfC	First assessment in UHI intensity Netherlands based upon literature survey and available data	2009-2010
3	Climate and Environmental change and Sustainable Accessibility of the Randstad (CESAR)	NWO programme Sustainable Accessibility of the Randstad (SAR)	1. Increased knowledge on the relationship between climate/weather change, behavioural choices and spatial configurations and 2. Insights on the necessary conditions to integrate expert knowledge on these issues in planning processes and planning support systems to support strategic spatial planning in the Randstad under changing climate conditions.	2010-2013
4	Climate Proof cities WP1: Urban climate system WP5: Integration	KfC, 2nd phase	To build up a multi-scale (from the level of buildings, via neighbourhoods to city agglomerations) quantitative knowledge base on: 1. urban climate 2. the vulnerability of cities to climate change 3. expected impacts of possible future changes in climate 4. the technical and economical effectiveness of adaptation measures 5. the governance required to achieve this adaptation.	2010-2013
5	Future cities	EU Interreg IVb	To develop sustainable solutions for the adaptation of urban structures to the impacts of a changing climate.	2010-2012
6	Sustainable Maintenance Policy for Infrastructure Networks in the Randstad: A climate change perspective	NOW programme Sustainable Accessibility of the Randstad (SAR)	to improve the strategic decision-making with respect to maintenance, renovation and reconstruction of infrastructure, at public agencies in the Randstad by integrating three interlinked areas of investigation: climate change, infrastructure asset performance, and policy development.	2010-2013

Appendix D: Types of Urban Surface Energy Balance Models: Acronyms, model names and publications with key details

(* participant in comparison project)

CODE	Model Name	Reference with details of model
BEP02*	Building Effect Parameterization	Martilli *et al.* (2002)
BEP05	Building Effect Parameterization	Hamdi (2005); Hamdi and Schayes (2005); Hamdi and Schayes (2007)
BEP_BEM08*	BEP coupled with Building Energy Model	Salamanca *et al.* (2007); Martilli *et al.* (2002)
CAT	Canyon Air Temperature	Erell and Williamson (2006)
CEB	Canyon Energy Budget	Arnfield (2000)
CLMU*	Community Land Model - Urban	Oleson *et al.* (2007a,b)
ENVImet	Environmental Meteorology Model	Bruse & Fleer (1998)
GCTTC*	Green Cluster Thermal Time Constant model	Shashua-Bar and Hoffman (2002; 2004)
HIM	Heat Island Model	Saitoh *et al.* (1996)
HIRLAM-U	Urbanised version of DMI-HIRLAM model	Baklanov *et al.* (2005, 2006); Mahura *et al.* (2006); Zilitinkevich *et al.* (2007)
JULES*	Joint UK Environmental Simulator – King's College London	Essery *et al.* (2003), Best (2005), Best *et al.* (2006)
LUMPS*	Local-scale Urban Meteorological Parameterization Scheme	Grimmond and Oke (2002), Offerle *et al.* (2003)
MORUSES*	Met Office Urban Surface Exchange Scheme	Harman *et al.* (2004 a; 2004b)
MUCM*	Multi-layer Urban Canopy Model	Kondo *et al.* (2005); Kondo and Liu (1998)
MUKLIMO	Microscale Urban Climate Model	Sievers (1995)
NJU-UCM-S*	Nanjing University Urban Canopy Model-single layer	Masson(2000); Kusaka (2001)
NJUC-UM-M*	Nanjing University Urban Canopy Model-multiple layer	Kondo *et al.*(2005); Kanda(2005)
NKUA*	University of Athens model	Dandou *et al.* (2005)
NSLUCM*	Noah land surface model/Single-layer Urban Canopy Model	Kusaka *et al.* (2001); Chen *et al.* (2004)
NSLUCMK*	Noah land surface model/Single-layer Urban Canopy Model King's college	Kusaka *et al.* (2001); Chen *et al.* (2004)
NSLUCM-WRF*	Noah land surface model/ Single-layer Urban Canopy Model	Kusaka *et al.* (2001); Chen *et al.* (2004)
PTEBU	Photovoltaic Town Energy Balance for an Urban Canopy	Tian *et al.* (2007)
R-AUSSSM	Revised Architecture-Urban-Soil-Simultaneous Simulation Model	Tanimoto *et al.* (2004)

CODE	Model Name	Reference with details of model
RUM2*	Reading Urban Model 2 tile version	Harman and Belcher (2006)
RUM4*	Reading Urban Model 4 tile version	Harman and Belcher (2006)
SEBM	Surface Energy Balance Model	Tso *et al.* (1991)
SHFTM	Surface Heat Flux Temperature	Carlson and Boland (1978)
SLUCM	Simple Single-layer Urban Canopy Model	Kusaka *et al.* (2001)
SM2U*	Soil Model for Submesoscales, Urbanized Version	Dupont and Mestayer (2006); Dupont *et al.* (2006)
SRUM2/SRUM4*	Single Column Reading Urban Model tile version	Harman and Belcher (2006)
SUEB*	Slab Urban Energy Balance Model	Fortuniak *et al.* (2004); Fortuniak *et al.* (2005)
SUES	Single source urban evapotranspiration model	Grimmond and Oke (1991)
SUMM	Simple Urban Energy Balance Model for Meso-Scale Simulation	Kanda *et al.* (2005a); Kanda *et al.* (2005b)
SUNBEEM	Simple Urban Neighbourhood Boundary Energy Exchange Model	Arnfield (2000)
TEB*	Town Energy Balance	Masson (2000); Masson *et al.* (2002); Lemonsu *et al.* (2004)
TEB08*	Town Energy Balance 08	Hamdi and Masson (2008)
TUF2D *	Temperatures of Urban Facets in 2D	Krayenhoff and Voogt (2007)
TUF3D*	Temperature of Urban Facets in 3D	Krayenhoff and Voogt (2007)
UCLM	Urban Canopy Layer Model	Mills (1997)
UCM	Urban Canyon Model	Sakakibara (1996)
UEB	Urban energy balance	Montávez *et al.* (2000)
UHSM	Urban Heat Storage Model	Bonacquisti *et al.* (2006)
VUCM*	Vegetated Urban Canopy Model	Lee and Park (2007)

Communication

Adequate dissemination of knowledge can take place only if there is a closely-knit network between researchers and end users. Climate changes Spatial Planning created this knowledge network and monitored conditions to ensure it functions properly. Knowledge was made available to a wider audience and translated so that it can be used to better support national policy-making. Specific products included a website, conferences, workshops, brainstorming sessions, visits by foreign experts and a front office.

Climate changes Spatial Planning

Climate change is one of the major environmental issues of this century. The Netherlands are expected to face climate change impacts on all land- and water related sectors. Therefore water management and spatial planning have to take climate change into account. The research programme 'Climate changes Spatial Planning', that ran from 2004 to 2011, aimed to create applied knowledge to support society to take the right decisions and measures to reduce the adverse impacts of climate change. It focused on enhancing joint learning between scientists and practitioners in the fields of spatial planning, nature, agriculture, and water- and flood risk management. Under the programme five themes were developed: climate scenarios; mitigation and land use; adaptation; governance, economy and decision support; communication. Of all scientific research projects synthesis reports were produced. This report is part of the communication series.

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