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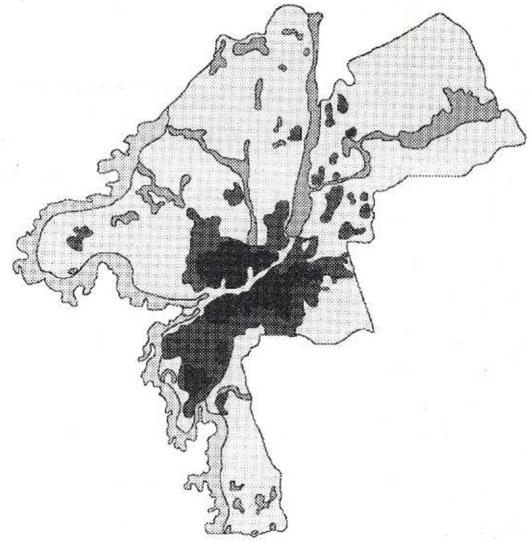
URBAN CLIMATE IN RELATION TO LAND USE, PLANNING AND COMFORT



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Front cover illustration: The image is a simplified illustration of local climate features in the Göteborg urban district.

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Akademisk avhandling

Som för avläggande av Filosofie Doktorsexamen vid Institutionen för Geovetenskaper, Naturgeografi, Göteborgs Universitet, kommer att offentligen försvaras onsdagen den 5 juni, kl 10:00 i Stora hörsalen, Geovetarcentrum, Göteborgs Universitet.

Fakultetsopponent: Dr Gerald Mills, Geography Department, University College Dublin, Ireland

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URBAN CLIMATE IN RELATION TO LAND USE, PLANNING AND COMFORT

Marie K. Svensson

ABSTRACT

The increasing numbers of people living in urban areas emphasise the importance of studying the spatial and temporal variations in the urban climate. The varying urban landscape creates differences in the local climate which are important for energy consumption and human comfort. Thus this knowledge is useful in urban planning. This thesis deals with the work of an urban climatologist with a view to establishing an urban planning perspective. It contributes to a better understanding of the local climate in urban areas during different weather situations at both night and day.

Measurements were conducted in Göteborg (57°N11°E), a city of approximately 500,000 inhabitants, situated on the west coast of Sweden. A dense network of thirty-one (31) air temperature stations was set up for a period of twenty-nine (29) months in addition to four wind masts which were set up for a period of approximately one year. Additional data from eight meteorological stations and car measurements were used. The continuously updated Master Plan of the urban district of Göteborg, used by planners and architects, was used as a land use database. Three methods for the characterisation of the surface cover based on the Master Plan, aerial and fish-eye photographs were compared.

The spatial air temperature pattern was studied thoroughly during different weather situations and the relative importance of altitude, distance from the coast, distance from the centre of the city and sky view factor (SVF) were examined by means of regression analysis. The importance of land use/land cover parameters were also determined. Statistically significant air temperature patterns were found between several land use categories during different weather situations.

A detailed study of the relationship between air temperature and SVF was performed and a relatively strong relationship was found. The SVF differs depending on the height above ground at which fish-eye images are captured; the results showed that it is better to use the SVF calculated from fish-eye images captured at ground level in urban climate studies.

A maximum urban heat island intensity during clear, calm nights of 8.5 °C, with a mean value of 4.2 °C, was observed. The measurement also showed a cool island during approximately 30 per cent of the days, with maximum magnitudes of up to 4 °C.

For regional and local applications the spatial distribution of local climate parameters are important but the number of climatic stations available are usually limited. Two empirical models for the simulation of air temperature patterns and the assessment of human comfort are presented. The local climate model is based on meteorological data from one station in the area, digital information on local climate and land use (Master Plan). The output is verified with data from the air temperature stations and the general pattern is good. In the human comfort model meteorological data are linked with geographical information about land use, elevation and distance to the coast in order to generate the spatial distribution of the physiologically equivalent temperature (PET). Variations in PET of up to 8 °C were calculated during a clear, calm day at 1200 h. The two models have the GIS approach in common. This gives the advantages of easily modified databases and the application is important for incorporating climate in the planning process. Simulations with both models are presented in the thesis.

Keywords

Air temperature, land use/land cover, GIS, sky view factor, urban heat island, local climate mapping, empirical modelling, human comfort, urban planning, Göteborg

To my family,
When you wonder what I have been doing all these years (as I know you are) consider this …

'Many have seen apples fall but only Newton wondered why'

With love Mi

ABSTRACT

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PREFACE

This thesis includes the following papers:

I Svensson, M. K., Eliasson, I., Holmer, B. (2001): A GIS-based empirical model to simulate air temperature variations in the Göteborg urban area during the night. In press *Climate Research*

II Eliasson, I. and Svensson, M. K. (2002): Spatial air temperature variations and urban land use - a statistical approach. Submitted to *Meteorological Applications*

III Svensson, M. K. and Eliasson, I. (2002): Diurnal air temperatures in built - up areas in relation to urban planning. Accepted for publication in *Landscape and Urban Planning*

IV Svensson M. K. (2002): Sky view factor analysis- implications for urban air temperature differences. Submitted to *Meteorological Applications*

V Svensson, M. K., Thorsson, S., Lindqvist, S. (2002): A GIS model for creating bioclimatic maps – examples from a high latitude city. Submitted to *International Journal of Biometeorology*

Paper I presents the GIS based local climate model and Paper V presents the human comfort model. The investigations of Papers II and IV are mainly performed to obtain a better understanding of the local climate and the parameters and processes involved. Finally Papers III and V include some application of climate knowledge in planning. The papers are referred to in the text by their roman numerals.

The work has been performed in close collaboration with colleagues. The basic idea of the model in Paper I was presented by Ass. Prof. B Holmer while I did the development and GIS adjustments. All three authors performed analysis and writing. I did the statistical analyses in Papers II and III, while the writing was conducted jointly with my co-author. Ass. Prof. B. Holmer contributed valuable comments on the statistics. In Paper V, the tasks of modelling construction, analysis and mapping were jointly performed by all the authors and writing by myself during a process of continuous discussion with the co-authors.

INTRODUCTION

The growth of urban areas and the accompanying landscape changes emphasize the importance of studying the spatial and temporal variations in the urban climate. The varying urban landscape creates local climate differences which, besides being interesting for the purposes of research, are important for energy consumption, human comfort and planning.

This thesis deals with the general works of an urban climatologist but with an applied design it also tries to extrapolate the results to fit an urban planning point of view. The different parameters that govern the spatial air temperature pattern in the urban environment are examined. It also includes discussions of how these variations can be presented and used in different disciplines.

Background

Temperature variations in the urban environment

The study of urban climates is basically the science of human modification of a natural climate. Urban climate is often discussed in terms of the urban heat island (UHI), an effect which accompanies city growth and urbanisation. Howard was the first to document the temperature difference between urban and rural areas in 1833 (Oke et al. 1991, Hafner and Kidder 1999). The term urban heat island was later introduced by Manley (1958) and observed in large urban areas (e.g. Sundborg 1951, Lindqvist 1968, Oke 1973, Taesler 1981). Several urban climate studies have since been performed on the subject.

The primary causes of the urban heat island are considered to be thermal properties of the urban material, increased absorption of short wave radiation (i.e., low albedo or multiple-reflection within canyons), reduced long wave radiation losses, anthropogenic heat, hard surfaces and reduced evapotranspiration, air pollution and decreased loss of heat by turbulence in deep canyons (Oke 1981).

Urban geometry is thus important for the heat island development and the effect of geometry has been investigated in several studies (e.g. Oke 1981, Bärring et al. 1985, Yamashita et al. 1986, Eliasson 1994). Urban geometry can be expressed either as the depth/width ratio (Oke 1981, Johnson and Watson 1984) or by the sky view factor (SVF), which in turn can be calculated from fish-eye photographs (e.g. Steyn 1980, Bärring et al. 1985, Holmer et al. 2001, Chapman et al. 2001), or as recently presented, from three-dimensional (3-D) building data sets (Brown et al. 2001). The sky view factor expresses the ratio between radiation received by a planar surface and that from the entire hemispheric radiating environment (Watson and Johnson 1987). Oke (1981) showed a strong correlation of the surface heat island and the SVF in city central areas for several cities and found that a heat island magnitude of 7 °C was possible as a direct result of the SVF.

Other intra-urban temperature differences with the same magnitude as the heat island intensities have been observed (e.g. Jauregui 1990/91, Eliasson 1996, Spronken-Smith and Oke 1998, Upmanis et al. 1998) and land use/land cover parameters have been shown to be important for temperature variations (e.g. Horbert et al. 1988, Katayama 1992, Alcoforado 1994, Eliasson 1994, Heisler et al. 1994, Shudo et al. 1997, Vogt et al. 1997).

Climate and urban planning

Climate has always been a natural part of the building tradition and climate planning can be traced back in literature more than 2000 years (Morgan 1960, Givoni 1981). The change from traditional to industrial building in the middle of the 20th century led to a situation in which the local climate got a secondary role in the modern urban planning and design process (Hawkes 1996). Several authors have discussed the importance of taking climate into consideration on different planning levels (e.g. Bitan 1988, 1992, Lindqvist and Mattsson 1989, de Schiller and Evans 1990/91, 1996, Lindqvist 1991, Mills 1999, Thamm et al. 1999, Eliasson 2000). Unfortunately the step from theory to practice is long and climate issues often have a low impact on the urban planning process (Oke 1984, Lindqvist and Mattsson 1989, Pielke and Uliaz 1998, Mills 1999, Eliasson 2000). Urban climate research also needs to include some predictive aspects if is to be of use to planners (Oke 1984).

Eliasson (2000) has listed several constraints such as time, politics, conflicting interests, low priority and economical reasons for this. Lack of knowledge was also another factor. Through interviews and questionnaires, Eliasson (2000) shows that urban planners are interested in climatic aspects but the use of climate information is unsystematic and planners and architects seek other sources of climate knowledge.

Local climate information in the form of maps has been shown to be useful tools (Lindqvist and Mattsson 1989, Paszynski 1990/91, Lazar and Podesser 1999) as planners and architects are familiar with cartographic material. Local climate mapping is traditionally performed manually from maps and aerial photographs, complemented with extensive field measurements (Lindqvist et al. 1983, Bogren and Gustavsson 1986, Lindqvist 1991, Pazynski 1990/91). Topoclimatic maps are indispensable in the illustration of existing climate conditions, as observations from one meteorological station do not give an overall impression of the surrounding area (Paszynski 1990/91). Despite this the traditional climate map has some disadvantages, one of which is that the maps show a static view of the climatic conditions.

The development of geographical information systems (GIS) leads to a new computer-based approach for terrain mapping and analysis (Eriksson 2001). A GIS is an important tool for collecting, storing, analysing (retrieving, transforming) and displaying geographical data for a specific purpose (Burrough 1986). Thus the GIS technique gives new opportunities not only to illustrate and analyse local climate variations but also to store data digitally.

Influence of weather conditions

Urban climate is governed by the type of land use, topography and distance to water bodies among other factors. The local climatic features such as heat island and cold airflows vary with time of day and season and it is important to have knowledge about these variations. The temperature pattern created by such features can be generalised according to the prevailing weather conditions since meteorological parameters are important; this was shown in many studies of the urban heat island development (Sundborg 1951, Lindqvist 1970, Park 1986, Oke 1993, Kidder and Essenwanger 1995). One approach is to distinguish characteristic situations. Urban climatologists usually focus on the clear, calm night situation when temperature differences are most pronounced (Oke 1981, Mills 1999). This weather type is however not very frequent in most middle and high latitudes. During cloudy and windy situations the spatial variations in temperature are smaller because of the well-mixed atmosphere. The effect of clouds is mainly to dampen the temperature differences (e.g. Holmer and Linderstad 1985, Oke 1993). Planners are however often interested in daytime differences in the local climate as this is the time when people are active and outside (e.g. Mills 1999); such situations are therefore important for a practical application of the results.

Human response on local climate

Thermal conditions, in contrast to air pollution, are often underestimated as relevant atmospheric conditions in urban areas from a medical point of view (Jendritzky et al. 2000). Urban climate, particularly the heat island, has however become important from the human environmental point of view, because of the increasing trend towards people living in urban areas (Pinho and Manso Orgaz 2000). The influence of climate on humans is important for many reasons, including urban planning, energy demand and the well-being of the residents. Urban climatology and the application to outdoor human comfort is a growing research area (Jendritzky and Sivers 1989, Grätz and Jendritzky 1994, Matzarakis et al. 1999, Jendritzky et al. 2000, Friedrich et al. 2001). Several studies have been made, mainly in Germany, where the effect of meteorological conditions have been expressed in terms of their influence on humans (e.g. Jendritzky and Grätz 1997, Höppe 1999, Li and Chan 2000, Friedrich et al. 2001). Such studies and their results have been shown to be interesting for planners, architects and the public (Grätz and Jendritzky 1994, Höppe 1999). Until today, few biometeorological studies have been performed in northern latitudes and human comfort studies in Sweden have mainly been restricted to the effects of wind and the amount of sun (Glaumann and Westerberg 1988).

Aim of thesis and objectives

Local climate maps have been shown to be of importance for climate planning. Interviews and other research have revealed that planners seek applicable tools which are easily used (Oke 1984, Svensson and Eliasson 1999, Eliasson 2000). The first approach was to explore the idea of using a GIS to create a model with the purpose of presenting a dynamical climate map (Paper I). Data on the climate, land use and topography were incorporated and the *local climate model* showed general agreement in describing the spatial variations of air temperature within the area. For improvement of the presented model, further research was necessary to examine the relationship between air temperature and influencing factors (Papers II, III and IV). The GIS technique was also used in a second model, the *human comfort model*, which was presented in Paper V.

The objectives of the thesis have been to:

- Develop a GIS-based method for the simulation of the urban air temperature climate to be used both for the illustration of present climatic conditions and as a predictive tool (Paper I)
- Examine intra-urban air temperature variations during different weather conditions and during both day and night (Papers II, III)
- Examine which parameters in the landscape structure, such as land use and sky view factor, are important for the air temperature pattern in an urban area (Papers II, IV)
- Examine if the observed air temperature variations between different land use areas are statistically significant (Papers II, III)
- Find objective and quantitative parameters that can be used to describe the urban environment and define the spatial variability within different land use classes (Papers II, III)
- Exemplify the effect of climatic parameters on humans with the aid of an existing comfort index (Paper V)

The common intention of these objectives was to contribute to a better understanding of the local climate in urban areas during different weather situations and times during the day. Another aim was to use urban climate research in a way which was more applicable to various disciplines and suitable for users in the society.

STUDY AREA

The data used in this thesis were collected in Scandinavia, western Sweden, in the city of Göteborg (57°42'N, 11°58'E) and its surroundings (Figure 1). From an urban climatological view this area is interesting because although it is rather small (72 200 ha), it includes several different urban and rural structures, differences in altitude and coastal proximity. Furthermore, several large scale studies (e.g. Eliasson and Holmer 1990, Eliasson 1994, Holmer and Haeger-Eugensson 1999, Nunez et al. 2000) and small scale studies (e.g. Eliasson 1996, Upmanis et al. 1998) of the urban climate have been previously performed in the area.

The city of Göteborg is the second largest city in Sweden with its 500,000 inhabitants. Göteborg was founded in 1621 and the central area is built according to Dutch patterns with streets and manmade canals in a strictly designed system, resulting in a classical European structure. The city is built up around the shores of the Göta river which divide the area into two parts. The city's centre is located on both sides of the river, with a concentration of older and denser buildings in the southern part, Figure 2 (See also Figure 1, Paper IV). Multi-family and detached houses are common in areas which are further out from the centre of the city and the suburban areas are dominantly green.

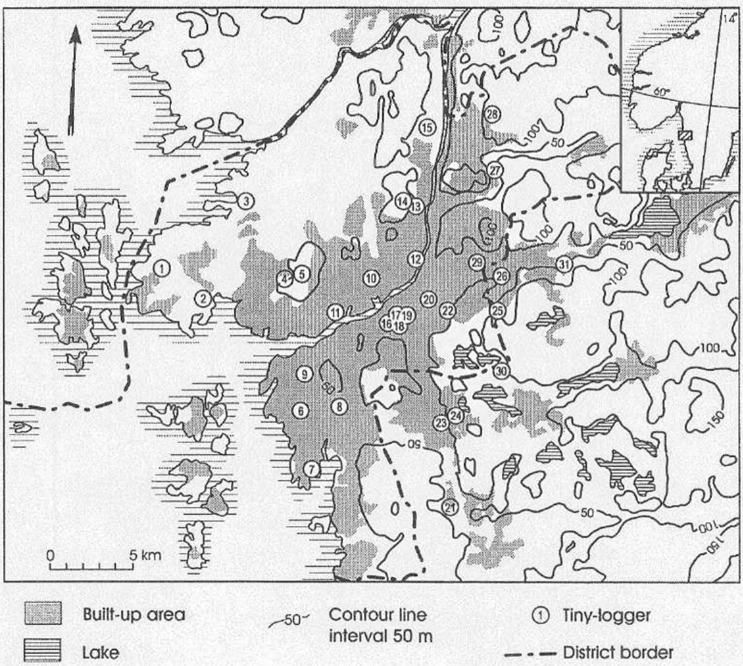
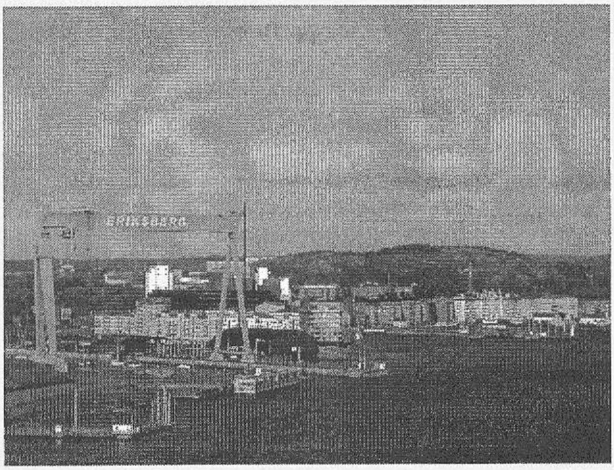


Figure 1. *Map of the study area Göteborg and its surroundings. The locations of the air temperature stations (Tiny-loggers) are also shown.*

a)



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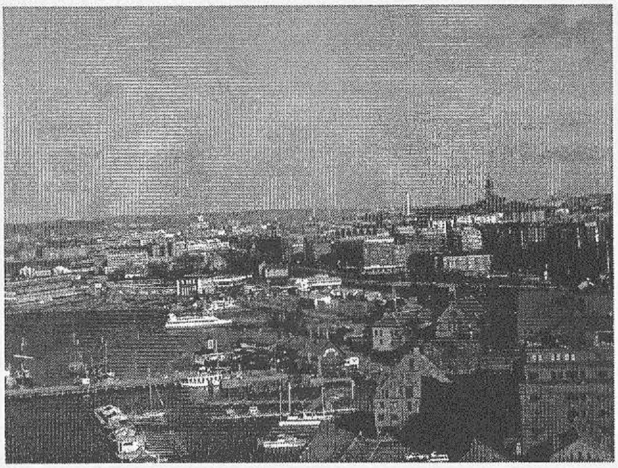


***Figure 2.** Structures in the city shown in photographs taken from Station B (See Fig 6). (a) View towards the north side of the city and (b) view towards the older and denser south part of the city. Photo: M Svensson*

The northern part of the area is predominantly green, with agriculture and meadow land to the west and the more forested areas in the east. Built-up areas occupy 31 per cent of the total land (2 % urban dense, 9 % multi-family, 9 % single houses and 11 % warehouses, working premises, institutions etc). Forest areas cover 44 %, agriculture/meadow land 11 % and other green areas (i.e. cottage gardens, cemeteries, parks etc) another 14 % (Figure 3).

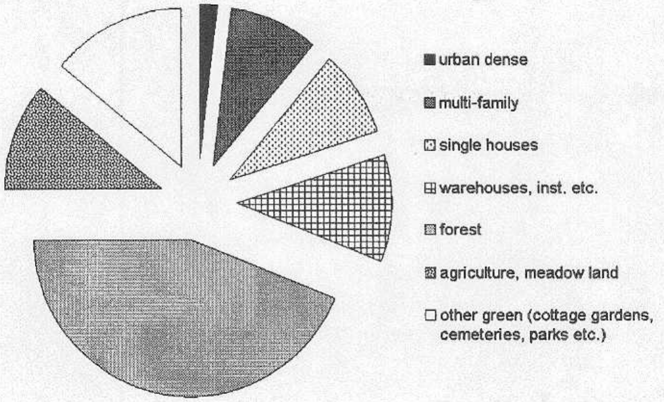


***Figure 3**. Land use categories in the urban district of Göteborg.*

The area is characterised by a complex topography because it is dominated by four flat, broad valleys (raised sea bottoms, Figure 1). Most of the built-up land is located within these valley bottoms around 0-10 m. a. s. l. The altitude rises gradually from the coast towards inland, and the most elevated areas (~150 m. a. s. l.) are found in the north-eastern section of the district. The coastline facing the Kattegat Sea is irregular and borders an archipelago with scattered small islands.

Climate

The Göteborg area has a maritime climate influenced by the westerlies and classified as *Cfb* according to the Köppen system. The area has relatively warm winters and cool summers for the latitude, with a mean diurnal temperature of -0.4 °C in winter (December-February) and 16.3 °C in summer (June-August) (Väder och Vatten 2000). The length of the night varies greatly throughout the year due to the high latitude of Göteborg. In the middle of June the nights are approximately 6 hours long and in December about 16 hours long.

In Figure 4 the frequencies of different weather categories during 18 months of the total measurement period (October-1998 to March-2001) are presented. Day is represented by data from 1200 h (UTC+1 h) and night by data 3 h after sunset. The figure shows that clear, calm occasions are rare in comparison to other weather situations, especially during the days.

a)

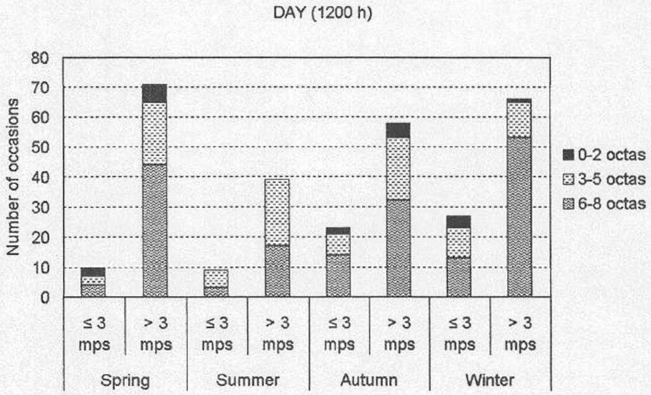


Figure 4a. *Frequency of different weather categories at daytime during an 18-month data period divided into seasons. Wind speed is in metres per second (mps).*

b)

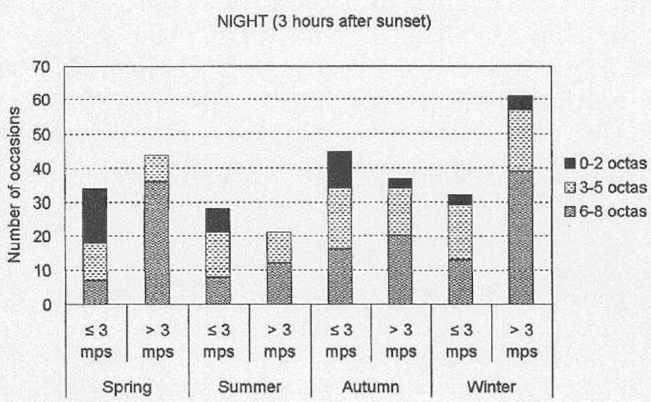


Figure 4b. *Frequency of different weather categories at night, during an 18-month data period divided into seasons. Wind speed is in metres per second (mps).*

DATA AND METHODS

The data used in this thesis are mainly from fixed stations in the area and they will be described generally in this chapter to give a background to the results and discussion. See the separate papers for further information.

Throughout the thesis the meteorological data have been divided into weather groups. As stated in each paper, the analyses have been performed on the basis of these groups. The main division has been into three different cloud groups and two wind groups, with the cloud groups being clear (0-2 octas), semi-cloudy (3-5 octas) and overcast (6-8 octas) and the wind groups being ≤ 3.3 m s^{-1} and > 3.3 m s^{-1}. The wind speed limit is chosen from the Beaufort scale, which quantifies wind in terms of the effect on humans (Lee 1987). Two Beaufort is 1.6-3.3 m s^{-1}.

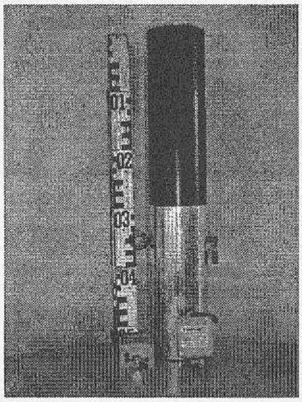
A division into day and night is also used where day is represented by data from 1200 h (UTC+1 h) and night by data 3 h after sunset (time of maximum temperature differences, Oke 1981). Thus the nocturnal data used are from different hours depending on the time of sunset.

Climate data

Temperature measurements

Temperature data were collected every hour with the aid of Tiny-loggers, i.e., combined miniature data loggers and sensors (Gemini Data Loggers), at 31 stations within the area. The air temperature sensor is an encapsulated thermistor with an accuracy of 0.2 °C (0 °C to 70 °C) and a time constant (63 %) of 11 minutes in air. The stations were located in different land use types and generally at open sites. The Tiny-logger instruments were sheltered with radiation shields constructed of black and silver coloured plastic pipes with radii of 90 mm. These were mounted at a height of approximately 2 m (Figure 1 and 5). The radiation shields are constructed as a 'chimney'; the air in the black part of the radiation shield is warmed and rises, increasing the ventilation and the amount of air which flows through. An inter-comparison and calibration of the Tiny-loggers were conducted before and after the field measurements. Refer to the separate papers for further technical details of the instruments.

a)



b)

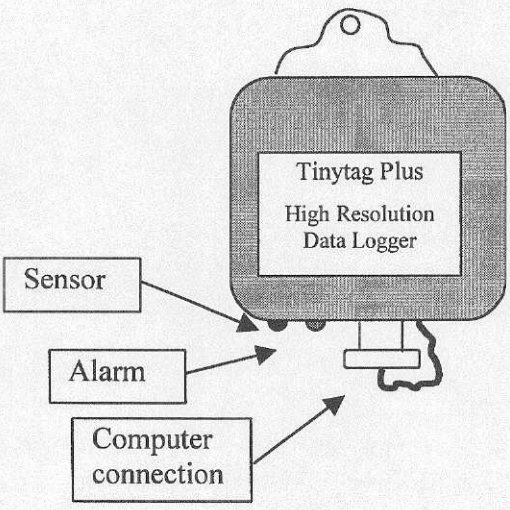


Figure 5. *Photograph showing the Tiny-logger and radiation shield (a) and a graphic illustration of the Tiny-logger (b).*

In addition to the Tiny-logger data set temperature data from 6 permanent masts in the area (Table 1, Figure 6) were used in Paper V and ancillary air temperature data from car measurements were used in Paper IV.

Wind measurements

A network of 12 wind masts in the area was used in Paper V (Figure 6). Maintenance and equipment are summarised in Table 1.

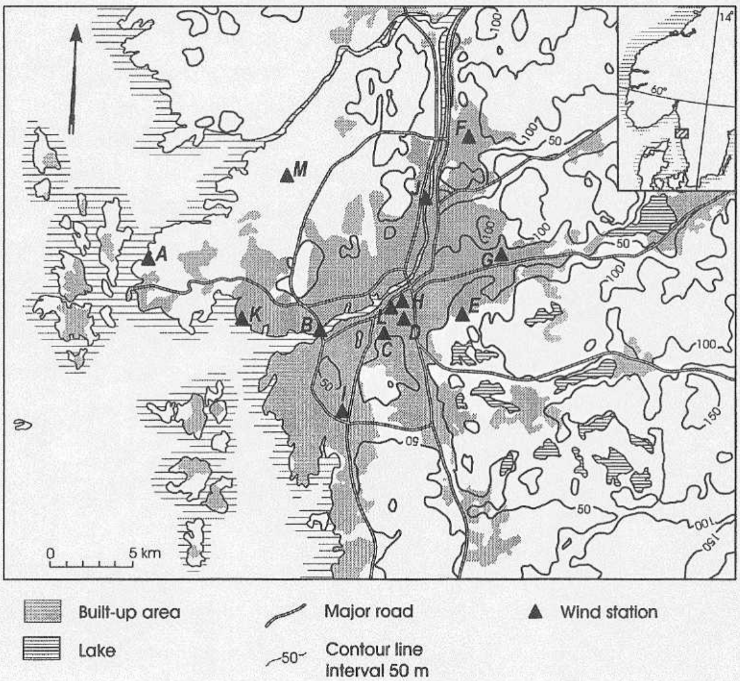


Figure 6. *Wind stations in the area. Station M is used as reference station and is referred to as Säve airport in some papers. Meteorological data from Station M is also used as input to the local climate model.*

Reference station

Wind and cloud data from one permanent meteorological station, run by the Swedish Military Weather Service, was used to divide the data into suitable weather categories (Station M, Figure 6). Meteorological data (air temperature, wind speed, wind direction and cloud cover) from this station was also used as input data to run the local climate model. At this station wind is measured at standard height, 10 m, with a Vaisala wind anemometer (accuracy 0.1 m s^{-1} below 10 m s^{-1}, threshold 0.4 m s^{-1}) and a Vaisala wind vane (accuracy 3°, 0.3 m s^{-1}).

Cloud cover is measured in octas (0/8 to 8/8) with mobile cloud cover equipment (CMBE).

Table 1. *The description of wind and temperature stations excluded stations with Tiny-loggers. The stations are maintained by the following groups: Department of Physical Geography (I), The Environmental Protection Board of Göteborg (II) and The Swedish Military Weather Service (III).*

Station	Parameter	Measuring level (m)	Instrumentation	Threshold (m s^{-1})	Accuracy (m s^{-1})	Maintenance
A	wind speed	10	Vaisala WAA 15	0.4	± 0.1	I
B	wind speed	100	Vaisala WAA 15	0.4	± 0.1	I
C	wind speed	7	Vaisala WAA 15	0.4	± 0.1	I
	temperature		Vaisala Pt 100	-	± 0.08	
D	wind speed	10	Vaisala WAA 15	0.4	± 0.1	I
	temperature	2	Vaisala Pt 100	-		
E	wind speed	10	Vaisala WAA 15	0.4	± 0.1	I
F	wind speed	10	Vaisala WAA 15	0.4	± 0.1	I
G	wind speed	10	Vaisala WAA 15	0.4	± 0.1	I
H	wind speed	10	Vaisala WAA 15	0.4	± 0.1	II
	temperature		Thermistor	-	± 0.2	
I	wind speed	16	Vaisala WAA 15	0.4	± 0.1	II
	temperature		Thermistor	-	± 0.2	
J	wind speed	10	Young (05103)	1.0	± 0.3	II
K	wind speed	10	Young (05103)	1.0	± 0.3	II
	temperature	10	Thermistor	-	± 0.2	
M	wind speed	10	Vaisala WAA 15	0.4	± 0.1	III
	temperature		Vaisala Pt100	-	± 0.08	

Measuring site characterisation

Land use/land cover information was extracted from the Master Plan of the urban district of Göteborg (scale 1:50 000). This map is a continuously updated and revised illustration of the present and future use of land in the area. Planners at the Comprehensive Planning Department, Municipality of Göteborg, use the Master Plan.

The geometry of the city was described by the sky view factor (SVF). Fish-eye photographs were taken at all Tiny-logger stations with a Nikon 8 mm fish-eye lens (f/2.8, picture angle 180°). The sky view factor was calculated with a GIS-based method (Holmer et al. 2001) designed for the commercially available software IDRISI (Clark University 1999). See Papers II, III and IV for further information.

A type description of each Tiny-logger station (Figure 1) was conducted with the aid of the land use database (Master Plan), fish-eye photographs and aerial photographs (Paper II). The percentages of *green* and *impervious* areas were calculated from the fish-eye photographs. With aerial photographs the site characterisations were performed within circles with radii of 100 m and 500 m respectively and the percentages of *impervious*, *green*, *built-up*, *water* and *built-up with green* were determined. The results within each land use category were compared and the three methods were evaluated by means of regression analysis with air temperature as the dependent variable.

DEVELOPMENT OF A GIS BASED EMPIRICAL MODEL FOR AIR TEMPERATURE SIMULATIONS

The local climate model presented in Paper I is the development of a technique presented by Holmer and Linderstad (1985). The GIS technique made it possible to develop the original idea and illustrate the spatial distribution of air temperature or wind. Such information is important for regional and local applications. An advantage is the use of digital databases, which are easily modified and updated.

In Figure 7 the conceptual framework of the grid based local climate model is presented. The input data to the model consist of digitally mapped information on land use and local climate as well as meteorological data from one nearby openly located meteorological station. In the local climate map, processes such as cold airflows which influence the local climate are presented. The climate map is the result of basic climatological measurements performed in the area and a parameterisation of the processes involved as described by Lindqvist et al. (1983) and Lindqvist and Mattsson (1989); the results are later expanded to include calibration measurements (Holmer and Linderstad 1985). The corrected values were then used to create the algorithms for the empirical model. The actual calculations are performed in a Matlab program (Paper I).

For the results presented in the thesis, the model is run with a grid resolution of 500 m × 500 m; this is selected because it corresponds to the comprehensive planning scale in Sweden.

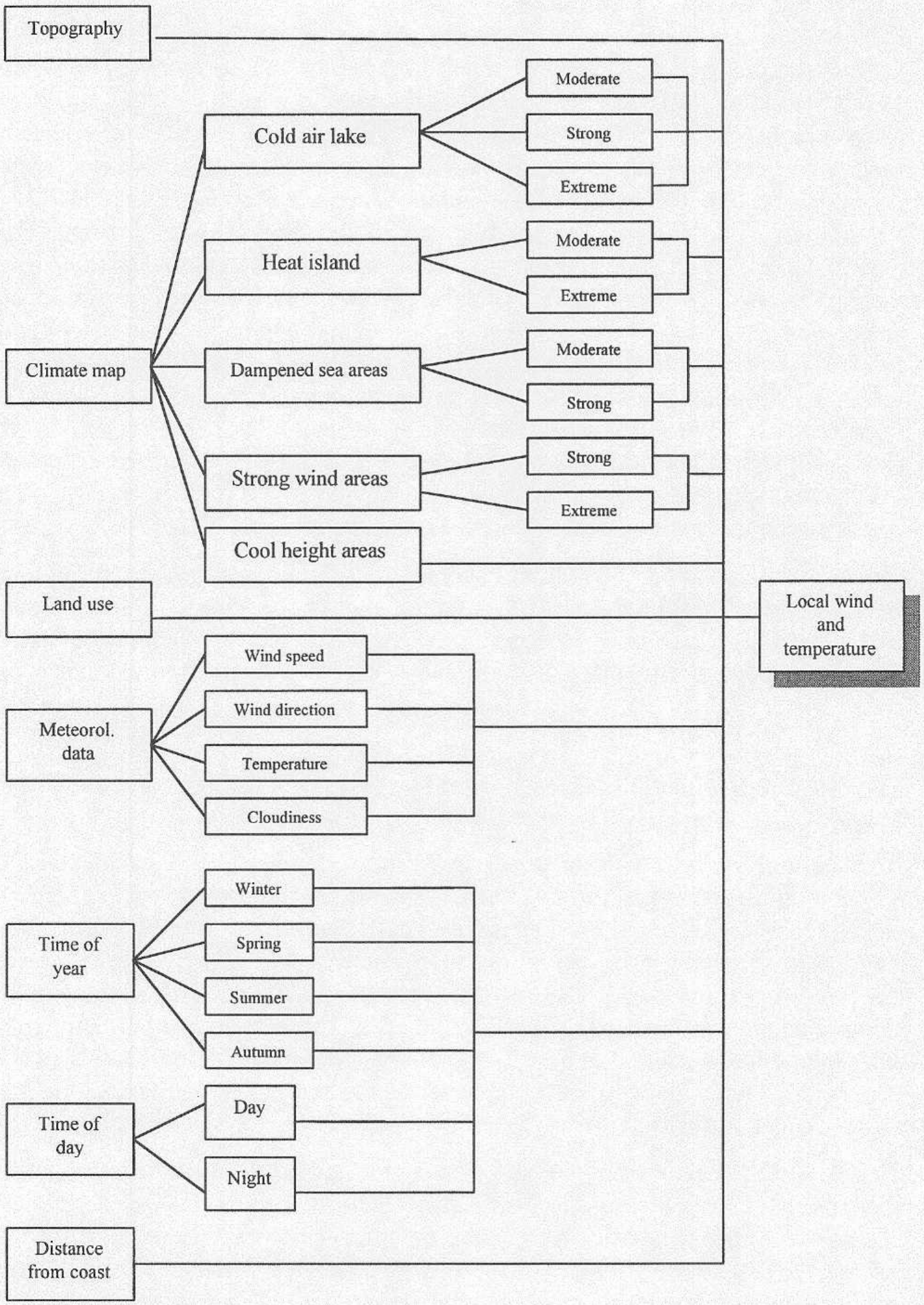


***Figure** 7. Descriptive diagram showing input parameters to the local climate model.*

THE THERMAL COMPONENT

Several thermal indices have been set up for outdoor climate analyses (e.g. Fanger 1970, Steadman 1971, 1979, Gates 1972, Jendritzky et al. 1979, Gagge 1980, Mayer and Höppe 1987, VDI 1998). Some of these indices are based on meteorological parameters alone, lacking thermo-physical relevance, whereas others also include models of the human energy balance (Höppe 1993). The Physiological Equivalent Temperature (PET) developed by Mayer and Höppe (1987) is one of the most frequently used indices. It is based on the Munich Energy-balance Model for Individuals (MEMI). PET is defined as the air temperature at which the heat budget of the human body in a typical indoor setting (no wind or solar radiation) is balanced with the same core and skin temperature as under the complex outdoor conditions to be assessed (Höppe 1999). The aim is to transfer the actual thermal conditions to an equivalent indoor environment in which the same thermal sensation is expected (Mayer and Höppe 1987). One advantage of PET is that it uses a common unit (degree Celsius) and that it can be used all year round and in different climates (Höppe 1999, Matzarakis et al. 1999).

The actual calculations of PET in Papers III and V are performed with the aid of the PC application RayMan. The radiation model RayMan is able to calculate precise and high-resolution radiation data of the whole area which is necessary for the evaluation of the thermal component of the urban and regional climate (Matzarakis et al. 2000).

Development of a GIS based model for assessment of the human response on climate

The thermal variations in an urban area are thoroughly described in this thesis. These climatic features can be further quantified and expressed in other ways which enables a person's response to be determined during specific climatic conditions. Spatial information on thermo-physiologically relevant indices is needed. A vector-based GIS model for presenting such information on a comprehensive scale was developed in Paper V. The advantage of the model is the GIS approach, which makes the model non-static. In the model meteorological data are linked with geographical information in order to generate the spatial distributions of the PET.

Based on the results from the site description analysis (Paper II), five land use categories (*urban dense, multi-family, single houses, industrial etc* and *green*) were identified. These categories were assigned an α-value based on surface roughness according to Givoni (1998). On the basis of land use, distance from coast and altitude, an air temperature map and a wind map with 18 and 26 zones respectively were created. These two maps were combined in the GIS model in order to create the zones for which the thermal component was calculated (Figure 8).

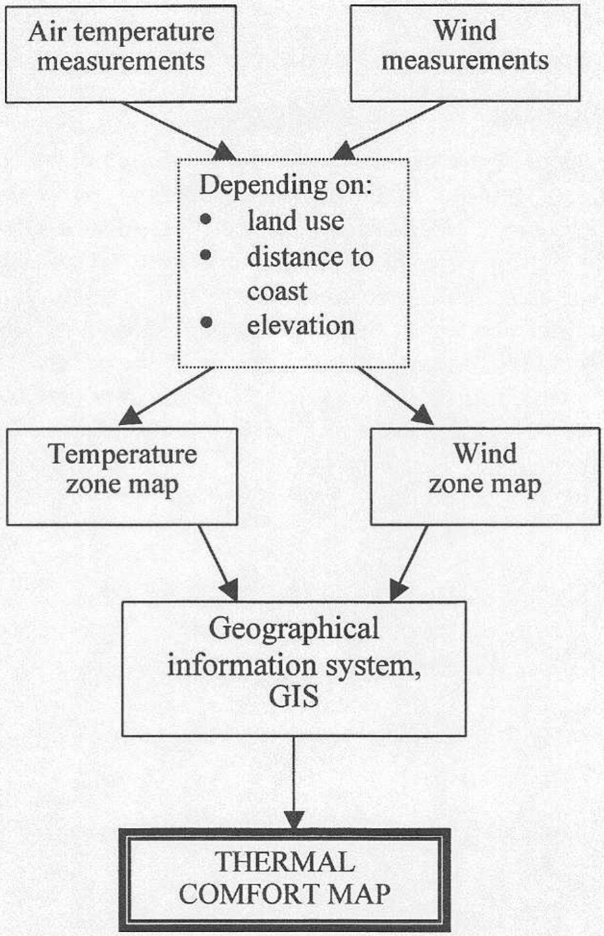


Figure 8. *Flow diagram showing the basic steps of the human comfort model for assessment of the thermal component.*

RESULTS

Several parameters in the landscape influence the local climate. The relationships between some of these features have been examined in this thesis in relation to air temperature, comfort and planning. Attempts to develop methods for better characterisation of the surface, surroundings and measuring sites have also been made.

Site description analysis

In Paper II the three methods used to characterise the urban surface, from fish-eye photographs and from aerial photographs with two different radii (100 m and 500 m), showed similar results. The three methods were also compared in a statistical analysis by means of regression analysis with the air temperature sampled at each Tiny-logger station (Figure 1) during the measuring period as the dependent variable. The percentage of different land use types, distance from the coast and from the centre of the city, the SVF and elevation were used as independent variables. During clear, calm situations the results from the statistical analyses were similar and independent of the method of analysis. With air temperature data collected during cloudy, windy situations however, the aerial photo classification, especially the 500 m circle radius, was slightly better compared to the classification based on the fish-eye photographs. One explanation could be that the aerial photograph approach includes a larger fetch area, i.e., an area which is more representative of the measurements, which improves the statistical results (Paper II).

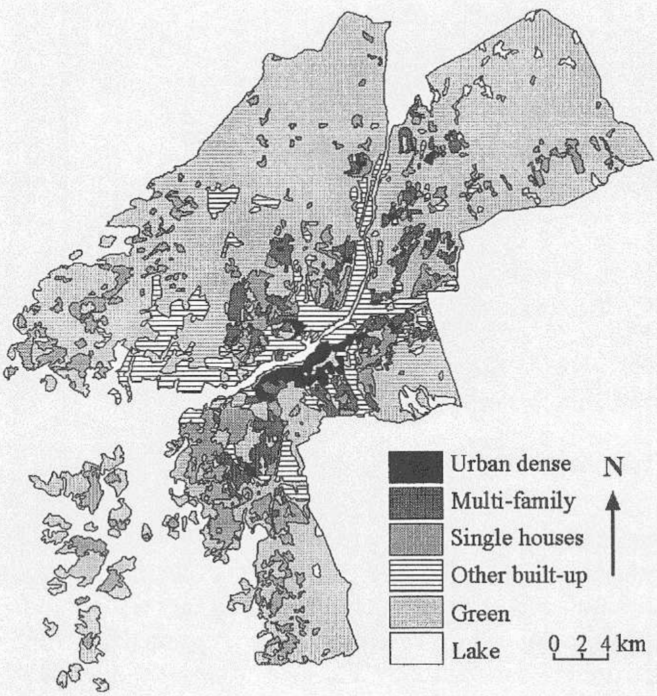


Figure 9. Land use map showing aggregated categories from the Master Plan.

The site description analysis conducted on the basis of the 31 temperature stations (Figure 1) resulted in the aggregation of the original 11 Master Plan land use classes into five new land use/land cover categories (Figure 9, see also Paper II).

The analysis revealed a successive transition of land use characteristics from the centre of the city to the outer areas, a pattern comparable with the structure of many other cities e.g. Malmö in Sweden (Bärring et al. 1985) or the Metropolitan St. Louis area (Auer 1978). The results showed that the amount of green cover increases with distance from the centre of the city. The type of vegetation covering also changes. In the city, green areas more commonly occur in the form of parks and cemeteries. In suburban areas the green sections are integrated with the built-up areas.

Parts of the results from the site description analysis are shown in Table 2 (See also Figure 1). The inner city of Göteborg is characterised by dense building structures (SVF below 0.5). Suburban areas with multi-family buildings surround the centre of the city and areas with single-family houses are more common further out from the inner city (Figure 9). As shown in Table 2, the *urban dense* category (1) has the least vegetation cover and consequently the largest part consists of built-up areas and impervious surfaces. The variation within this category is, however, large and the two stations presented in Table 2, Station 17 – a narrow canyon of five storey buildings – and Station 16 – a market place – represent two characteristic sites (See Paper III).

The sky view factors for the seven stations in category 2, *multi-family*, have an average value of around 0.8. The results from the site description analysis, however, show that the proportion between vegetation and built-up/impervious surfaces varies greatly between the stations. This category therefore represents a transitional category between *urban dense* and *single house* categories in terms of surface covering.

The surface covering at the eight stations in category 3, *single-houses*, is dominated by vegetation (Table 2). Analysis of the fish-eye photographs shows that the percentage of vegetation is twice that of the impervious part for all stations and the class 'built-up and vegetation' dominates in the aerial photograph analysis (Paper II). With one exception (Station 29) the SVF in category 3 is over 0.9.

Category 15, *other built-up*, is a mixed category as a result of the regrouping of four original land use classes (Paper II). This category makes up eleven percent (11 %) of the Master Plan and is represented by five (5) stations in Table 2. The results from the site description analysis show that vegetation and built-up/impervious surfaces occupy equal amounts of space on average but the variation is large within this class. The SVF ranges between 0.7 and 1.0. This category is, however, rather inhomogeneous, ranging from a large open gravel area to asphalt covered surfaces with warehouse buildings (See Paper II).

The *green* category (16) is also a result of a regrouping of original land use classes (Paper II). This is, however, a very uniform category with SVF values higher than 0.9 and vegetation dominating the surface covering at all eight stations. The *green* category makes up sixty-nine percent (69 %) of the Master Plan, Figure 9.

Table 2. *Parts of the results from the objective site description analysis presented in Paper II. The sky-view factor (SVF) is calculated from fish-eye photographs and the percentage of land use/land cover is calculated from aerial photographs within a 500 m radius of the station. The land use/land cover categories are urban dense (1), multi-family (2), single houses (3), other built-up (15) and green (16).*

Station No	New category	SVF	Per cent vegetation	Per cent built-up with vegetation	Per cent water	Per cent built-up	Per cent impermeable
16	1	0.9	14.7	39.3		44.1	2.0
17	1	0.4	10.7	22.0		58.8	8.5
10	2	0.9		64.6			35.4
12	2	0.8	34.7	47.2			18.1
18	2	0.7	16.1	83.9			
22	2	0.8	55.7	42.9			1.4
23	2	1.0					
28	2	0.9	64.1	20.9	15.0		
31	2	0.9					
1	3	0.9	83.3	16.7			
6	3	1.0	16.4	83.6			
7	3	0.9	14.1	77.1		5.7	3.1
8	3	1.0	15.8	63.3			20.9
9	3	0.9	17.8	82.2			
15	3	1.0	82.5	17.5			
25	3	-	17.8	82.2			
29	3	0.7	54.0	30.8			15.3
2	15	0.8	70.9				29.1
11	15	0.7	13.6	24.0	31.6	5.9	24.9
26	15	1.0	20.1	44.4			35.6
19	15	1.0	9.9	55.9		19.2	15.0
20	15	0.7	27.1	57.1			15.8
14	16	0.9	98.8	1.1			
24	16	0.9					
3	16	1.0	83.9	16.1			
4	16	0.9	68.4				31.6
5	16	0.9	95.8				4.2
13	16	0.9	68.6		7.6		23.7
27	16	0.9	72.0	28.0			
30	16	0.9	95.2				4.8

The grouping into five new land use/land cover categories and the similarities within these categories lead to a further analysis of the temperature pattern on the basis of these land use/land cover categories.

Intra urban air temperature differences

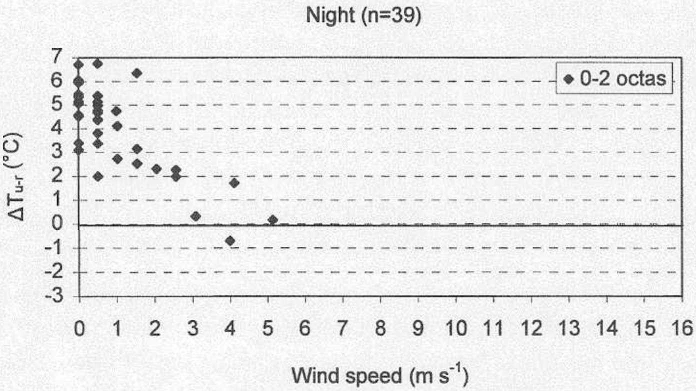
The data collected showed large intra-urban temperature differences, up to 8.5 °C (Paper I). Parameters known to influence the temperature pattern, such as the heat island, distance from the coast and elevation were examined during clear, calm nights in Paper I. Based on measurements taken on 30 occasions the mean urban heat island intensity in the area was 4.2 °C, three hours after sunset. The coastal effect showed an average maximum difference of 3 °C between an inland station (19 km from the coast) and a coastal station (1 km from the coast). The air temperature pattern was the same during clear, calm situations, independent of season.

Land use is another parameter which is important for the temperature pattern of both the air and the surface. Data were therefore analysed on the basis of land use and the more or less uniform categories resulting from the site description analysis were used. Cloud cover and wind speed are meteorological parameters known to affect the air temperature pattern and were also incorporated in the analysis (Papers II, III).

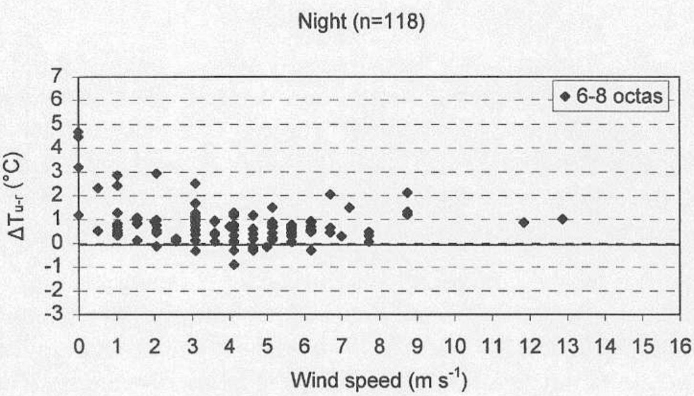
Figure 10 shows the urban heat island intensity plotted against wind speed. Data are collected during an 18-month period and divided into clear conditions (0-2 octas) and overcast conditions (6-8 octas). The $\Delta T_{u\text{-}r\,(max)}$ is calculated with a mean value of two urban dense stations (Station 16 and 17) and Station 3 is used as a 'rural' site (Figure 1). Day is again represented by data from 1200 h (UTC+1 h) and night by data taken three hours after sunset.

At night there is usually a rather intense urban heat island present during clear conditions ($\Delta T_{u\text{-}r\,(max)}$ up to 7 °C) and one with a somewhat lower intensity during cloudy conditions (Figure 10a and b). In daytime a cool island appears on some occasions, especially during cloudy conditions (Figure 10c and d). Similar results are also presented in Paper III where another 'rural' station is used and the cool island magnitude is generally larger. The coastal location of Station 3, which is used as a 'rural' site (Figure 10), probably causes the difference in magnitude.

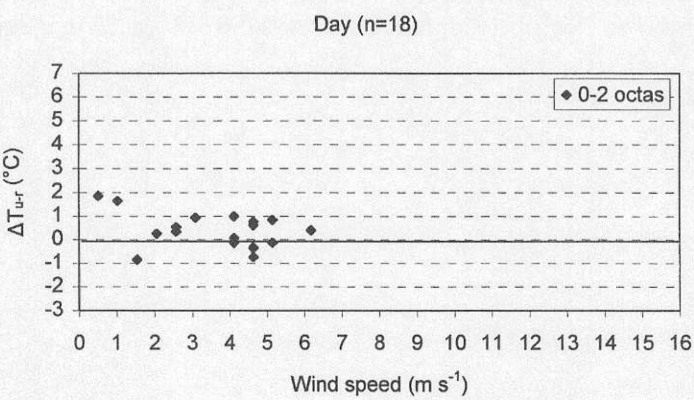
a)


Night (n=39)
0-2 octas
ΔTu-r (°C)
Wind speed (m s-1)

b)


Night (n=118)
6-8 octas
ΔTu-r (°C)
Wind speed (m s-1)

c)


Day (n=18)
0-2 octas
ΔTu-r (°C)
Wind speed (m s-1)

d)

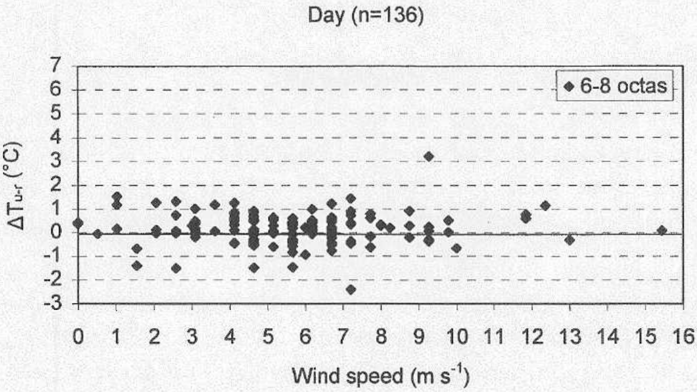


Figure 10. *Scattergram showing the urban heat island intensity $\Delta T_{u\text{-}r}$ (°C) versus wind speed. The number of occasions is denoted n, day is represented by data from 1200 h and night from 3 h after sunset.*

Urban geometry

The urban geometry is important for the energy balance, especially at night, since it regulates the long-wave radiation losses and consequently affects the air temperature. A detailed study of the relationship between air temperature and SVF, calculated from fish-eye photographs, was made in Paper IV. In the literature it was found that fish-eye photographs have been taken at different heights, for example at the level of measurements (height of instruments) or at ground level (e.g. Yamashita et al. 1986, Heisler et al. 1994, Eliasson 1996, Blennow 1998, Brown and Grimmond 2001). The hypothesis was that the relationship between air temperature and SVF depended on where and on the height from which the fish-eye images were captured. Thus fish-eye photographs taken at each air temperature station (Figure 1) at two levels, at ground and at the height of measurement (approximately 2 m above ground), were compared. The difference in SVF at ground level and at sensor height, varied. For some stations the difference between the two heights was ten per cent but generally it was smaller. The differences were statistically significant however and, although small, they influenced the results (Paper IV).

The results based on data from 16 permanent stations (Tiny-logger) located within the three main built-up land use categories (urban dense, multi-family and single houses) indicated that a fairly strong relationship existed (R^2 between 0.51 and 0.58). This relationship varied depending on the height for which the SVF values were calculated. The ground acts as the energy exchange surface and the results from the permanent stations indicated that it is better to use the SVF calculated for the ground level. The correlation was improved and the explanation factor increased from 7 to 12 per cent. Car measurements carried out within the urban dense land use verified the results.

Statistical analyses

Although large variations in air temperature are observed in the landscape, statistical significance could give these differences further validity. A statistical approach was therefore made to analyse the spatial air temperature variation and the relation to geographical parameters and land use in Papers II and III.

Regression analysis is often used to select independent variables for models. It is usually chosen for its simplicity and is the most widely used technique in the development of empirical models (Lanzante 1996). In Paper II the relative influence of land use and other parameters (altitude, SVF and distance to the sea and to the centre of the city) were analysed by means of regression analysis. The air temperature difference was more dependent on weather than on season and the best correlations were found during clear, calm conditions. The regression analysis determined the importance of land use as a parameter affecting air temperature. The effect of different surface coverings (land use/land cover) on the energy balance is more pronounced during clear, calm weather with high air stability. The results showed that most of the variation during cloudy, windy conditions were determined by altitude and land use, while the variation during clear, calm conditions was determined mainly by land use. Wind and cloud smooth out air temperature differences between land use categories and other parameters such as altitude become more important (Paper II).

The statistical significance of the air temperature differences based on the five land categories presented was further tested. An analysis of variance test was performed on the data with the null hypothesis 'no significant differences between the five land use categories'.

Both the observations and the statistical analyses of air temperature differences revealed that there were differences according to land use/land cover, especially during clear, calm conditions but the results also showed that large differences existed during cloudy conditions at both day and night. This is interesting from a planning perspective since this type of weather is common in Sweden, Figure 4 (See also Postgård 2000). The Master Plan could, with some regrouping of categories, be used to categorise temperature variations across the city. The analysis of variance showed that the air temperature within *green* and *urban dense* areas could, with few exceptions, be statistically separated from other areas. The results also proved that statistically significant temperature patterns occur between other land use/land cover categories.

Model simulations and calculations of the spatial pattern of air temperature and PET

Two different models are presented with the GIS approach in common. The local climate model uses meteorological data (air temperature, wind speed, wind direction, cloud cover) from one station and has the advantage of not requiring a lot of data to be run. However, several observations are necessary in order to construct the local climate map incorporated in the model (Paper I). The human comfort model for assessing the thermal component is based on a rather dense station network and requires meteorological data (air temperature, wind speed) from several stations representing different land use categories and altitudes. Additional meteorological data on humidity and radiation (or cloud cover) are also necessary for the calculation of PET with Rayman.

Few biometeorological studies have been performed in high latitude areas previously. In this thesis a new method for illustration of spatial variation of the thermal component expressed as PET is presented (Paper V). Bioclimatic maps for the month of July are developed for the Göteborg urban area with the human comfort model. The results show the spatial pattern of PET within urban areas, where variations in PET of 8 °C are calculated during a clear, calm day at 1200 h. During average diurnal conditions the variation in PET is still relatively large, 5 °C. A comparison of four land use categories revealed a temperature difference of 4.6 °C, while a difference in PET of 7 °C was calculated.

The local climate model showed a general agreement with observations in describing the spatial variations of air temperature within the area (Paper I). During an average day at 1200 h the range in air temperature within the study area is 2.3 °C as shown in Paper III and during a clear, calm night air temperature variations of around 8 °C are obtained from the model (Paper I).

The air temperature pattern simulated with the local climate model is also visible in the calculations of PET. The highest values of PET and air temperature are observed in the city-centre area. One reason is the effect of surface roughness and the corresponding lower wind speeds in the central built-up area. The coastal area is also relatively warm. High PET values are however found in the built-up areas near coast due to land use and wind influence near the ocean.

DISCUSSION AND CONCLUSIONS

Urban climatology is generally seen as a specialist field within climatology where research findings, in addition to the academic interest, have the potential of being applied in the planning and design of urban areas (Mills 1999). For incorporation of urban climate knowledge in the planning process the climatologists first need to demonstrate the importance of climate information. They then need to be able to predict the climatic impact of different planning strategies (Oke 1984). Applicable tools are necessary to succeed in this regard. Urban climatology also needs to be more of a predictive science if it is to be of real value in planning as implied by Oke (1984). Paszynski (1990/91) mentions prognostic maps showing expected modifications of local climate as a consequence of land use changes but the development of models is another useful method.

The results presented in this thesis are empirically based and empirical knowledge has the advantage of illustrating 'real world' conditions. Oke (1984) discusses different types of models. There are, of course, limitations with empirical models which cannot be overlooked. The accumulated experience of the urban climatologist based on case studies and empirical knowledge is, however, a major resource according to Oke (1984). It could be stated that the results are restricted to a specific study area unless the material represents a geographical diversity and is large and general enough to be applied to other areas. By performing a thorough description of the study area, measuring sites and method, results or conclusions from empirical studies may be transferred to similar areas.

In this chapter the results are compared with those from other studies and limitations and improvements of the work will be discussed.

Temperature variations in the urban landscape

In Göteborg, a maximum heat island intensity of almost 9 °C with a mean value of 4.2 °C was observed during clear, calm nights. Simulations show values around 7 °C during a clear, calm situation. These figures are comparable with the value of 7.1 °C for $\Delta T_{u\text{-}r\,(max)}$ by Oke (1981) for a city with a similar population to Göteborg. Besides the verification of a relatively strong urban heat island in Göteborg the measurements show a cool island, a phenomenon known for several cities (Chandler 1970, Ludwig 1970, Taesler 1981, 1991, Oke 1993, Steinecke 1999).

The cause of the negative heat island needs further investigations. However blocking of direct solar beam in dense environments may during clear, calm daytime conditions result in the cool island effect (Chapman et al. 2001); according to Oke (1993) such occurrences are restricted to dense urban canyons. In Reykjavik, Iceland, the cool island, observed during daytime in the middle of summer is enhanced because of the associated low solar altitude (overshadowing in urban sites) and the cooling effect of the ocean close to the centre of the city (Steinecke 1999). Reykjavik is located at a higher latitude (64°) than Göteborg. In the case of Göteborg the air temperature data are collected during the whole year and the sun path varies on a yearly basis. The urban temperature value used is also a mean value from two stations (where one is open), which implies that the cool island exists in the Göteborg area. Furthermore, the use of different rural stations verifies the cool island. Reykjavik and Göteborg have the coastal nearness in common which might enhance the cool island effect. The restriction to only dense canyons is limited since these do not exist in Reykjavik and two urban stations have been used in Göteborg. The cool island has a magnitude of up to 4 °C in both Reykjavik and Göteborg although it usually is much smaller. Taesler (1981) reports differences of around 0.5 to 1 °C. Although the causes of the cool island are uncertain the fact that a negative ΔT_{u-r} difference is observed makes it interesting to examine the energy exchange as well as the mixing and transportation of air in urban areas during both day and night. The frequency of cool islands in central London is fairly high, thirty percent (30 %) of the days and fifteen percent (15 %) of the nights; this is another reason for further investigation (Chandler 1970). The results show that thirty percent of the days experience negative ΔT_{u-r} differences at 1200 h in Göteborg.

Statistically significant air temperature variations were found between different land use/land cover categories (*urban dense, multi-family, single houses, other built-up* and *green*) on a diurnal basis and for all types of weather conditions. On some occasions relatively large variations in air temperature were observed in the area but these differences were not statistically significant. These differences are, nevertheless, equally important and thus statistics is not always the best method to present such information even thought it often is requested.

Models

Human comfort model

There is a considerable amount of knowledge about impacts of climatic elements on human health and comfort. The application of this knowledge is held back by the lack of measures to evaluate the quality of the atmospheric environment. Models or 'design tools' are mentioned by Taesler (1991) to demonstrate the bioclimatic impacts and to analyse the outcome of different design alternatives in terms of human health and comfort. Wind in combination with low temperature, for example, strongly increase the heat loss of the human body (Taesler 1991, Gehl 1996). It is thus important to be able to express and show the human response on climatic parameters.

The human biometeorological field is still a rather young research area compared to urban climatology. Bioclimate maps and the zoning of urban areas with respect to bioclimatic conditions is a way to reach out with this type of information and in this thesis a method for constructing bioclimate maps is presented. Bioclimatic information can however be presented in other ways, for example as the number of hours with wind discomfort, cold or heat stress. The model has the advantage of its non-static approach with GIS maps and the use of observational data. The method is based on a relatively dense network of wind and temperature data, which improves the resolution and results presented in Paper V. Thus measurements within different environments are required for the application of the method in another area.

In this thesis the model is used for zoning of the urban area and a PET value is calculated for each zone. Other common bioclimatic indices such as the Standard Effective Temperature (SET) (Gagge et al. 1986) or Predicted Mean Vote (PMV) (Fanger 1970) can naturally also be calculated.

The climate index PET considers all thermally relevant climatic parameters (air temperature, radiant temperature, wind speed, humidity). By providing PET values as well as air temperature people get the additional information they need to adapt their behaviour and clothing, based on their own experience, to the prevailing weather conditions. Thus the PET is not an absolute measure of thermal comfort since it has to be adjusted to subjective characteristics. However the thermo-physical background makes the PET more appropriate than other biometeorological indices e.g. wind-chill temperature, apparent temperature or effective temperature (Höppe 1999).

Other factors than climatic parameters are important for how the climate conditions in an area are interpreted. Parameters such as the amount of greenery, the surface, building colour and material are important as well as human demographic parameters (e.g. gender, nationality, health conditions, experience and clothing). In cold or moderate climates the opinion of what is experienced as comfortable weather conditions varies considerably from that in warmer climates. People also accept and accommodate to prevailing thermal conditions and take action to avoid discomfort by modifying clothing and activity (Forwood et al. 1999, Donaldson et al. 2001, Nikolopoulou et al. 2001).

Local climate model

As mentioned local climate maps are useful in describing climate variations in an area and they have a great practical significance, especially in town planning (Paszynski 1990/91). This 'traditional' information as well as predictive information, such as the influence of land use/land cover changes, earlier discussed by Oke (1984) can be given with the local climate model described. The GIS approach and digital land use information make it easy to change and modify input parameters. However the model requires input in form of the static climate map which still needs to be constructed in the traditional way by climatologists. The model has advantages compared to the classical interpolation techniques of temperature since problematic areas such as valleys are included in the basis of the model, the climate map. These areas usually experience cold air and are therefore included in the climate map and thus incorporated in the model. Observations are, however, necessary for an interpolation approach in such areas. Elevation has also been shown to cause problems in other interpolation techniques. Tveito and Førland (1999) used *kriging*, an objective and consistent application for mapping air temperature. They found that elevation causes problems, with the largest errors occurring where stations are close in space, but with a large difference in elevation.

Further development of the local climate model

The GIS technique is a valuable instrument for this kind of research and most suitable for geographers and climatologists since the mapped information is easily changed after the prevailing conditions. By using GIS it is also possible for planners and decision-makers to explore possible scenarios and obtain an idea of the consequences of a certain action before real changes are made in the landscape (Burrough 1986). Studies which include both GIS models of climatological variables and statistical relationships between different parameters have been recently performed (Blennow and Persson 1998, Ninyerola et al. 2000, Eriksson 2001).

The results show that the GIS model presented needs some improvements and that it is basically the climate map which needs to be revised. Some areas outside the city centre are assigned a heat island effect of the same magnitude as in the city centre areas. An earlier discussion (Paper I) implied that an algorithm describing distance from the city centre, shown by Alcoforado (1994) to be important for the air temperature pattern, could reduce the maximum urban heat island effect in suburban areas. Results, presented in Paper II, could not verify that this effect is important in Göteborg and this is something which needs further investigation if the model is to be improved.

Information from the land use map could also be used more extensively. By assigning roughness parameters for more land use categories a better description of the wind climate and consequently the temperature climate is received. Useful roughness parameters are presented in Oke (1993) and Givoni (1998), for example. From such information the large forested areas could be extracted from other green structures and used in the model separately.

The model has been verified for clear, calm weather conditions i.e., conditions which favour large climatic variations. Observations show however that large variation also appears during other weather conditions and the model needs to be verified for such conditions as well (Papers II, III). Simulations performed during more average conditions (Paper III) show a smaller temperature range, 2.3 °C which corresponds to measurements. In a verification of this particular day situation 84 % of the simulations were found within a range of 2 °C and the model generally produced lower air temperature values than those observed. A thorough verification of average weather situations is nevertheless necessary.

It is important to identify a suitable method for verification of the model. Large differences in local climate occur over short distances and the grid size (500 × 500 m) may therefore cause difficulties in the verification of the model (Paper I). Grid data and point observations are difficult to compare and evaluate. See discussion below.

What is actually measured?

The urban canopy layer (below roof level) is strongly influenced by small-scale urban elements. Thus, climate conditions below roof level exhibit a high degree of non-homogeneity in response to different land uses, building densities, street width and orientation (Oke 1988). The presence or absence of vegetation and water is also important (Taesler 1991).

The scale on which measurements are performed is chiefly important in climate studies and difficult when considering urban environments. To evaluate the human response of the climate, measurements need to be performed in inhabited areas.

For measurements on a regional scale (10^4-10^6 m) a close response at the point of location of the instruments and the characteristics of the area are necessary. For example, in Göteborg, where forested areas occupy 44 % of the land area it can be argued that 44 % of the measurements should be performed in such environments. On the other hand forested areas in Swedish cities are usually classified as protected areas for recreation purposes, i.e., these areas will not be considered for planning new built-up areas. If selecting a local scale of measurement (10^2-10^3 m) it is more important to include all types of land use/land cover categories which are interesting. These should be grouped into categories where other geographical parameters which are known to affect the local climate are also incorporated, for example the topography and the distance from the coast. For a comprehensive planning perspective this local scale of measurements is important but difficulties appear when it comes to the location of measurement equipment. Measurements are usually performed in the micro scale (10^1 m). The results presented in this thesis show that measurement stations can represent a larger area and measurements performed in the micro scale can thus be representative of the local scale. The results further show that there are variations in air temperature between different land use/land cover categories and that similar temperatures are observed within the same land use category. Coastal nearness is important and measuring stations are located so as to represent an area. Studies in Aveiro, Portugal, also show the effect of coastal proximity as well as urban morphology on the urban heat island intensity (Pinho and Manso Orgaz 2000).

Additionally, the scale or grid resolution of models is important. The scale of local climate maps has been discussed. Climatic maps at scales varying from 1:25000 to 1:250000 were established during the 1970s and 1980s, mainly in central and east European countries but also in Sweden (Lindvist and Mattsson 1989, Paszynski 1990/91). A scale of 1:50000 is used by Lindqvist and Mattsson (1989) for the general survey level and comprehensive planning activities. To clearly define different climatic parameters in maps with this scale may, however, induce problems which affect the accuracy of the climate map (e.g. boundaries between features).

The spatial temperature pattern from simulations (Paper I) shows strong similarities to the patterns obtained from observations performed in the area, yet the comparison of grid data to point observations is difficult. The use of isothermal maps constructed from temperature measurement has been tested as a verification method. Due to the low number of stations in problematic areas such as valleys a complete spatial view of the air temperature patterns was difficult to obtain and this method was therefore rejected. However, car measurements give a spatial distribution of temperature and could perhaps be used to verify the temperature pattern.

In general, the scale of measurements needs great and careful consideration partly for verification but also for the scale for which climate can be simulated. This is important in all studies and not exclusively for this one.

Surface characterisation

Changes in land use do not directly cause shifts in climatic elements, but eventually set up new climatic factors. Examples are building materials with different thermal properties, changed size and the distribution of roughness elements. It is therefore necessary to determine the actual spatial distribution of the relevant climatic factors (Scherer et al. 1999).

The choice of land use/land cover database is important. The Master Plan of the urban district of Göteborg has been used throughout this thesis. The Master Plan, which shows the present and future land use, has advantages as it is continuously updated and revised every three to five years. It serves as a guideline for planners at the Comprehensive Planning Department and is a common tool for urban planners.

Other sources of land use information, for example satellite derived land use databases are often not updated. Moreover, for urban climate studies an aggregation of existing land use classes is usually necessary to avoid 'overlapping' classes. The decision of which classes to choose is difficult and studies have shown that land use aggregation may induce several errors (Shudo et al. 1997, Brown et al. 2000, Burian and Brown 2002). The difficulty of classifying different homogeneous land use/land cover categories as well as successful aggregation is shown in this thesis with the categories *other built-up* and *green* (Paper II).

The careful choice of land use/land cover information and the thorough site description analysis could make the results presented in this thesis valuable for other areas. The site description analysis makes it possible to compare the area and land use/land cover units used with that of another area and general results might be subsequently transferred.

Conclusions

The following main conclusions can be drawn from this thesis:

- Statistically significant air temperature differences exist in urban areas during both day and night and during different weather situations.
- Land use/land cover is an important parameter for air temperature differences in the urban environment.
- Information about the air temperature pattern can be obtained by quantifying the land use structures in the landscape.
- There is a relationship between air temperature and sky view factor and fish-eye photographs taken at ground level gives the best correlations.
- Air temperature simulations with the local climate model developed show general agreement with observations in the area.
- The results from the human comfort model developed show large variations in PET during clear, calm conditions as well as during average diurnal calculations.

APPLICATIONS OF CLIMATE KNOWLEDGE

Possibilities for the improvement of urban climatic conditions by deliberate planning have been poorly exploited (Taesler 1991). There is a need to integrate climatic knowledge in all levels of planning, from regional planning to the design of single buildings. Experience shows that planning according to climatic rules does not necessarily result in higher economic costs. On the other hand it results in improved quality of life and economic benefits due to lower energy costs (Bitan 1988).

Good communication between practitioners and urban researchers is important for good climate planning (Oke 1984, Eliasson 2000). The term 'heat island' commonly used by urban climatologists for the temperature difference between urban and rural areas is one example, which in the field of architecture and urban design often refers to daytime urban heat stress, a crucial difference between the two disciplines. The climatologist needs to know that architecture considers individual structures while urban design concerns groups of structures; in other words, it is within urban design that climatologists can interpret their results. It is also important that urban climate research knowledge is accessible to design practitioners (e.g. Mills 1999).

The calculation and presentation of the thermal component are useful for both planners and the public as shown by Höppe 1999, Jendritzky et al. 2000. The PET index is already applied in urban areas for the prediction of changes in the thermal component due to projected changes in land use (Höppe 1999). The PET is also recommended as an index in 'German guidelines for urban and regional planners'

(VDI 1998). These guidelines strongly emphasise the need for an intensive cooperation between climatologists and planners to incorporate the requirements of human biometeorology in the planning process in an appropriate way.

In Sweden aspects of the local climate are included in the Environmental Impact Assessment (EIA), which is part of The Swedish Planning and Building Act as well as The Swedish Environmental Code. Thus planners and architects are bound to take climate aspects into consideration at both detailed and comprehensive planning levels (Eliasson 2000).

Glaumann (1993) states that the following questions are important to answer in climate planning: What is the climate required? What are the present conditions? and What will be the resulting climate with the land use changes suggested? Planners, residents or climatologists may answer the first question. The second two questions are more difficult. However, with a local climate model such as the one presented in this thesis, useful information which shows the value of these types of studies for planning purposes is provided.

FURTHER RESEARCH

This thesis is written from the view of an urban climatologist and one aim is to interest other disciplines in the large climatic variations which actually exist in the urban environment. It is hoped that this work will contribute to improved communication between climatologists and planners working with urban questions: it is also hoped that it will serve as one step in translating the results of urban climatology into tools which can be applied in planning disciplines. Further investigations are, however, necessary.

The work with the local climate model presented in this thesis will continue. The next step is to apply data from Göteborg on a numerical model, HOTMAC (High Order Turbulence Model for Atmospheric Circulation), (Williams et al. 1995), developed at the Los Alamos National Laboratory (LANL). This test will be used to develop the local climate model. Another aim is to evaluate the advantages and disadvantages of the model from an applied point of view. This will hopefully be done in collaboration with the Comprehensive Planning Department in Göteborg.

During the process of the work the advantages of completely representing the model as a GIS application were realised; this was not possible at the start of this project. It would therefore be interesting to completely convert the model to a GIS software where all analyses and presentation can be made.

The statistical analysis performed in this thesis should be seen as an approach to meeting the demands of research concerning average conditions and statistical significance. The statistical analyses have, however, some limitations and a principal component analysis (PCA) could be used to eliminate the effect of covariance between variables in the regression analysis. This could verify the statistical discussion in the material.

An objective interpolation method as geostatistics or a more sophisticated method which incorporates geographical information such as *co-kriging* (Ninyerola et al. 2000) would also be interesting to test on the data.

Winter climate in high latitudes presents both physiological and psychological bioclimatic problems. The occurrence of cold, wind and snow or ice on the ground, short periods of daylight and frequently cloudy skies strongly influences human behaviour and well-being in Scandinavia (Taesler 1991). Thus cold stress is perhaps more interesting to study than heat stress since Scandinavians seldom complain about conditions being 'too hot'. The vector based human comfort model will therefore be applied to winter conditions in Göteborg.

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