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The surface energy balance and climate in an urban park and its surroundings

Markytans energibalans och klimatet i en urban park och dess omgivning

Erika Bäckström

Abstract

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The world's growing population and the increasing urbanization has made problems related to the urban heat island phenomenon to become more pronounced and since urban parks reduce the stress produced by the urban heat island they can be powerful tools in urban climate design. The temperature near the surface in a park is determined by the energy exchanges between the surface and the air above and it is therefore necessary to understand the surface energy balance of parks to intelligently manage their thermal microclimate. The objectives of this work were to study how the energy balances differ between different surfaces inside parks and in their built-up surroundings and to relate the surface energy balances to temperature differences.

Measurements were conducted during three clear summer days in the park Humlegården located in central Stockholm. The measuring instruments were mounted on a cart, which was transported from observation site to observation site. The observation sites represented typical surfaces found in an urban park and its surroundings: one shaded and one open grass surface, one open and one shaded gravel surface and two paved surfaces representing streets running in the north-south and east-west directions respectively. The energy fluxes were calculated using air and surface temperatures, wind speed, air humidity and net radiation data.

The most pronounced differences between the shaded and open surfaces in the park was that the shaded surfaces in general had smaller energy fluxes during daytime and that they had a downward directed sensible heat flux while the open surfaces had an upward directed sensible heat flux during the day. The most significant difference between the grass and the gravel surfaces in the park was that the grass surfaces had a bigger downward directed latent heat flux during the night and a smaller ground heat flux during both day and night. The largest differences between the surfaces inside the park and those in its built-up vicinities were that the paved surfaces had a larger upward directed sensible and ground heat flux during the night than the other surfaces. During the day the north-south directed paved site had a downward directed ground heat flux that was much larger than the ground heat flux for the other sites.

The coolest site during the night was the non-shaded grass surface, which was the only site with a downward directed sensible heat flux during the night. Compared to the other non-shaded sites the open grass surface had a much smaller ground heat flux. Warmest sites during the night were the paved surfaces, which had a larger upward directed sensible and ground heat flux than the other surfaces. At the built-up sites the walls also contributed with sensible heat flux, i.e. the total sensible heat flux in the built-up area was larger than what comes from the street surface only. During the day the shaded surfaces in the park were the coolest sites. The shaded surfaces had less net radiation compared to the other non-shaded surfaces and were the only sites that had a downward directed sensible heat flux.

Keyword: Surface energy balance, urban climate, urban parks, park cool island

Referat

Energibalansen vid markytan och klimat i en urban park och dess omgivning

Erika Bäckstöm

På grund av världens växande befolkning och urbaniseringen blir problem relaterade till fenomenet urbana värmeöar mer och mer påtagliga. Eftersom urbana parker kan minska påfrestningen skapad av urbana värmeöar kan de vara ett kraftfullt verktyg vid klimatdesign i städer. Temperaturen nära en yta bestäms av energiutbytet mellan ytan och luften ovanför och det är därför nödvändigt att man förstår energibalansen vid markytan för att kunna hantera parkernas mikroklimat. Syftet med det här arbetet var att studera skillnaderna mellan energibalansen för olika ytor i parken och i dess omgivning och att relatera skillnaderna i energibalanserna till temperaturskillnaderna.

Mätningarna utfördes under tre klara sommardagar i parken Humlegården i centrala Stockholm. Mätutrustningen var monterad på en kärra som flyttades från mätplats till mätplats. Mätplatserna representerade olika typiska ytor i Humlegården och i dess omgivning: en skuggad och en öppen gräsmatta, en öppen och en skuggad grusyta och två asfaltytor, varav en löper i nord-sydlig riktning och en i öst-västlig riktning.

Energiflödena beräknades med hjälp av data för luft- och yttemperatur, vindhastighet, luftfuktighet och nettostrålning.

Resultaten visade att den tydligaste skillnaden mellan gräs- och grusytorna i parken var att gräsytorna hade ett större nedåtriktat latent värmeflöde under natten och ett mindre markvärmeflöde under hela dygnet. Den mest distinkta skillnaden mellan de skuggade och öppna ytorna i parken var att de skuggade ytorna hade mindre energiflöden under dagen och att de till skillnad från de andra ytorna hade ett nedåtriktat sensibelt värmeflöde under dagen. Den största skillnaden mellan ytorna i och utanför parken var att asfaltytorna hade ett större uppåtriktat sensibelt värmeflöde och markvärmeflöde under natten.

Under natten var den svalaste mätplasten den öppna gräsmattan, vilken också var den enda mätplasten med ett nedåtriktat sensibelt värmeflöde under natten. Jämfört med de andra icke-skuggade mätplasterna hade den öppna gräsmattan ett mindre markvärmeflöde. Varmaste mätplasterna under natten var asfaltytorna som även hade ett större uppåtriktat sensibelt och markvärmeflöde än de andra ytorna. Under dagen var de skuggade ytorna i parken de svalaste platserna. De var de enda ytorna med ett nedåtriktat sensibelt värmeflöde och nettostrålningen vid ytan var mindre än för de flesta andra mätplatser.

Nyckelord: markytans energibalans, stadsklimat, urbana parker, park cool island

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Preface

This thesis work was done for the department of Department of Land and Water Resources Engineering and is a part a M.Sc. education in aquatic and environmental engineering at Uppsala University.

Supervisor: Christer Jansson, Department of Land and Water Resources Engineering, Royal Institute of Technology, KTH

Subject reviewer: Per-Erik Jansson, Department of Land and Water Resources Engineering, Royal Institute of Technology, KTH

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TABLE OF CONTENTS

1. INTRODUCTION

1.1 BACKGROUND

Concerning climate, weather and etc., the urban areas differ in many ways from rural areas. The location of buildings in an area gives rise to radiative, thermal, moisture and aerodynamic modifications of the surrounding environment (Oke, 1987). The process of urbanization therefore causes radical changes in the nature of the surface and in the atmospheric properties of a region. For example; the modern urban construction materials both make the city an efficient heat store as well as waterproofs the surfaces; the geometry of the buildings creates the possibility of radiation trapping and air stagnation; and the heat and water released because of human activities supplement the natural sources of heat and water (Oke, 1987). All these factors contribute in making the city warmer than its rural surroundings in most mid- and high latitude cities. The cities create their own climate (Australian Bureau of Meteorology, 2005) and this phenomenon is called the urban heat island effect (Taha, 1997). Other factors contributing to the urban heat island is the lesser amount of trees and other natural vegetation that can shade buildings, block incoming solar radiation and cool the air by evapotranspiration (Estes et al., 1999). The heat island is a reflection of the total amount of microclimatic changes brought about by man-made alterations of the surface. The clearest evidence of the urban heat island is the fact that the local temperatures in cities have risen as the cities have grown. For example in Tokyo the temperatures has been rising since 1920 over and above the regional trend and during the period of rapid re-construction, after being largely destroyed during World War II, the temperature rose nearly 1°C (Landsberg, 1981).

In warm regions the heat island is an unwanted phenomenon because it increases the air conditioning costs, the heat-related illness and the mortality (U.S. Enviromental Protection Agency, 2005). Some studies also has shown that a warmer climate gives people a more offensive and aggressive behaviour (Australian Bureau of Meteorology, 2005). However, in high latitude cities during the winter, the urban heat island can be beneficial since it can reduce the amount of energy needed for heating (Taha, 1997). But even though the urban heat island reduces the energy demand in the winter, it increases the total yearly energy demand in many places since the additional energy needed for air-conditioning in the summer outweighs the energy savings in the winter (Landsberg, 1981). Even in high latitudes very high temperatures can occur in the cities during the summer and cause discomfort and illness. Figure 1 illustrates the urban heat island along a transect from the countryside to the city.

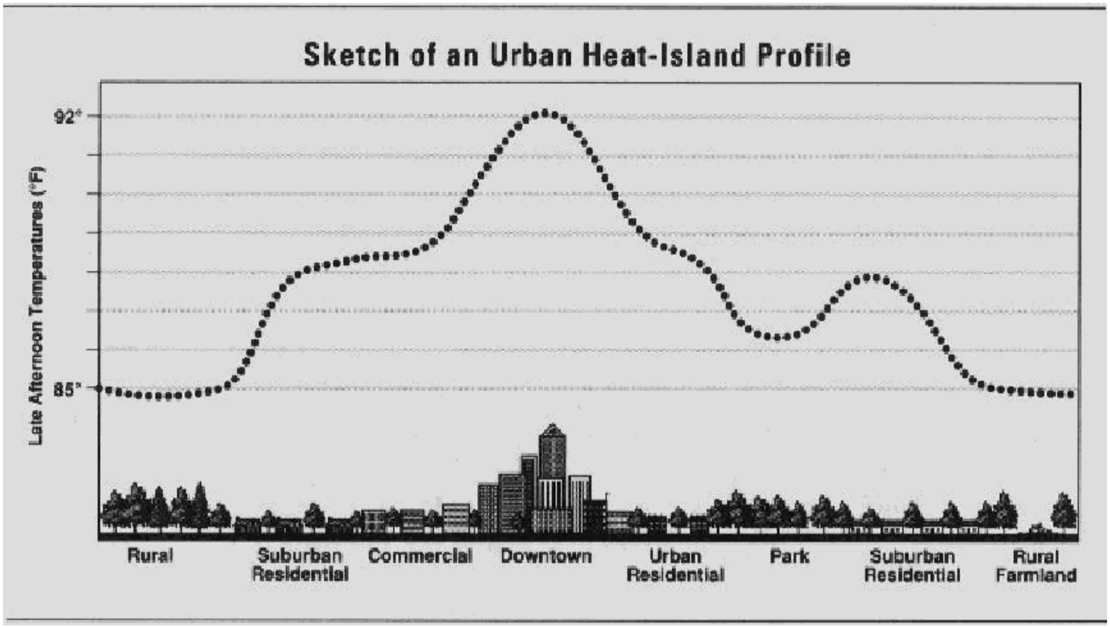


Figure 1. A schematic view of the urban heat island (Estes et al., 1999)

The temperature profile in figure 1 illustrates that the temperature is reduced in the urban park compared to its built-up surroundings. Studies have shown that urban parks establish their own climate and that a vegetated park usually is a cool patch in the city (Upmanis et al., 1998). This phenomenon is sometimes called the park cool island effect and is especially pronounced during the night. For work related to daytime climate the results are more ambiguous and indicates that the park can be both cooler and warmer than its vicinities (Upmanis et al., 1998). It seems like moist parks with growing vegetation and trees are relatively cool while open parks with dry grass or bare soil can be warmer than their built-up surroundings (Spronken-Smith and Oke, 1999). Lower temperatures inside parks at daytime are usually explained by shading due to trees (Upmanis, 1999). The magnitude of the park cool island effect varies with park type, park size (Upmanis et al., 1998) and the extent to which the park differs from its surroundings (Spronken-Smith and Oke, 1999). It has also been shown that the cold park climate can extend beyond the park borders, thus cooling the surrounding built-up areas (Upmanis et al., 1998).

When a city, or part of a city, is designed to create a wanted microclimate it is called urban climate design and it is done by using knowledge of how different designs the urban environment affect the climate in the city. For example, urban climate design, by using vegetation, can be used to lower the temperature in cities in warm regions.

1.2 PROBLEM FORMULATION

The world's growing population and the trend of increasing urbanization cause the world's cities to grow and become more densely populated. This causes problems related to the phenomenon of urban heat islands to become more emphasized. Therefore, it is of great interest to find ways to counteract the urban heat islands and to lower the temperature in cities. Since the urban parks reduce the stress produced by the urban heat island (Landsberg, 1981) they can be powerful tools in urban climate design. The air temperature near the surface in a park is determined by the energy exchanges between the surface and the air above (Ackerman and Knox, 2003) and it is therefore necessary to understand the surface energy balance for parks to intelligently manage their thermal microclimate (Spronken-Smith et al., 1999). Questions that need to be addressed are; how do the surface energy balance in a park differ from the energy balance in its built vicinity; and can the thermal differences be related to the surface energy balance? Many studies have been done that examines the temperature differences between parks and their built-up surroundings, but not many studies have been done that investigates the underlying reasons for the temperature differences by examining the surface energy balance.

1.3 PURPOSE

The objectives of this work were to study how the energy balances differ between different surfaces inside parks and in their built-up surroundings and to relate the surface energy balances to the temperature differences.

2. THEORY

2.1 THE SURFACE ENERGY BALANCE

The net radiation, the net of all in- and out-coming radiation of a surface.

The surface radiation balance at daytime:

$$Q = K{\downarrow} - K{\uparrow} + L{\downarrow} - L{\uparrow} \qquad (1)$$

At night when solar radiation is absent:

$$Q = L{\downarrow} - L{\uparrow} \qquad (2)$$

$K{\downarrow}$ stands for the incoming direct and diffuse short-wave. $K{\uparrow}$ stands for reflected short-wave radiation, $L{\downarrow}$ for incoming long-wave radiation from the atmosphere and $L{\uparrow}$ for outgoing long-wave radiation from the surface.

$K{\uparrow}$ and $L{\uparrow}$ are site-specific terms and govern the differences in radiation budget between surfaces in the same local region. How much of the incoming short-wave radiation that is reflected depends on the albedo for the surface, the surfaces reflection ability, which varies greatly between surfaces with different characteristics. The portion of $K{\downarrow}$ that is not reflected is absorbed by the earth's surface and converted from radiation into thermal energy, which warms the surface. The warm surface emits long-wave radiation that is proportional to T_s^4, where T_s is the surface temperature. The atmosphere absorbs a large part of the outgoing long-wave radiation and emits long-wave radiation to the space and back to the earth's surface. The typical diurnal course of Q (figure 2) involves a daytime surface radiant surplus when the net short-wave gain exceeds the net long-wave loss and a nocturnal radiation deficit when the net long-wave loss is unopposed by solar input (Oke, 1987).

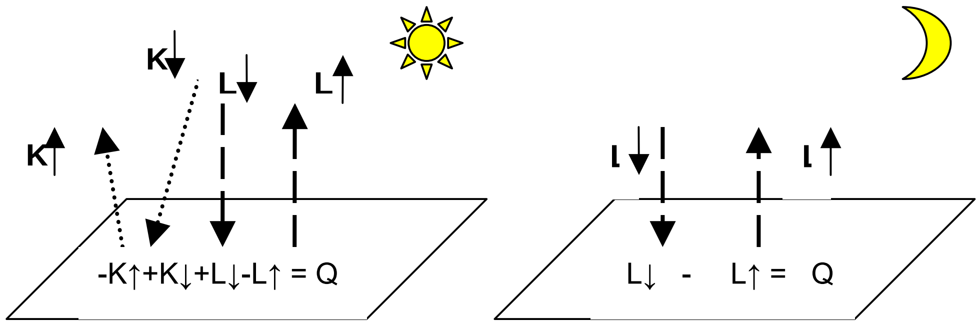


Figure 2. The schematic radiation balance of a surface at day- and nighttime.

The net radiation flux, Q, is the basic input to the surface energy balance. The energy balance for a surface is the sum of latent, sensible and ground heat fluxes. Sensible heat, Q_H, is the turbulent transport of heat between the surface and the atmosphere. Latent heat, Q_E, is the energy that is absorbed or released when water is changing state. Ground heat, Q_G, is the heat transferred from or to the soil below the surface. At any given time any surface radiative imbalance is accounted for by a combination of convective exchange to or from the atmosphere, either as sensible or latent heat, and conduction to or from the underlying soil. The surface energy balance:

$$Q = Q_E + Q_H + Q_G \tag{3}$$

The sign convention employed is that non-radiative fluxes directed away from a surface are positive. Thus the terms on the right hand side of equation three are positive when they represent losses of energy from the surface and negative when they represent gains. On the left hand side is the net radiation positive as a gain and negative as a loss. Figure three illustrates normal situations during day and night (Oke, 1987).

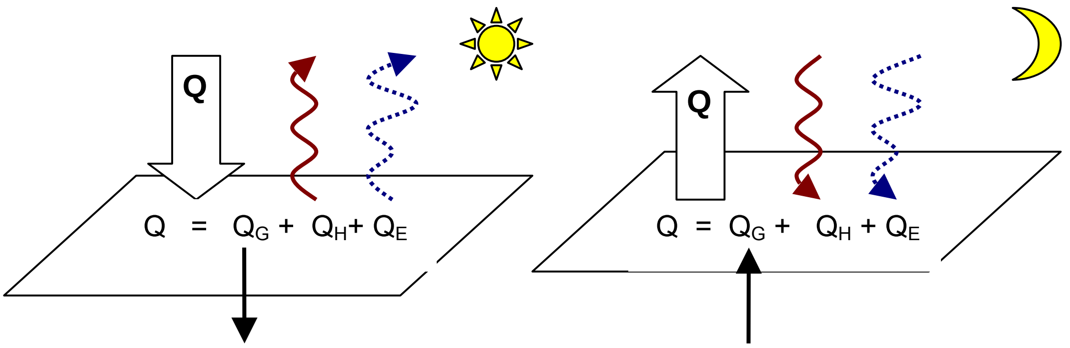


Figure 3. The energy balance for a surface at day- and nighttime.

How Q is divided into Q_E, Q_H and Q_G depends on the nature of the surface and the abilities of the soil and atmosphere to transport heat. The relative importance of Q_E versus Q_H is mainly governed by the amount of water available for evapotranspiration, but it also depends on the air humidity and temperature gradient (Oke, 1987).

2.1.1 Sensible heat flux (Q_H)

The sensible heat is given by:

$$Q_H = - C_a K_H(\partial\theta/\partial z) \quad (4)$$

Where C_a is the heat capacity of air, K_H the eddy conductivity, $\partial\theta/\partial z$ is the potential temperature gradient and z the height. $\theta \approx T$ (T=temperature) when the height interval is small. The sign of the temperature gradient determines the direction of the heat transfer. By day the gradient is negative and Q_H is positive and by night it is the opposite. The sensible heat is carried from warm surfaces to the cooler air above by turbulent eddies and the reverse transport occurs when the air is warmer than the surface (Oke, 1987). Equation 4 is the general equation for the sensible heat flux but there are other ways of applying this equation. The following equation is another more practical way of applying equation 4 since the sensible heat flux can be calculated using more easily accessible meteorological data:

$$Q_H = \rho_a C_p(T_s - T_a)/r_a \quad (5)$$

where ρ_a is the density for damp air, C_p is the specific heat of air at a constant pressure, T_s and T_a is the surface and air temperatures and r_a is the aerodynamic resistance. The aerodynamic resistance is the bulk metrological descriptor for the atmospheric turbulent transport of water vapour and heat. (Oke, 1987). The aerodynamic resistance:

$$r_a = \ln((z_u-z_d)/z_{0m})\ln((z_h-z_d)/z_{0h})/(k^2 u) \quad (6)$$

Where u is the wind speed at height z_u, z_u is the height above the surface where the wind is measured, z_d is the zero plane displacement, z_{0m} is the roughness length governing momentum transfer, z_{0h} is the roughness length governing the transfer of heat and vapour, z_h is the height above the surface where the air humidity or temperature is measured and k is the von Karmans constant (Allen et al., 1998).

2.1.2 Ground heat flux (Q_G)

Heat transfer in the soil is dominated by conduction. The effectiveness of this type of heat transfer can vary widely between different soils and the thermal conductivity can be used to describe these differences. The thermal conductivity, k_s, is a measure of the soils ability to conduct heat and it varies both with depth and time. If you look at the bulk average k_s it depends upon the conductivity of the soil particles, the soil porosity, the soil structure and the soil moisture content. The ground heat flux is given by the equation:

$$Q_G = k_s(\partial T_s/\partial z) \quad (7)$$

$\partial T_s/\partial z$ is the soil temperature gradient (Oke, 1987).

2.1.3 Latent heat flux (Q_E)

The evaporation process depends on the availability of water, the availability of energy to enable a change of state, the existence of a vapour concentration gradient and a turbulent atmosphere to transport the vapour away. The transport of latent heat is tied to the transport of water vapour that is transported upwards by eddy diffusion in a process analogous to that for sensible heat. The latent heat equation:

$$Q_E = - L_v K_V(\partial\rho_v/\partial z) \qquad (8)$$

K_V is the eddy diffusivity for water vapour, L_v is the latent heat of vaporization which is the energy required to vaporize water, and $\partial\rho_v/\partial z$ is the vapour density gradient. ρ_v is the vapour density which is an expression of the vapour content in the air. ρ_v relates to the mass of water vapour molecules in a volume of air. The evaporative loss is largest during the day but often continues at a reduced rate throughout the night. Under certain conditions, mainly during the night, water vapour can be transported downward, condensate, as dewfall. Radiative cooling at night may cause the surface temperature to fall below that of the contacting moist air, and thereby causing a negative vapour density gradient which results in condensation (Oke, 1987). The following equation is another, more practical way, of applying equation 8:

$$Q_E = - L_v \,\Delta\rho_v/r_a \qquad (9)$$

where $\Delta\rho_v$ is equal to $\rho_v(air)$- $\rho_v(surface)$ (Oke, 1987). An equation that often is used for estimation of the latent heat flux from vegetation is the Penman-Monteith equation. The benefit of this equation compared to equation 9 is that the air humidity at the surface does not need to be known. This so-called combination method is based on calculating the evaporation as a rest term of the energy balance. The Penman-Monteith equation (Monteith, 1980):

$$Q_E = (sQ+(\rho_a C_p(e_{sat}(T_a)- e_a)/r_a))/(s+\gamma(1+r_c/r_a)) \qquad (10)$$

where r_c is the integrated stomatal resistance for the whole foliage, T_a is the air temperature (°C), γ is the psychrometric constant, e_{sat} is the saturated vapour pressure, e_a is the airs vapour pressure and s is the slope of the saturation vapour pressure temperature relationship. In this form of the Penman-Monteith equation the ground heat flux is assumed to be zero ($Q= Q_E+Q_H$).

2.2 URBAN AREAS

Even though urbanization alters all the components of the radiation budget, the net effects on urban/rural radiation differences are small. The energy balance is altered considerably by urbanization and the most important effect is probably that evapotranspiration in the city is much lower, compared to rural areas. This leads to a channelling of energy into sensible heat and therefore a warming of the enviroment. In the morning the sensible heat flux is directed towards the surfaces and contributes to the energy storage, and in the late afternoon and evening the stored energy is released to the atmosphere as sensible heat. However, the greater heat storage of urban systems is not due to changed thermal properties. The reason could be the lack of insulation provided by vegetation in urban zones, the reduced latent heat uptake due to the dryness of urban materials, or the greater surface area for absorption caused by the urban geometry (Oke, 1987).

3. MATERIAL AND METHOD

3.1 OBSERVATION

3.1.1 Humlegården and the observation sites

Humlegården is one of Stockholm's oldest parks and was from the beginning a royal garden founded in 1568 by king Johan III. It has been a public park since 1869 and the royal library has been located there since 1886 (susning.nu, 2005).

Figure 4. Humlegården and its neighbourhood (With permission from Lantmäteriet, National Land Survey of Sweden)

Humlegården is a 0.11 km^2 vegetated park that is mostly covered with grass. Groves of deciduous trees cover approximately 50 % of the park's surface and the park is in all directions delimited by streets (figure 4 and 5). Gravel paths lead trough the park and there are also a few gravel playing fields. Beside the large library, only a few minor buildings are situated in the park. The soil in the uppermost ground layer is classified as light clay (Linde, 2005). The mean annual precipitation in the area is 500 – 600 mm, the mean annual temperature is 4 – 6°C and the mean annual global radiation is 950 – 1000 kWh/m^2 (SMHI, 2005).

The measurements were conducted at six different locations, four inside the park and two in the park's surroundings. The sites were chosen based on their characteristics and represents typical environments.

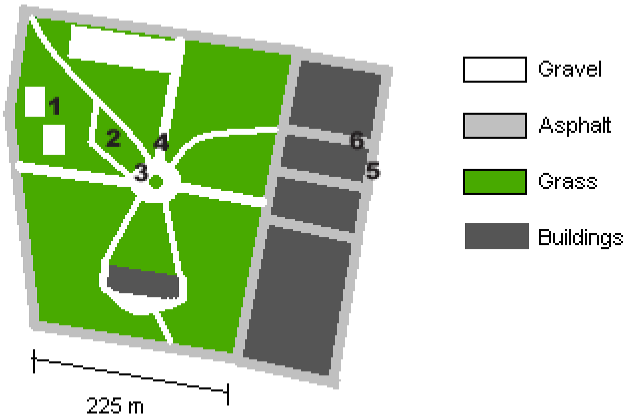


Figure 5. A map over Humlegården with the six observation sites marked out.

The sites:

1. A shaded grass area partly surrounded by trees.
2. An open lawn.
3. A non-shaded gravel path partly surrounded by trees
4. A shaded gravel path lined with trees
5. An asphalt street running in the north-south direction.
6. An asphalt street running in the east-west direction

For the locations of the sites see figure 5.

3.1.2 Measuring instruments

The measured variables were:

- The air temperature at three different heights (T_a).
- The surface temperature (T_s).
- The surface temperature of the surrounding walls at location 5 and 6.
- The relative air humidity at two different heights (h).
- Net radiation (Q).
- Wind direction and wind speed
- The soil temperature (not at location 5 and 6) at 0.06-0.12 m depth.

The air temperature was measured with 0.1 mm copper-constantan thermocouples at the heights 0.78, 1.6 and 2.05 m. The surface temperature was observed with an infrared temperature sensor mounted at a height of 0.6 m. A 2-D sonic anemometer measured the windspeed and wind direction at a height of 2.2 m. Two Vaisala HMP243 sensors mounted inside radiation shelters at two different heights, 1.00 and 1.78 m, recorded the air humidity. The net radiation was measured with a Siemen Ersking net-radiometer at a height of 0.6 m above the surface. A stick-thermometer was used to measure the ground temperature at different depths. All the measuring instruments except for the stick-thermometer were mounted on a cart (Figure 6).

Figure 6. The cart with the measuring instruments

The cart was transported around the park from site to site, starting with site one and ending with site six. One round, from observation site one to site six, took about two hours. At every site most of the data were sampled and stored in a datalogger every five seconds during a period of about fifteen minutes. The observation period was chosen with respect to the net radiation instrument, which had a response time of 10 minutes. One variable that was not collected every five seconds was the ground temperature that was measured manually roughly 2 to 4 times during each observation period. Because of trouble with the measuring instruments the surface temperature was also measured manually during the last observation day.

An attempt was made to calibrate the net-radiometer by mounting it next to a stationary net-radiometer so the data from the both net-radiometers could be compared. But there was a power failure at the station and the data from the stationary net-radiometer was lost.

3.1.3 Observation days

The observations were conducted during clear and calm days, when the thermal differences between the park and its surroundings were expected to be the most pronounced (Spronken-Smith and Oke, 1999). The observations were made on July 7, July 28 and on August 17.

On July 7 one observation round, from location 1 to 6, was completed in the early morning and data were recorded at some of the sites during the evening. July 7 was a hot day and it had been warm and dry for about a week and temperatures as high as 32 °C had been noted in Stockholm. The week after it began raining and the temperature fell.

On the second observation day, July 28, data were collected during the night and during a part of the day. July 28 was a clear day but in the afternoon clouds shaded the sun at times. It had rained almost every day for two weeks so the soil moisture was high and at some spots there were pools of water. The average wind speed was 0.8 m/s but it could be as big as 4 m/s at times. The temperature during the night was 13-15°C and about 20°C during the day. After July 28 it continued to rain almost every day.

On the third observation day, August 17, the measurements were conducted during 24 hours, except for a short period in the morning (Table 1). August 17 was also a clear day with only few clouds covering the sun occasionally in the afternoon. Because of all the previous raining the soil was very moist and the grass was wet during the night and morning. The wind speed was in average 0.5 m/s during the 24 hours. The temperature during the night was 10-12°C and about 20°C during the day.

Table 1. Observation times for the observation days

	July 7	July 28	August 17
Time of observation (hh:mm)	05:47 – 08:42 18:00 – 22:17	00:50 – 09:12 11:42 – 14:13	00:32 -08:10 11:38 – 23:40

Table 1 shows the observation times for the each observation day. The cause for the odd data series is that one of the data loggers sometimes malfunctioned. Because of the time limit for this work and the fact that the summer almost was over, no more measurements were done after August 17.

3.2 DATA TREATMENT

3.2.1 Outlier tests

Outlier tests were done to identify values that were divergent relative to the mean. The data were plotted in so called Scatter plots which provide a good overview and allows individual outliers to be identified. (Håkansson and Roberts, 1995) Some outliers representing erroneous values were identified from the scatter plots and removed. Some of these values were caused by problems with one of the data loggers that at times caused unreasonable values. At low windspeeds the data sometimes showed negative windspeeds. Since the wind speed never can be negative those values were changed to zero. Very high temperature values caused by cars passing by too close to the temperature sensors were removed. One odd surface temperature value on August 17 was identified. An approximation of that value was done using interpolation between the two closest values.

3.2.2 Interpolations

For three observation periods on August 17 net-radiation values were missing. Q was then approximated by linear interpolation from neighbouring values. The approximated values were nighttime values so the interpolated values ought to be trustworthy since it is not probable that the net radiation should change drastically during the night. Because of the malfunctioned data logger there were also some air humidity values missing. Linear interpolations between the neighbouring values approximated those values.

3.2.3 Mean formations

Since all variables was not measured at exactly the same time during the observation periods and the net-radiometer needed time to stabilize, a mean for all the variables was calculated for every fifteen minutes long observation period. Since the response time for the net-radiometer was about ten minutes, the net-radiation mean was calculated for the last five minutes of the observation period.

3.3 ENERGY BALANCE CALCULATIONS

Since the amount of data from the first day of observation was quite small the following calculations were done only for the two last days, July 28 and August 17. Equation 5, 9 and 10 are used for calculating the energy balance components. It should be noticed that the formulation for the aerodynamic resistance, equation 6, is applied for homogenous terrain and may not be strictly valid within the heterogeneous urban environment.

3.3.1 Sensible heat flux

The sensible heat flux was calculated with equation 5. The aerodynamic resistance was calculated using equation 6. The z_d and z_{0m} values for grass, gravel and asphalt were taken from the literature (Table 2). The roughness length governing transfer of heat and vapour, z_{oh}, was approximated as 1/10 of the roughness length governing momentum transfer (Allen et al., 1998).

Table 2. Roughness lengths and zero plane displacements

Surface	z_{0m}	z_{0h}	z_d
Asphalt[1]	0,01	0,001	0
Gravel[2]	0,01	0,001	0
Short grass[2]	0,01	0,001	0,067

1) z_{0m} from Bruse 2005; 2) z_{0m} from Oke 1987

The air temperature used for the Q_H calculations was taken from the sensor at 0.78 m height.

3.3.2 Latent heat flux, grass surfaces

The air humidity of the leaf surface was not measured and therefore equation 9 could not be used for calculation of the latent heat flux. However, since the ground heat flux can be presumed to have been small the Penman-Monteith equation, equation 10, was used. The integrated stomatal resistance for well-watered grass is 20 -50 sm^{-1} (Jones, 1992). r_c=20 sm^{-1} was used since a higher water availability gives a lower integrated stomatal resistance and the soil in Humlegården was very moist during the observation days. The air humidity used for calculating the latent heat flux was taken from the sensor at 1 m height.

3.3.3 Latent heat flux, Gravel surfaces

The ground heat flux for the gravel surfaces can not be assumed to be small and therefore the Penman-Monteith equation was not used for these surfaces. Instead equation 9 was used for the calculation of the latent heat flux for the gravel surfaces. The vapour density was calculated from the relative air humidity. See appendix 2 for the equations used to estimate e_{sat}, s and ρ_v.

The relative air humidity, h, at the gravel surfaces was not measured and was therefore approximated. Because of previous days raining and lack of sunshine, the gravel surfaces were expected to be moist at the beginning of the observation period. According to the observation the sunrays hit the ground in Humlegården at around six a clock. The gravel surfaces are therefore presumed to start drying up at bout six a clock. h for the open gravel surface was approximated to decrease during the day reaching its minimum about four a clock in the afternoon when the temperature in the park was peaking and the ground should have been the most dry. The relative air humidity for the open surface was then assumed to increase a little since the surface ought to have gotten so dry that it would have absorbed some of the water from the more humid air. The shaded gravel surface was observed to have been more moist throughout the day compared to the open surface and was therefore assumed to dry less than the open gravel surface. Figure 7 demonstrates how h at the gravel surfaces was approximated to vary during the day.

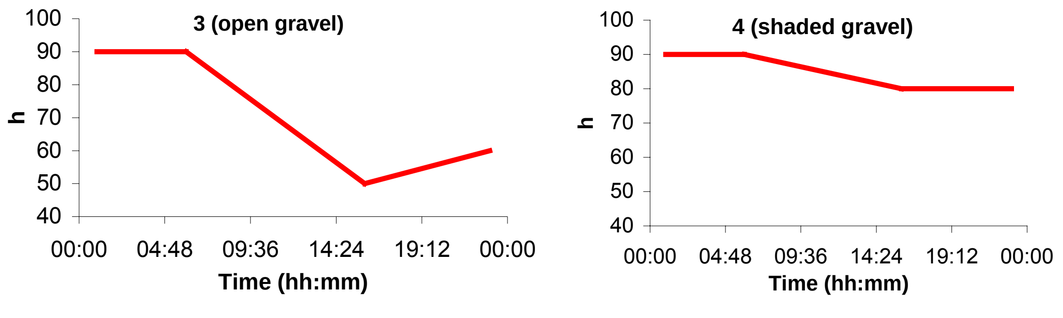


Figure 7. The approximated relative air humidity, h, at the gravel surfaces, site 3 and 4 on August 17.

3.3.4 Latent heat flux, Asphalt surfaces

At site 5 and 6 the surface material was asphalt. Asphalt is almost waterproof which results in the water access at the surface is very poor, hence the latent heat flux becomes very small. During the night were no dew observed on the paved surfaces. Q_E is therefore assumed to be zero for site 5 and 6 during the whole 24-hour period.

3.3.5 Ground heat flux

Unfortunately the ground heat flux could not be calculated according to equation 7 using the measured soil temperature data because of problems with the stick thermometer. It seems like the contact between the stick thermometer and the soil was poor, which caused air to seep down between the thermometer and the soil, which caused strange soil temperatures. But the ground heat flux could still have been calculated according to equation 7 if soil temperatures and thermal conductivities were approximated. The ground heat flux could also have been calculated using methods that allows you to calculate the ground heat flux from the surface temperature if the soils thermal properties were approximated. However, since the net radiation, Q, was measured and Q_E and Q_H estimated, the only component in equation 3 that was still missing was the ground heat flux, Q_G. This approach requires no approximations of the soil heat properties and the ground heat flux was therefore calculated as a rest term.

4. RESULTS

4.1 THE ENERGY BALANCE

4.1.1 Differences between the observation days.

The energy balances for July 28 and August 17 follows approximately the same patterns. However for the built-up sites there were some differences between the observation days. One difference for site 5 can be seen in figure 8 and 9, which is that the net radiation and ground heat flux was greater during the day on August 17 than on July 28. The differences between the observation days for site 6 were minor. See appendix 3 for all graphs of the energy balances on July 28.

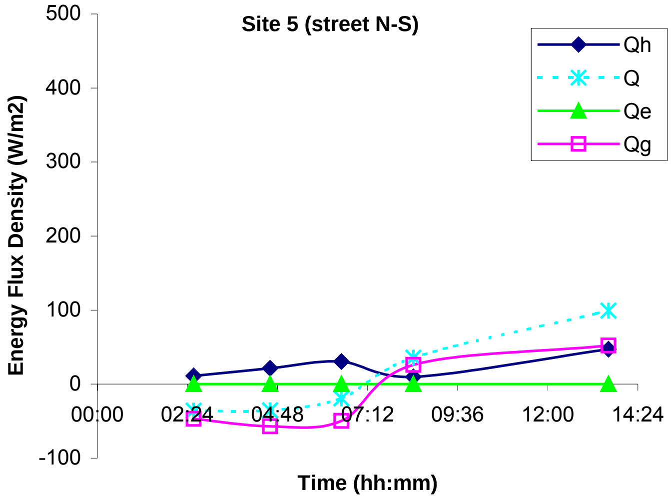


Figure 8. The energy balance at site five on July 28.

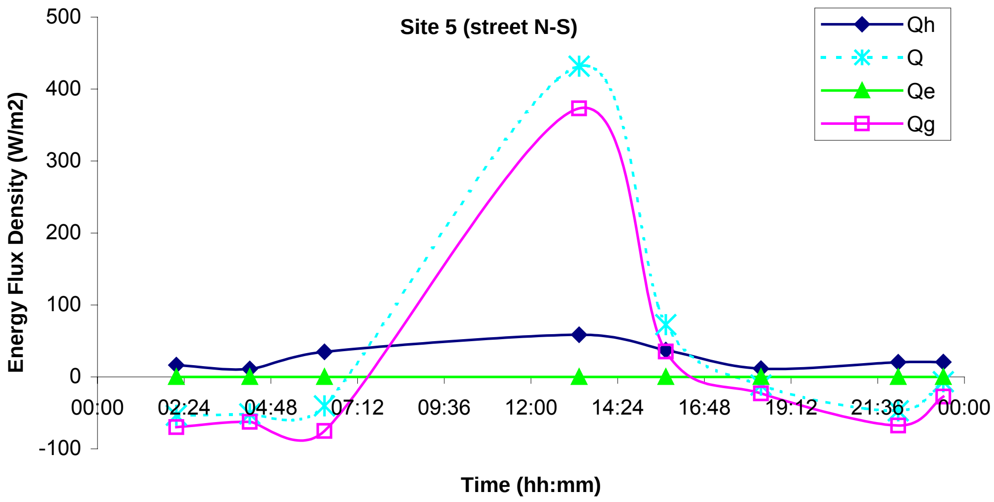


Figure 9. The energy balance at site five on August 17.

4.1.2 The energy balances for the different surfaces

When comparing the energy balances for the different sites only data from August 17 was used since it is the only data series that illustrates the variations in the components of the energy balance during a 24-hour period.

The most significant differences between the shaded and open surfaces in the park were that the open surfaces had a much larger Q and Q_E and that the shaded surfaces had a downward directed sensible heat flux during daytime while the open surfaces had an upward directed sensible heat flux. The open surfaces also had larger Q_G during daytime (Figure 11 and 12). The most pronounced differences between the grass and gravel surfaces were that the grass surfaces had a greater downward directed latent heat flux during the night and that the grass surfaces in general had a smaller ground heat flux than the gravel surfaces during the whole 24-hour period.

When comparing the energy balances for the park sites with the sites in the parks built-up surroundings it was hard to identify any specific differences. Apart from the latent heat flux there seem to have been almost as much differences between the surfaces within the park as it was between the surfaces in the park and the surfaces in the parks built-up surroundings. However, during night the paved surfaces had a larger sensible and ground heat flux than the other surfaces. During the day site 6 had a ground heat flux that was much larger than the ground heat flux for the other sites.

The shaded grass surface, site 1, was characterized by small energy fluxes and an upward directed latent heat flux during daytime that was greater than the net radiation. The sensible heat flux was directed downward during the day and upward during the night. The shaded grass surface was the only park surface that had a ground heat flux that was directed towards the surface during the whole 24-hour period. The other park surfaces had a ground heat flux that was directed away from the surface during the middle of the day and towards the surface during night, which is more realistic.

The open grass surface, site 2, was characterized by positive energy fluxes during the day and negative energy fluxes during the night. This is according to the theory (see section 2.1) the typical situations during day and night. The latent heat flux was almost as large as the net radiation during daytime. Both grass surfaces had a latent heat flux that was negative during the night and positive during the day. The open grass site had a larger Q during daytime and upward directed Q during nighttime than the shaded grass site.

The non-shaded gravel surface, site 3, was characterized by having the greatest net radiation and sensible heat flux during daytime of all the surfaces in the park. Compared to the open grass surface the non-shaded gravel surface had a smaller latent heat flux and a larger sensible heat flux. The non-shaded gravel surface had the largest sensible heat flux during the day of all the sites and it was the only park site which had an upward directed Q_H during the whole 24-hour period.

The shaded gravel surface, site 4, had, unlike the open gravel surface, a sensible heat flux that was directed downward during the day just like the shaded grass surface. Similar to the shaded grass the shaded gravel surface had a latent heat flux that was larger than the net radiation during parts of the day. The ground heat flux for the shaded gravel surface varied suddenly and was directed downward during the day and upward during the night. Contrary to the grass surfaces the gravel surfaces had an upward directed latent heat flux even during the night (Figure 12).

During the night the energy fluxes for the two asphalt surfaces, site 5 and 6, were similar while the results for the day were different. The net radiation for site 5 was more like the non-shaded sites in the park while Q for site 6 was more like Q for the shaded sites. Both asphalt surfaces had rather large sensible heat flux during the day, about the same magnitude as the sensible heat flux for the non-shaded gravel surface. Site 6 had a sensible heat flux that was larger than the net radiation during most of the day. The ground heat flux at site 5 was directed downward during the day, energy was stored, and directed upward during the night, energy was released. For site 6 it seems like heat was being released from the ground during the whole 24-hour period.

Figure 10 shows that the walls surrounding the street at site 6 were warmer than the air and that the surface temperatures of the walls were at least as high as the surface temperature of the street. This indicates that the sensible heat fluxes at the built-up sites were larger than the fluxes illustrated in figure 11 since the walls, and not only the asphalt surfaces, were significant sources for sensible heat.

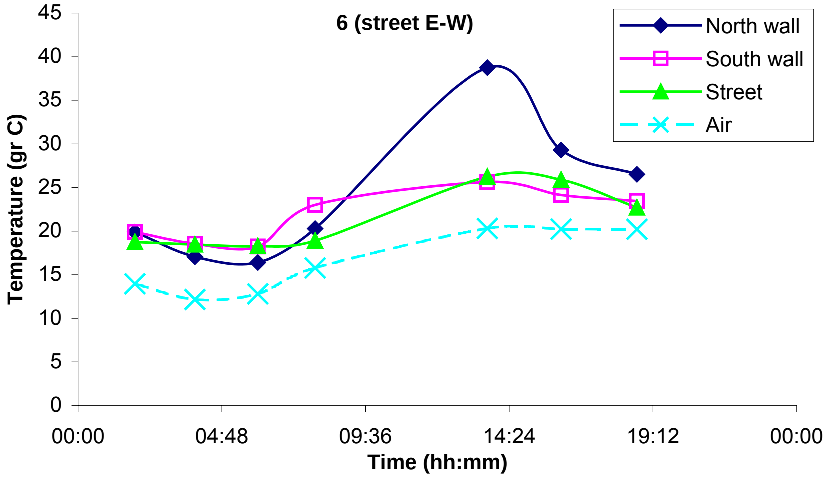


Figure 10. The air temperature and surface temperatures of the street and the walls surrounding the street at site 6 on August 17.

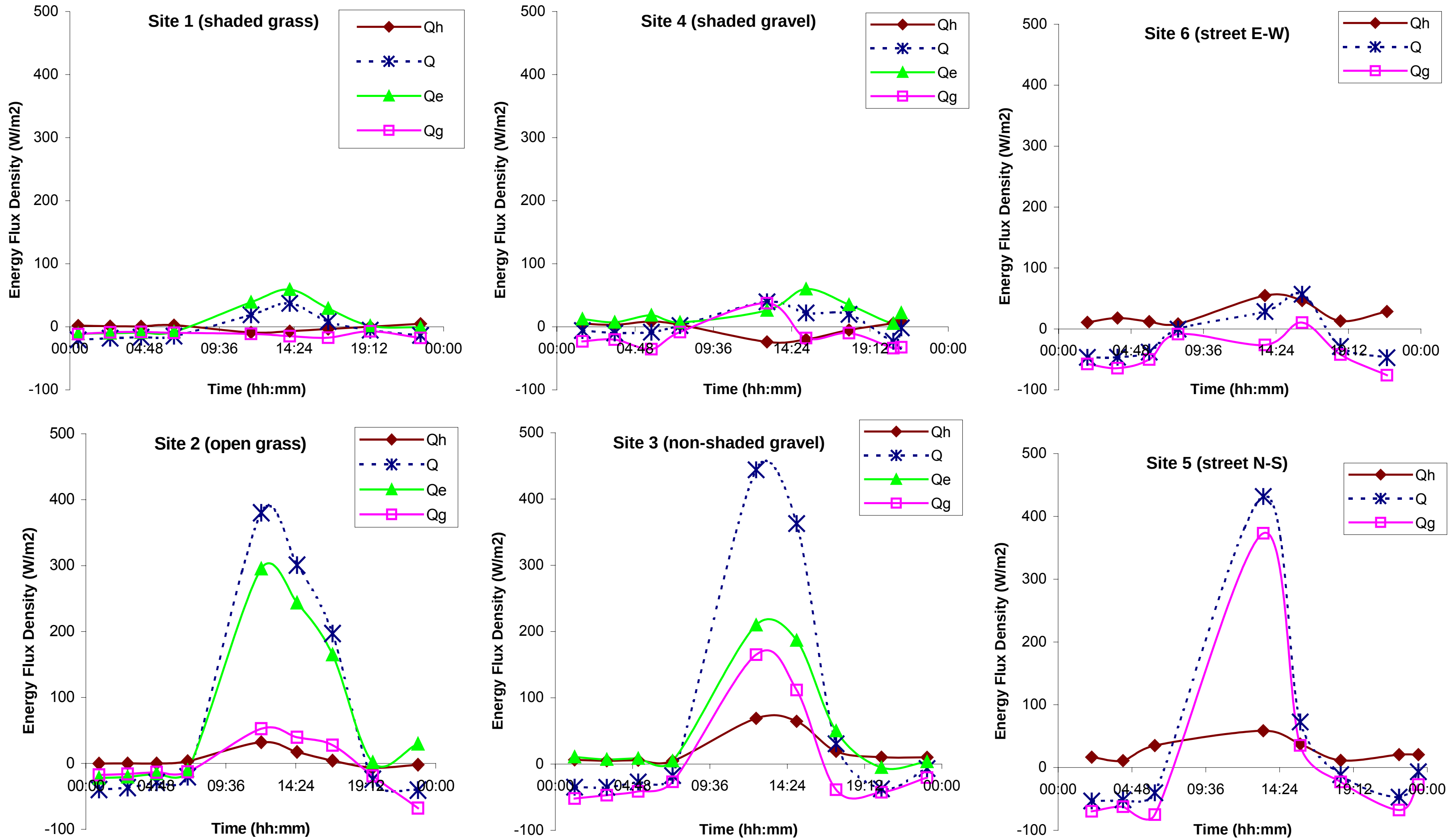
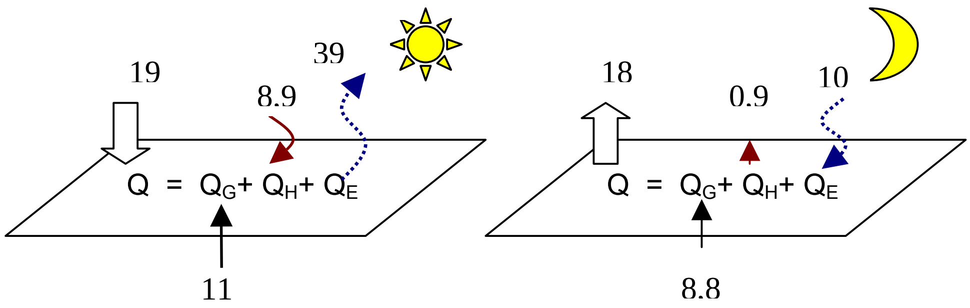
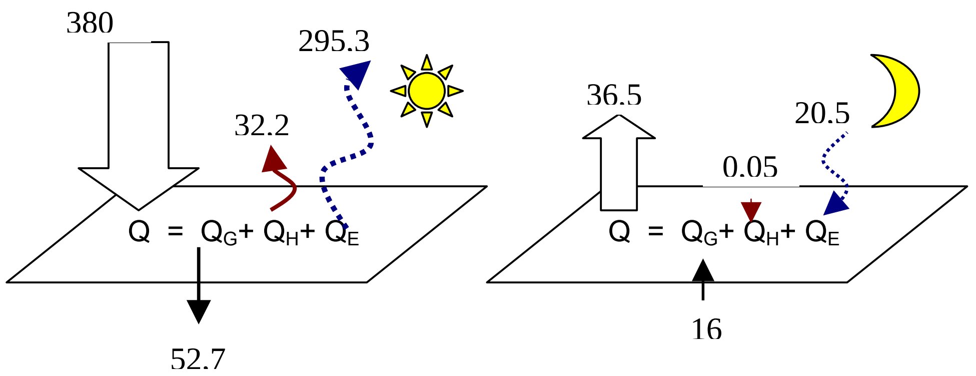


Figure 11. The estimated energy balance for the six sites

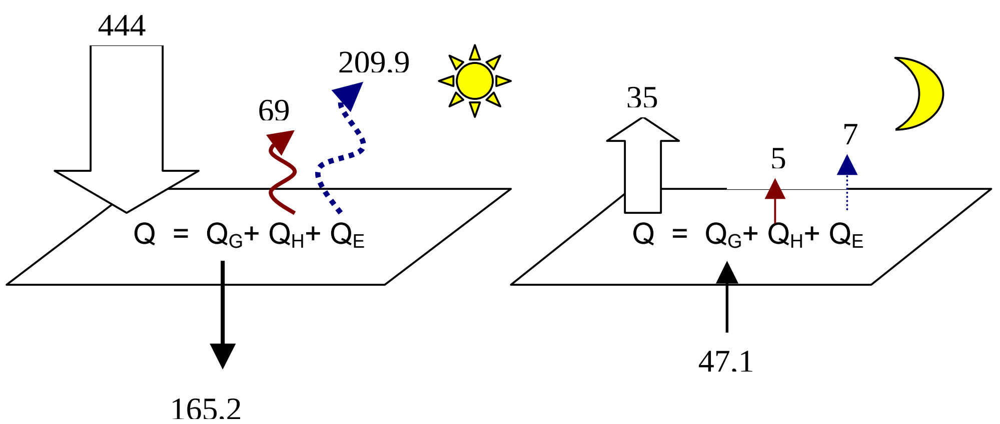
The shaded grass surface (site 1):



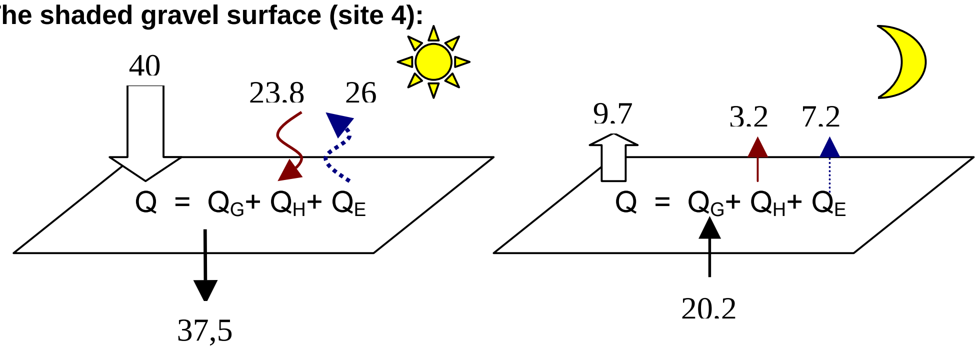
The open grass surface (site 2):



The open gravel surface (site 3):



The shaded gravel surface (site 4):



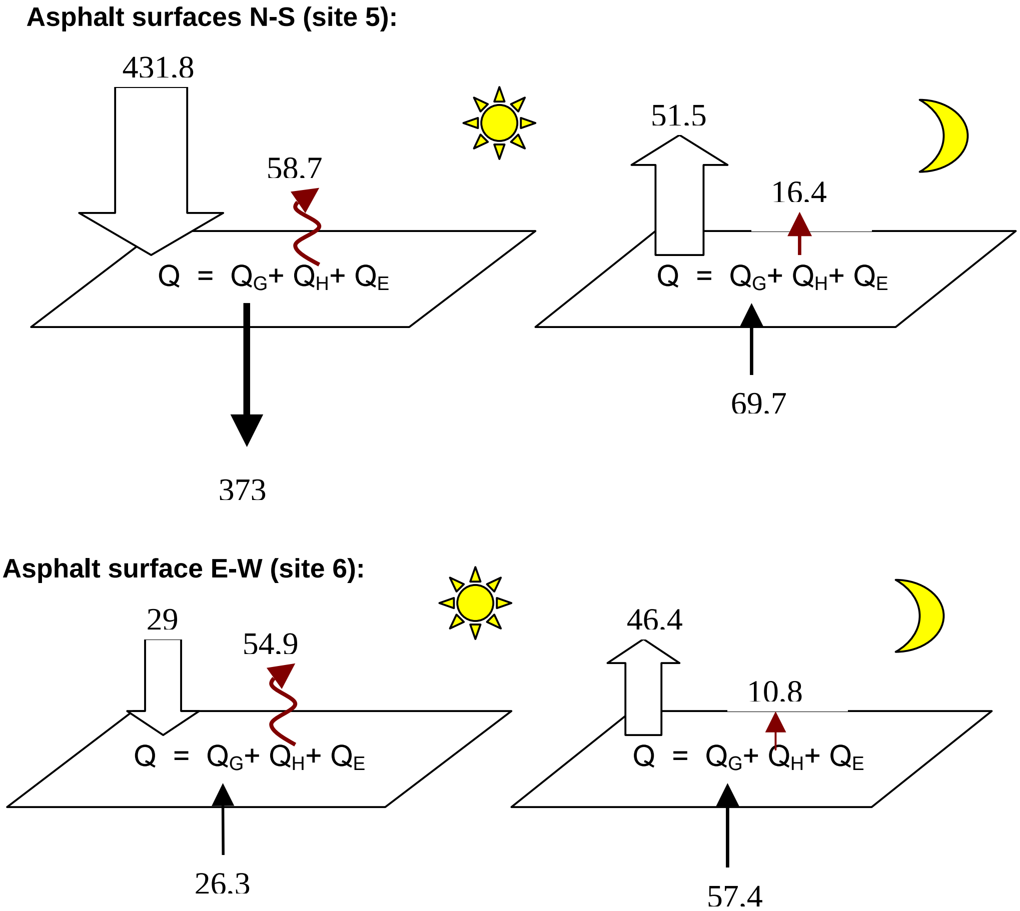


Figure 12. An illustration of the energy fluxes for the studied surfaces. The values given in the figure are the energy flux density in Wm^{-2} for the different fluxes. The values for daytime are those measured between 12:00 and 14:00 and for night time those measured between 02:00 and 04:00 on August 17.

4.2 THERMAL DIFFERENCES

The temperature data from all the observation days shows similar results. But since the data series for August 17 were used when examining the energy balance the same data series were used in this section. Graphs illustrating air and surface temperature on July 28 are presented in Appendix 4.

4.2.1 Night

Figure 13 and 14 shows that the park, site 1 to 4, was cooler than the built-up surroundings, site 5 and 6, during the night.

Coolest site during the night was the open grass site and the second coolest site was the shaded grass site. The asphalt sites were the warmest sites during the night.

4.2.3 Day

During the day only the shaded park sites were clearly cooler than the asphalt sites. The open grass surface had a lower surface temperature than the asphalt surfaces during most of the day. Warmest sties during the day were the open gravel sites and the asphalt sites. However, since the park is covered to approximately 50 % by tree canopies, the park on average was cooler than its built-up surroundings also during the day.

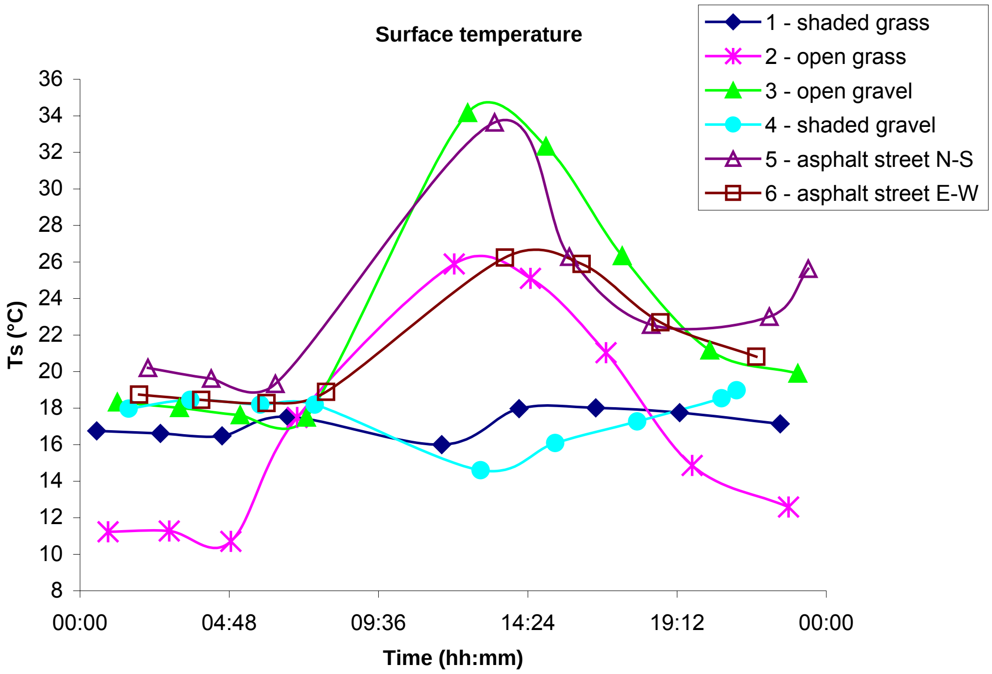


Figure 13. The surface temperature, T_s, at the six sites during August 17.

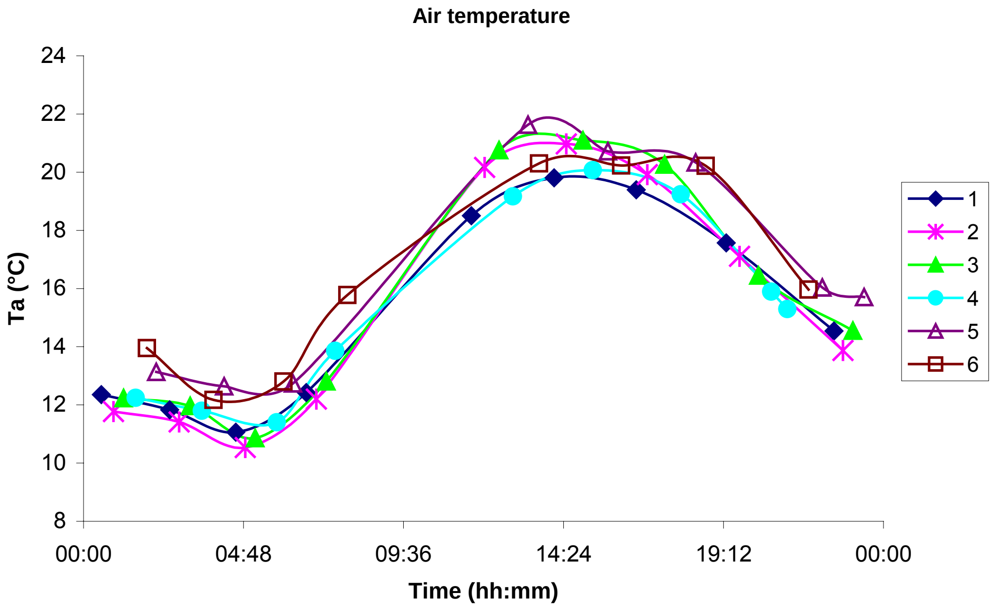


Figure 14. The air temperature, T_a, at the six sites August 17.

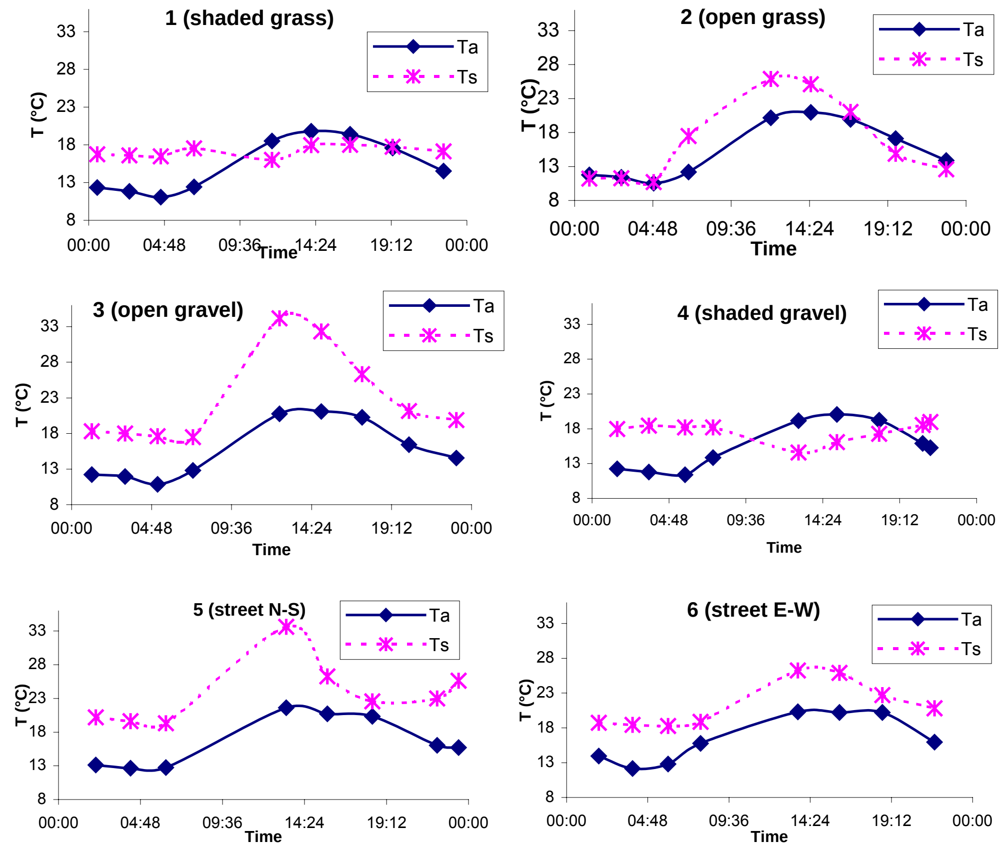


Figure 15. The air and surface temperature on August 17 at the six sites.

5. DISCUSSION

5.1 THE ENERGY BALANCES

As noted earlier the energy balances at the built-up site, site 5, for the two last observation days, July 28 and August 17, did not look identical. Site 5 had a net radiation and ground heat flux that was larger on August 17 than on July 28 during daytime (Figure 8 and 9). Considering the energy balance at site 5, the geometry of nearby buildings and streets were important since the direct short wave radiation at one time could reach the surface and then, a moment later the street could be shaded. Since the observations was not made at exactly the same time both days this could be the reason why the energy balances for the two days looked different. Another explanation to the differences between the days is the variation in radiation input due to clouds. For example, July 28 and August 17 were partly cloudy in the afternoon and the energy balance differences between the days might have been caused by differences in the cloud cover (Figure 8 and 9).

The ground heat fluxes for the two shaded park sites, site 1 and 4, both looked odd. Q_G for site 1 was directed upwards during the whole 24-hour period and since the ground heat flux was small compared to the potential error in the term the direction of the flux probably was the cause of errors. The ground heat flux for site 4 varied greatly which is not realistic since Q_G is expected to be the most conservative component in the energy balance. Since Q_G was estimated as a rest term was the rapid changes in the ground heat flux probably caused by errors in the other terms of the energy balance.

The open gravel surface was the only park surface that had an upward directed sensible heat flux during day and night. The open gravel surface also had a greater ground heat flux during day and night than the other park surfaces. During the day the sensible heat flow was directed upward because of that the large amount of direct short wave radiation hitting the surface. This made the downward directed ground heat flux during the day large and therefore the upward directed ground heat flux large during the night too. Hence the cause for the upward directed sensible heat flow during the night was the upward directed ground heat flow. The other park surfaces was either shaded during the day or covered with grass, which made their daytime ground heat flows smaller.

The latent heat flow for the grass surfaces were directed downward during the night au contrary to the latent heat flow for the gravel surfaces, which were directed upwards during the night. This corresponds well with the observations done during the measurements that dew developed during the night on the grass surfaces but not on the other surfaces.

The energy balances for the two asphalt surfaces looked different during the day. The difference could be the consequence of a missed peak in Q since the net radiation was not measured continuously, or an effect of that site 5 received more direct short wave radiation while site 6 was more shaded during the day. As mentioned in the result the asphalt surfaces had an upward directed sensible heat flux during the whole 24-hour period. Since the heat storage in urban structures in general are good, the upward directed sensible heat flux in the evening and night probably was an effect of heat being stored during the day and released during the night. This behaviour of energy being put into storage during the day and released during the night can be seen in the energy balance for site 5 (Figure 11). But for site 6 was the ground heat flux directed away from the surface during almost the whole 24-hour period. This seems rather strange since energy is expected be put into storage during the day to enable an energy release during the night. This odd ground heat flux could be the consequence of a missed peak in Q during the day. A peak in Q would have given a downward directed Q_G during part of the day and energy would have been put into storage.

5.2 THE ENERGY BALANCES AND THERMAL DIFFERENCES

5.2.1 Night

As noted earlier was the park cooler than its built-up surroundings during the night. This corresponds well with earlier results that the park cool island phenomenon is especially pronounced during the night (Upmanis et al., 1998). A difference between the urban sites, site 5 and 6, and the parks sites, site 1-4, was that the urban sites had larger upward directed Q_G during the night (Figure 11 and 12). Q_H for the asphalt sites were approximately two to three times as big as Q_H for the non-shaded gravel site, which had the largest Q_H of the park sites. The asphalt surfaces also had the largest upward directed ground heat flux of all the sites during the night. The ground heat flux was more than three times as large as Q_G for the grass sites. Thus, one factor that contributed to the large sensible heat flux was probably the heat storage in the urban structure. Another factor affecting the sensible heat flux in the city was that some of the outgoing long wave radiation was absorbed and reemitted to the surface by the walls surrounding the street. This made the asphalt surfaces warmer than they would have been otherwise which gave a greater sensible heat flux. As commented earlier the sensible heat flux was larger at the built-up sites than what is illustrated in figure 11. So the difference between the sensible heat fluxes for the park sites and the built-up sites were larger than what can be seen in the figures.

The coolest site during the night, the non-shaded grass surface, was the only site that had a surface temperature that was lower than the air temperature (Figure 15) and hence the only site with a sensible heat flux directed towards the surface. This means that the non-shaded grass surface was the only surface that cooled the air above it during the night. As can be seen in figure 12 the sensible heat flux was fairly small during the night of August 17 and it is probably because the wind speeds were very low at that time. The second coolest site during the night was the shaded grass surface. The reason why the shaded grass did not cool as much during the night was probably because the foliage above the surface absorbed and reemitted parts of the outgoing long wave radiation from the surface. This and that cool air advected in over the surface was probably the cause for the upward directed sensible heat flux at the shaded grass surface during the night and also the reason for the differences in the surface temperature between the two grass sites. The two grass surfaces were the only ones with a downward directed latent heat flux during the night, probably because these surfaces had a lower surface temperature than the other surfaces. The fact that site 1 had a smaller Q_E than site 2 is probably due to the difference in the surface temperature between the sites. The two grass sites were cooler than all the other sites during the night and they were also the sites with the smallest sensible heat fluxes (Figure 12). The gravel surfaces had sensible heat fluxes that were at least three times larger than Q_H for the grass surfaces. The asphalt surfaces, which were the hottest during the night, had a much larger Q_H. The grass surfaces also had a smaller ground heat flux during the night than the other surfaces. This is probably one of the reasons why the grass surfaces were cooler during the night, since a smaller amount of energy was released from the soil at the grass sites. One explanation to why Q_G was smaller for the grass surfaces could be that the grass provided insulation, which made the daytime ground heat flux smaller (Figure 11 and 12) and hence the nighttime Q_G too.

5.2.2 Day

The results showed that the shaded sites, site 1 and 4, in the park were cooler than the built-up surroundings while the non-shade gravel site, site 3, was almost as warmer, or warmer than, the sites located in the built-up vicinity, site 5 and 6 (Figure 13 and 14). This corresponds well with previous results that moist parks with growing vegetation and shading tree canopies are cooler than their surroundings while open parks with dry dead grass or open soil can be hotter than their built-up vicinities during daytime (Spronken-Smith and Oke, 1999).

The shaded sites were the coolest sites during the day and they were also the only sites that had surface temperatures that were lower than the air temperatures. The shaded sites were therefore the only sites with a downward directed sensible heat flux and hence the only sites cooling the air above them during the day. The shaded surfaces even had surface temperatures that were slightly lower during daytime than during nighttime. An explanation to why the shaded surfaces had such low surface temperatures is that the tree foliage above the surfaces absorbed and reemitted parts of the outgoing long wave radiation from the surface and blocked part of the incoming short-wave radiation. This made the net-radiation at the surfaces small during the whole 24-hour period. During the day the sensible heat flux was directed downward and the surfaces were drawing heat from the air to the evaporation, which made the evaporation larger than the net-radiation during the day. Thus the upward directed latent heat flux during the day and the tree foliage above the surfaces made the surfaces cool during the day and in this case even cooler than their nightly surface temperatures too. An explanation to why the air above the shaded surfaces were warmer than the surfaces is that the tree foliage, absorbing much of the incoming short-wave radiation, were heating the air below, or that warmer air were advected in over the surfaces from warmer parts of the park or from the built-up vicinity. The phenomenon of advected warm air feeding heat to a surface is sometimes called an 'oasis-effect' (Oke, 1987). The shaded surfaces also had smaller latent heat fluxes than the open surfaces in the park. Since the water availability at all sites in the park was good the reason why the latent heat fluxes were smaller was most likely a result of that the shaded surfaces had lower surface temperature than the open surfaces.

The open grass surface had a notably lower surface temperature than the open gravel surface. This could for example be an effect of that the open grass was cooled more by evaporation than the open gravel or an effect of differences in the albedo for the surfaces. The open gravel surface had a surface temperature that was even higher than the asphalt surfaces during the day and that is probably an effect that the open gravel surface received more direct short wave radiation than the apshalt surfaces.

5.3 SOURCES OF ERROR AND IMPROVEMENT PROPOSALS

For the observations, data processing and calculations conducted in this work there are several sources that can contribute with errors and thereby affect the result. One problem was that one of the data loggers malfunctioned. Sometimes the data logger stopped working and other times the data became erroneous. The data that were clearly unreasonable was removed but some erroneous values that not were too unlikely could still have sneaked through the outlier tests. This makes the results a little more uncertain than they would have been with a fully functional data logger. The malfunctioning data logger also made it necessary to do a few interpolations to approximate some values for the net radiation and the relative air humidity. This is of course also a source of error since the values are only approximated and not measured. Another possible source for errors in the observations was that, since the attempt to calibrate the net-radiometer failed, was it about 30 years since the net-radiometer was calibrated. This means that the calibration could be inaccurate today and that there could be an error in the net radiation term.

Maybe the largest error was that the ground heat flux was calculated as a rest term of the energy balance equation. All errors in the other terms are reflected in the ground heat flux and even small errors in all the other terms could add up to a big error in Q_G. The ground heat flux for site 4 and 6 strongly indicates that errors in the other terms are reflected in Q_G since it is not realistic that Q_G would vary so abruptly. To avoid this type of errors, the soil temperature needs to be measured more accurately and the thermal properties of the soil needs to be surveyed. Another alternative is that the ground heat flux is measured directly. It would probably also have been useful to calculate the ground heat flux in another way and compared the results from the different calibration methods.

When calculating the latent heat flux for the gravel surfaces and the grass surfaces some assumptions were made. These assumptions of course add a small uncertainty to the results. For the latent heat flux at the grass surfaces was the integrated stomatal resistance, r_c, assumed as 20 ms^{-1}. If the integrated stomatal resistance had been assumed to be larger the latent heat flux had been smaller and vice versa. Since the ground heat flux was calculated as a rest term of the energy balance this would also have affected Q_G. But to obtain a result that are much different from the result presented here r_c would need to be changed beyond what is reasonable. The relative air humidity at the gravel surfaces was approximated to follow a pattern given in figure 7. If the relative air humidity had been assumed to be larger had the latent heat flux been larger and vice versa. This would of course also have affected the ground heat flux. The approximations of the air humidity would have needed to be changed fairly much for the result to have been much different from the result presented here.To reduce these errors the latent heat flux should ideally the have been measured directly.

Yet another source of error is the limited amount of data. It would have been useful to have data from more days and especially days with other conditions. More data would also have made it easier to see what the normal variations were and what were erroneous. But I do not think that the result would have been much different if more data would have been collected and used.

Another possible method to get more accurate result could have been to use a simulation tool to calculate the energy-balance components instead of doing the calculations as presented in this work. These type of simulation tools are often called SVAT-models (Soil-Vegetation-Atmosphere Transfer). The benefits of using such a simulation tool is that they calculate the energy and water transport in a profile below the surface and no term need to be calculated as a rest term. The models use almost the same input data as used in this work but the soil characteristics such as the heat capacity of the soil, ground heat conductivity and hydraulic properties need to be known as well.

6. CONCLUSIONS

The most pronounced differences between the shaded and open surfaces in the park was that the shaded surfaces in general had smaller energy fluxes during daytime and that they had a downward directed sensible heat flux while the open surfaces had an upward directed Q_H during the day. The most significant difference between the grass and the gravel surfaces was that the grass surfaces had a larger downward directed latent heat flux during the night and smaller Q_G during day and night.

The largest differences between the surfaces inside the park and those in its built-up vicinities were that the paved surfaces had larger upward directed sensible and ground heat flux during the night than the other surfaces. During the day site 6 had a downward directed ground heat flux that was much larger than the ground heat flux for the other sites and probably, site 5 also had large Q_G.

The coolest site during the night was the non-shaded grass surface, which was the only site with downward directed sensible heat flux during the night. Compared to the other non-shaded sites, site 2 had much smaller ground heat flux. Warmest sites during the night were the paved surfaces, which had larger upward directed sensible and ground heat flux than the other surfaces. At the built-up sites the walls also contributed with a sensible heat flux making Q_H larger than what is presented in the energy balance figures.

During the day the shaded surfaces were the coolest sites. The shaded surfaces had less net radiation compared to the other non-shaded surfaces and were the only sites that had a downward directed sensible heat flux.

6.1 CLIMATE DESIGN IN CITIES

Based on the represented results, climate design in cities to reduce nocturnal air temperatures should incorporate parks that are open vegetated and moist. If the temperature during summer days need to be lowered areas that are moist and shaded by tree canopies should be incorporated. Since the paved site 6 was shaded during most of the day and still was warmer than the other shaded sites it seems like the sites not only need to be shaded but also moist to enable evaporative cooling. Thus if the need is to design a park that should be cool during both night and day the park should be moist and consist of open vegetated areas as well as areas shaded by trees. Non-shaded gravel surfaces or other dry surfaces like dry grass or asphalt should be avoided.

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7.3 PERSONAL COMMUNICATION

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APPENDIX 1

Symbols	Description	Unit
Δe	vapour pressure deficit	Pa
γ	psychrometric constant (= 66)	PaK^{-1}
θ	potential temperature	K
ρ_a	density for damp air (=1.2047)	kgm^{-3}
ρ_v	vapour density	kgm^{-3}
C_a	heat capacity of air	$Jm^{-3}K^{-1}$
C_p	specific heat of air at a constant pressure (=1010)	$Jkg^{-1}K^{-1}$
e	vapour pressure	Pa
e_{sat}	vapour saturation pressure	Pa
g	gravity (=9.81)	ms^{-2}
h	relative air humidity	
$K\downarrow$	incoming short-wave radiation	Wm^{-2}
$K\uparrow$	reflected short-wave radiation	Wm^{-2}
K_H	eddy conductivity	m^2s^{-1}
K_V	eddy diffusivity for water vapour	m^2s^{-1}
k	von Karmans constant (=0.41)	m
k_s	thermal conductivity	$Wm^{-1}K^{-1}$
$L\downarrow$	incoming long-wave radiation from the atmosphere	Wm^{-2}
$L\uparrow$	outgoing long-wave radiation from a surface	Wm^{-2}
L_v	latent heat of vaporization (= $2.4518 \cdot 10^6$)	Jkg^{-1}
Q	net radiation flux density	Wm^{-2}
Q_E	latent heat flux density	Wm^{-2}
Q_G	soil heat flux density	Wm^{-2}
Q_H	sensible heat flux density	Wm^{-2}
R	specific gas constant for water vapour	$Jkg^{-1}K^{-1}$
r_a	aerodynamic resistance	sm^{-1}
r_c	integrated stomata resistance for a whole foliage (canopy resistance)	sm^{-1}
s	slope of the saturation vapour versus temperature curve	PaK^{-1}
T	temperature	K
T_a	air temperature	K
T_s	surface temperature	K
u	wind speed	ms^{-1}
z	vertical distance	m
z_0	roughness length	m
z_{0h}	the roughness length governing the transfer of heat and vapour	m
z_{0m}	roughness length governing momentum transfer	m
z_d	zero plane displacement	m
z_u	height above a surface where the wind is measured	m

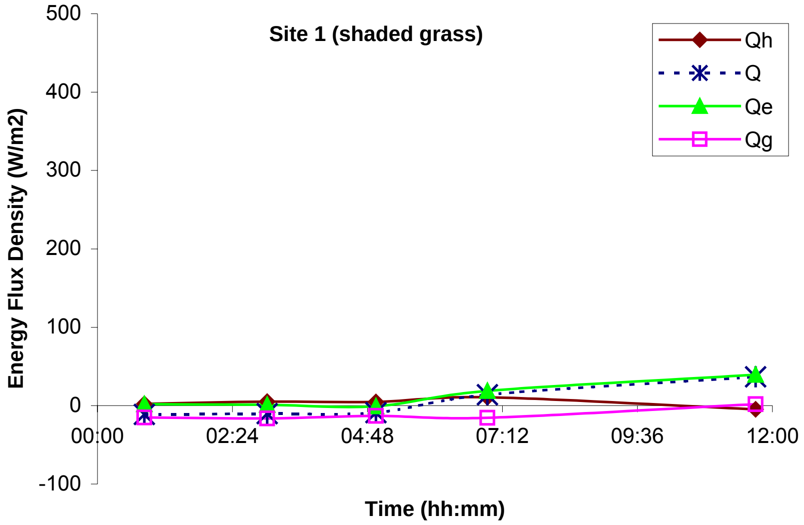
APPENDIX 2

$e_{sat} = 0{,}61078e^{(17{,}269T/(T+237{,}3))}$

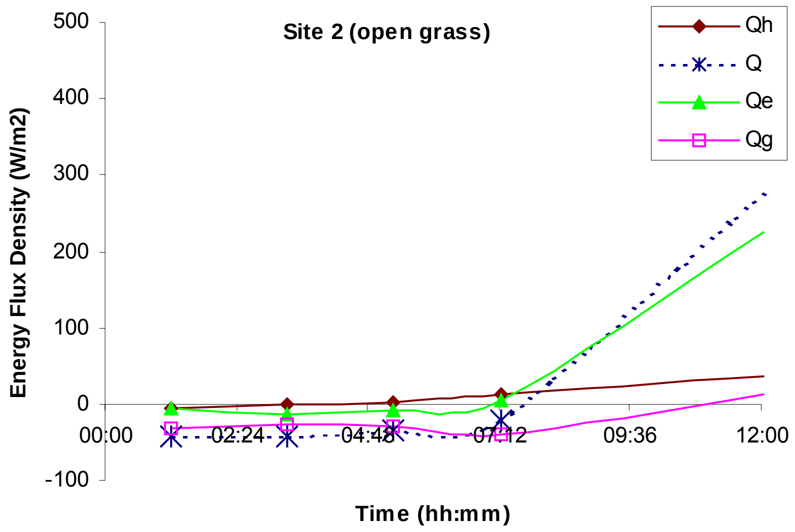
$s = 4089 \cdot (0{,}6108 \cdot e^{(17{,}27 * T/(T+237{,}3))})/(T+237{,}3)^2$

$\rho_v = e/(RT) \approx \quad 2{,}17e/T$

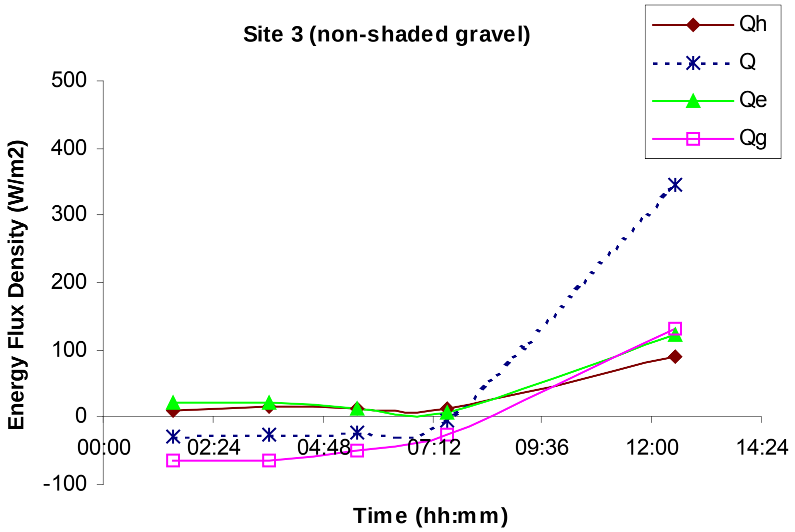
APPENDIX 3



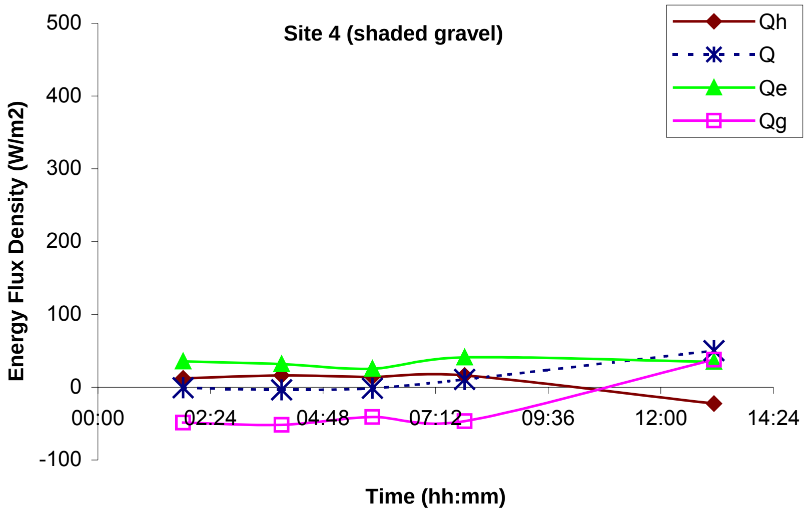
The energy balance on site one on the July 28.



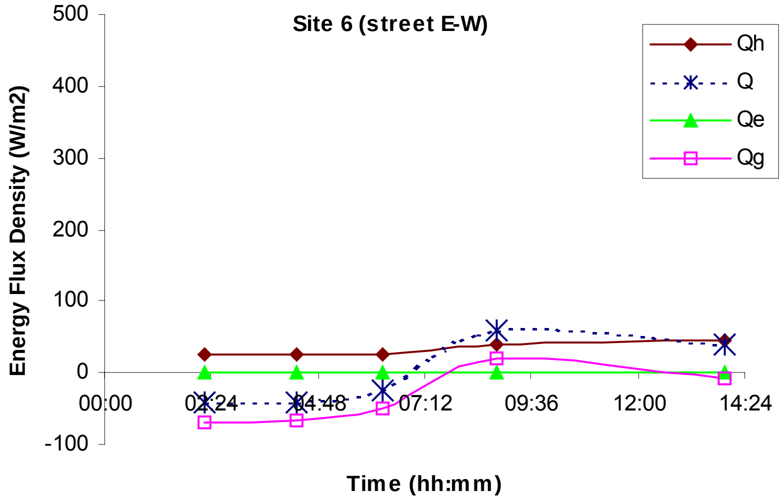
The energy balance on site two on the July 28.



The energy balance on site three on the July 28.

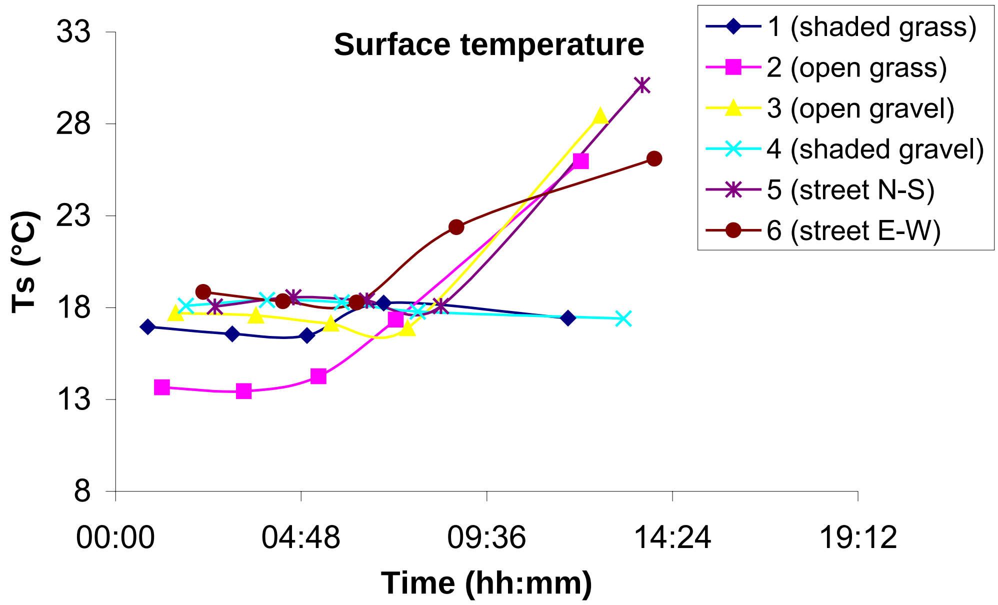


The energy balance on site four on the July 28.

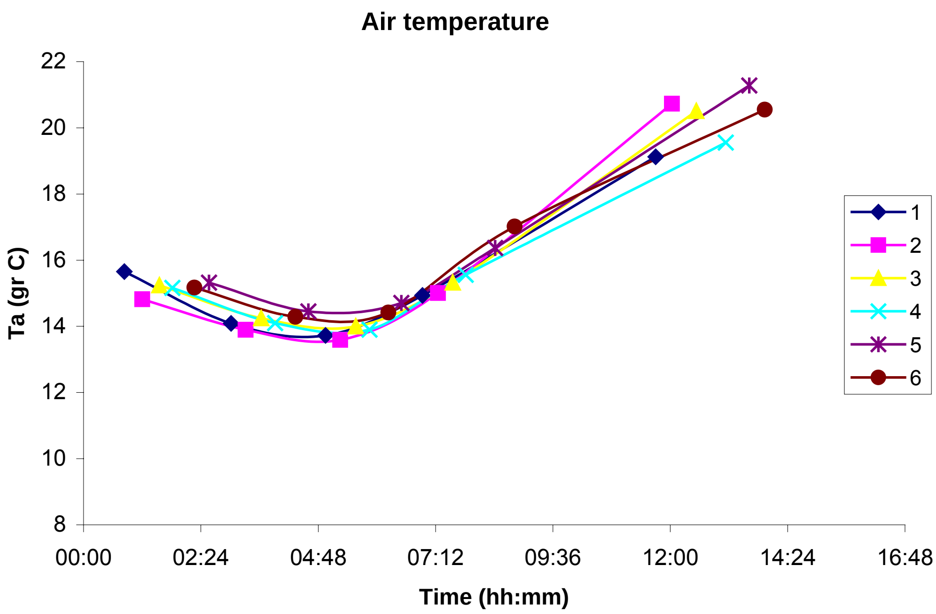


The energy balance on site six on the July 28.

APPENDIX 4



Surface temperature at the observation sites on July 28.



The air temperature at measured at 0.78 m height at the observation sites on July 28.