THE UPPSALA URBAN METEOROLOGY PROJECT

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Abstract. An extensive urban meteorology project in Uppsala, Sweden, is described. The city itself is considered suitable as a kind of model city, being almost circular, having sharp urban/rural boundaries and being situated in a relatively flat area. The project incorporates numerous measurements. A main station with a 100-m mast is situated at the NE urban/rural border. Its instrumentation consists of a slow-response ('profile') system and a turbulence system. The profile instrumentation is described in detail. In addition to the main station, the project comprises: measurements from two 14-m masts, one on the top of a centrally located building, the other mobile; pilot balloon ascents; tethered balloon soundings, car-borne temperature traverses etc. Some preliminary results are presented: analyses of wind profiles from the mast and three-dimensional heat island studies.

1. Introduction

In the autumn of 1969 a severe gale struck large parts of southern Sweden causing unexpectedly severe damage to buildings in many cities. This was the starting point of a discussion among a group of building experts and meteorologists about the need for architects and city planners to have better knowledge about the behavior of the actual atmosphere above cities of the kind typical for Sweden. This led ultimately to the Uppsala urban meteorology project.

As reviewed by Landsberg (1969), the atmosphere over cities is modified in many different ways. Urban meteorology has been the subject of a great many studies in the past, see e.g., the recent literature survey by Oke (1974). For a long time the studies were mainly of a descriptive, climatological character. Particularly numerous were the studies of the so-called urban heat island with the aid of car-borne equipment. One of the very first studies of that kind was performed in the present study city, Uppsala, by Sundborg (1950). In the last decade, however, attention has been focused towards studies aimed at a deeper physical understanding of the basic physical processes of the urban atmosphere. These studies have been experimental (see e.g., Bornstein, 1968; Oke and East, 1971) as well as theoretical (see e.g., Oke's 1974 review).

The Swedish building experts around 1970 required increased knowledge of the wind field over a 'typical Swedish city'. But there was also a desire expressed among city planners to have better understanding of the atmosphere-city interactions in general. Thus a project was designed to undertake a rather general search of the physics of the urban atmosphere. The city of Uppsala was considered in many ways ideal as a model. The reason for this is that the city is almost circular, has very distinct city – urban borders and is situated in relatively flat terrain.

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2. General Outline of the Project

The experimental program was designed to give, as far as possible, a three-dimensional picture of the urban boundary layer. A *main station* equipped with a 100-m mast was set up at the north-east city edge, at Gränby (symbol 'G' on Figure 1). The site was chosen because it offers an unusually clear-cut distinction between urban and rural fetch. In the rural sector, between 0° and 60° from N, there is nearly horizontal open farmland for several kilometers (see Figure 2a).

On the urban side, the built-up area, consisting of three-storey buildings, commences 100 m south of the mast, see Figure 2b. The immediate surroundings of the

Fig. 1. Schematic map of Uppsala. Legend: G: Main station Gränby (for measuring program, see text). U: City-center roof-top station (for measuring program, see text). RÅ: City center thermograph-station. VÄ, HJB, FL: Urban thermograph-station. MI: Met. Inst., climatological station, wire-sonde station. F16: Military airbase, hourly synoptic observations. UL: Ultuna agrometeorological station. MA: Marsta meteorological observatory, 10 km N of Uppsala. G, H, GT, VT, RÅ, P, UM, MI, R, C, UE: Mobile-mast stations (see text). UKAB: Central heating plant, temperature-station.

Fig. 2a. View from the 50-m level on the Gränby tower looking northeast.

Fig. 2b. View from the 50 m level on the Gränby tower looking south.

mast are shown on Figure 3. Located 20 m west of the mast is a low (ca. 2.5 m) 11 m long and 2.5 m wide building which accomodates the recording equipment and some laboratory facilities. An area surrounding the mast and the building is enclosed by a fence, length 40 m in the E–W direction and width 15 m in the N–S direction. The ground in that area is covered by grass which is kept 5–10 cm high. The area between the 3-storey houses and the small road running roughly E–W is

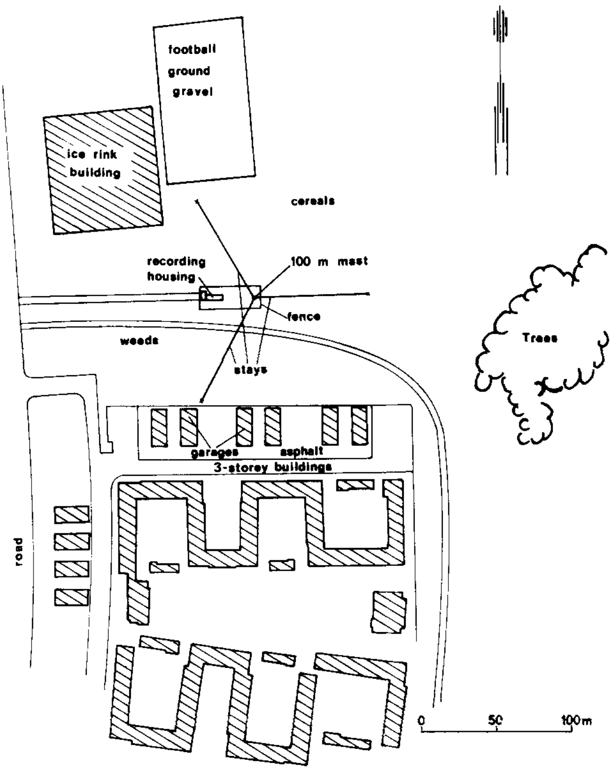


Fig. 3. The Gränby site.

covered mainly by weeds. North of this road is agricultural land where cereals are grown in summer. Immediately north of the mast, beginning at a distance of 70 m is a football ground covered with gravel. Two sectors must be considered as disturbed: 300°–340° because of a huge isolated building (an ice rink) at only ca. 80 m distance and 80°–120° where there is a nearby (140 m) forested area.

The 100-m mast is equipped with instrumentation for measuring wind, temperature and humidity at eight levels. In addition to this, net radiation, global radiation, ground heat flux and air pressure are measured at the station. The profile instrumentation is described in detail in Section 4. A turbulence instrument – a wind vane with an associated three axial hot wire anemometer system plus temperature and humidity sensors – has been developed for the project. Measurements will be carried out at three levels simultaneously beginning in the spring 1978.

Besides the main station at Gränby the measuring program comprises: tethered-balloon ascents with a Väisälä low-level radiosonde at the Meteorological Institution (MI); temperature profiles, measurements of wind speed and direction and global and net radiation from a 14 m high mast on top of a 7-storey building in the city center (U); temperature profiles in the canopy-layer at various points in the city with the aid of a 14-m telescoping mast attached to a car. A total of 10 fixed temperature stations together with mobile measurements, using a fast-response thermistor, provide data for the analysis of the horizontal urban-rural temperature field at screen-level. In order to study the airflow in the canopy layer, smoke-puffs have been released at various points. The flow above the city is further studied by double-theodolite-tracking of pilot balloons released from Gränby.

Profile data from Gränby have been recorded more or less continuously since 1974. Measurements at the city center station (U) were taken during two periods, each lasting about two weeks during 1976 but will be taken up again on a more continuous basis. Special studies, including most of the measurement program described above have been carried out during 13 nights so far.

3. Physical Characteristics of the Urban Area

Uppsala (59°50'N, 17°38'E, population 100 000) is situated 70 km north of Stockholm and 80 km inland from the Baltic Sea. The local topography is characterized by open, flat farmland ranging in elevation between 5 and 25 m above sea level. S and W of the main urban area, somewhat higher and wooded terrain is found. A rather marked ridge with elevations up to 45 m above sea level runs approximately N–S through the western parts of the city. A small river, the Fyris, flows parallel to the ridge from NNW to SSE. East of the river, the ground rises slowly from 8 m above sea level reaching 20 m above sea level at the eastern fringe of the urban area. This slope is nearly compensated by the gradual increase in building heights from 1–2 stories in the eastern parts to 5–6 stories in the central parts of the urban area. Thus the general roof-top level is nearly horizontal at 25–30 m above sea level.

The city is a commercial and administrative center with no heavy industry and few light industries. Heat production for space heating is concentrated at one central oil-fired heating-plant supplying at present 70% of the heat consumption in the city. This plant with its 100-m stack is the only significant point source of air pollutants. Contributions from traffic emissions are largely concentrated on certain main routes. A large part of the city center is closed to private cars and heavy traffic.

Building density, expressed as the percentage of land occupied by buildings, increases from 5–10% in the outer parts to 50–60% in the central parts. The variation in building heights and building density is reflected in the area-distribution of heat requirements for space-heating. With a daily mean temperature of −20 °C, the heat requirement ranges from 10 to 150 W/m^2.

4. Description of the Measuring System at the Main Station

The design of the slow-response ('profile') measuring system at the main station, Gränby, was based to a large extent on the experience gained during the Marsta field experiment. The 'profile system' used there is described in detail in Smedman-Högström and Högström (1973). Insofar as the two systems are identical, reference will be made to that article (refered to as S-H). Certain important improvements have, however, been introduced, and they will be described in some detail.

The automatic data-logging system used at Gränby is the same as that used in Marsta, a Solartron system with paper tape as output medium. The sampling interval is usually 4 min (in special studies a shorter interval is chosen; 1 min or $\frac{1}{2}$ min is often used). A full scan, comprising 50 channels, takes 5 s. The resolution of the digital voltometer is 10 microvolts. The paper tapes are processed on the University's IBM 360/370. The program converts the signals to physical quantities, prints out these values as well as hourly averages of each parameter.

The following parameters are recorded on the 50 channels (number of channels in parenthesis): net radiation (1), global radiation (1), ground heat flux (1), air temperature (8), humidity (16 channels, giving humidity data for 8 levels), wind speed (16 channels, giving wind data for 8 levels), wind direction (3), air pressure (1), reference voltages (3).

Temperature, *humidity* and *wind speed* are measured at the following levels (approximate heights are given): 7.3, 20, 35, 50, 75 and 100 m above ground. In addition, temperature and humidity are measured with intakes at 1 and 2.7 m. Wind speed is measured on separate poles at the same heights above the ground. Wind direction vanes are placed at three levels on the mast: 7.3, 50 and 100 m. The anemometers on the mast and the wind vanes (except for the sensors at the top of the mast) are placed on booms projecting 2.5 m from the mast. The booms are fastened to antenna rotors which can be operated from the ground, allowing the booms to be moved over a sector covering almost 300°. Thus the booms can be preset into a direction of expected minimal mast interference for the period of a run to be started.

Net radiation and *global radiation* are measured with a CSIRO net radiometer and a Moll-Gorszinsky radiometer, respectively (see S-H for details) placed on a separate stand 1 m above the mown grass surface of the site enclosure. *Ground heat flux* is measured with four CSIRO ground heat flux plates buried around this stand.

The instrument used for *wind speed* measurements is a modified Casella sensitive anemometer. The instrument has been made weather-proof and durable by replacing the original cup rotor arms by delta-shaped, flat arms made of aluminium and by replacing the original jewel bearings by miniature ball bearings. Wind-tunnel calibrations showed that these modifications had no effect on the sensitivity or the distance constant. The 8 anemometers used in Gränby were calibrated individually over the wind speed range 0.5–35 m s^{-1} before they were installed on the mast and again after $1\frac{1}{2}$ years of continuous operation. The recalibration gave a satisfactory result: the difference between the two calibrations was entirely random and of the order of the accuracy of the wind-tunnel speed determination, i.e., about 1% for wind speeds above ca. 4 m s^{-1} and better than ± 0.05 m s^{-1} for lower wind speeds.

The *temperature* and *humidity* measuring system consists of three sets of 500 Ω Pt-sensors. One set is for measuring the air temperature at the various levels, placed in ventilated shields at the air intakes; the other two sets provide measurements of 'dry' and 'wet' bulb temperatures. They are placed in a special screen at the base of the mast as described in S-H. The air is led from the intake levels to the screen through entirely water resistant polyethene tubes. These are equipped with copper leads the diameter of which is chosen differently for tubes of different lengths, so as to give approximately the same heat output per meter tubing (6 W m^{-1}). This heating system is introduced in order to prevent condensation in the tubings, which was a problem in the Marsta version of the system (c.f., S-H). In addition to this 'summer heating system', a 'winter heating system' which enables humidity measurements to be taken during below-zero conditions has been installed. This heats the air strongly (to +15 °C) just before it enters the screen. A thyristor temperature control system reduces the temperature amplitude to less than ca 0.1 °C. This is also an improvement compared to the Marsta system where an appreciably larger temperature amplitude was shown to introduce error in the wintertime humidity measurements.

Each of the three sets of Pt-sensors consists of one sensor for measuring the temperature itself and seven pairs of sensors for difference measurements. All sensors are placed in Wheatstone bridges. The lead-compensating system employed for the temperature difference measurements is shown schematically in Figure 4. It is based on the system described by Stevens (1967), but instead of using dual-wound sensors and eight-conductor cables we use single wound sensors and four-conductor cables.

By careful matching of the sensors used for each pair, very good stability of the difference measurements has been achieved. Repeated zero checks (with the sensors in a stirred water bath) performed over a period of four years has shown that there is no systematic offset of the bridges, the standard deviation of the 'zeros'

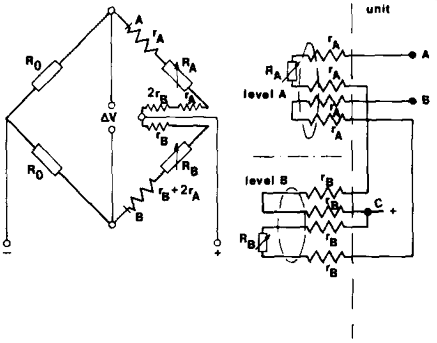


Fig. 4. The bridge used for temperature difference measurements; the leads have complete temperature compensation.

being about 0.015 °C. This is compatible with an overall accuracy of ±0.02 °C for the difference measurements. The corresponding accuracy of the humidity measurements is estimated to ca. ±0.03 mb.

5. Results of Some Preliminary Data Analysis

5.1. Wind profiles

A preliminary analysis of the vertical wind structure at Gränby comprises profile data from the period May to December 1974. The aim of this analysis is to give a descriptive picture of how the wind profiles are influenced by type of fetch, stability and wind speed, by grouping them according to these factors and studying the variation between the classes.

Each hourly profile has been normalized by dividing the wind speed value at each level by the 100-m value. The normalized profiles have been grouped in a number of classes according to the wind speed at 7.3 m, the net radiation and the wind direction. The combination of wind speed and net radiation has been used to indicate stability. The wind at Gränby has exhibited widely different types of roughness fetch for the various sectors. The following sectors have been selected as representing clear-cut conditions: 0°–30° and 30°–60° rural fetch, 105°–135° short urban fetch, 150°–180° and 180°–230° long urban fetch (c.f. Figure 1).

Figure 5 shows mean profiles for winds from varying directions (the sector associated with each profile is marked) but for one particular stability (near neutral). The abscissa in this figure gives the normalized wind speed on a linear scale. The

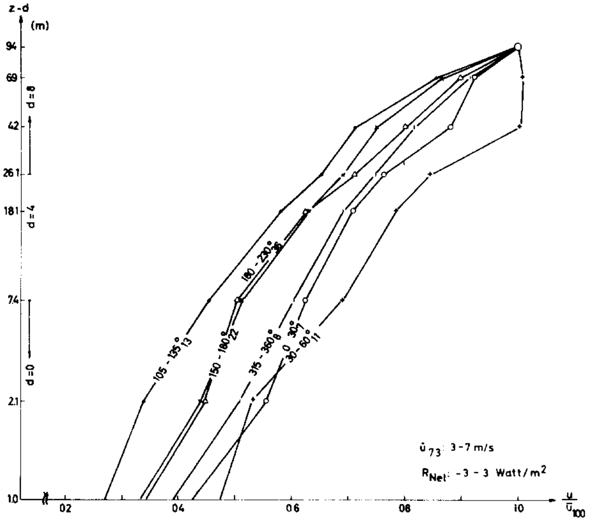


Fig. 5. Relative mean wind profiles for various wind direction sectors at Gränby for near-neutral stratification. The abscissa gives $\bar{u}(z)/\bar{u}_{100}$ on a linear scale, the ordinate $z-d$ on a logarithmic scale, where d is the zero displacement length, which varies with fetch. Figures on the profiles give sector direction and number of individual hourly profiles used to form the mean.

ordinate gives, on a logarithmic scale, the measuring heights less a zero-plane displacement *d* for those upper parts of the profiles which are due to urban fetch. The *d* value chosen is 7–8 m or about 0.75 times the mean height of the buildings. For profiles in the rural sector, no *d* value is applied. Also, in profiles from the urban sectors there is a lower part, generally below 20 to 35 m, representing a post-urban layer due to grass fetch next to the mast. The relative profiles in Figure 5 are ordered roughly from left to right according to the length of rough fetch, in accordance with the increasing shear felt over a rough area. The mean profile given for the distinct rural fetch sector 30°–60° exhibits a strange behavior in its upper part where there is a tendency for a maximum. Figure 6 shows an individual case with wind from roughly the same direction, the dots and the solid curve giving data from the Gränby mast. The rings and the hatched curve represent data from a simultaneous double-theodolite pilot balloon ascent. The figures give horizontal travel distances. Because the balloon was released not far from the Gränby station, this curve represents to some extent the wind profile that is being continuously modified over the city area. From dynamic considerations, one expects a low-level maximum to develop *over* the city. The solid curve of Figure 6 and the 30°–60°-curve of Figure 5 indicate that a maximum may develop *upwind* of the city area. This problem will be the subject of continued research. Figure 7 illustrates the influence of stability on the profiles. The graph is for one particular sector (the long urban fetch sector 180°–230°) and for the

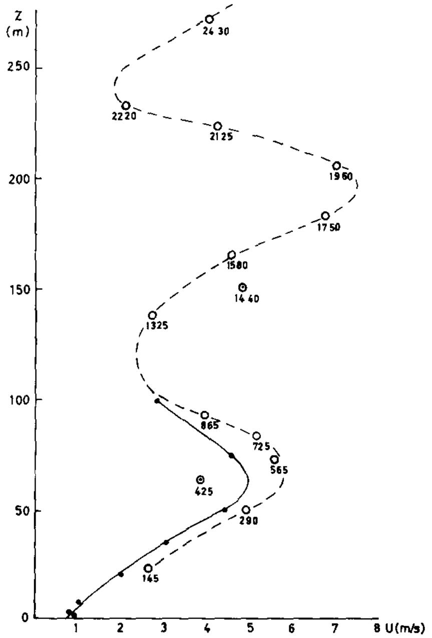


Fig. 6. Simultaneous 20-min mean mast wind profile (full line curve) and double theodolite pilot balloon wind profile (hatched curve) from 6 May 1975 21:15–21:35. Figures give downwind distance from Gränby in meters. Winds are from the northeast.

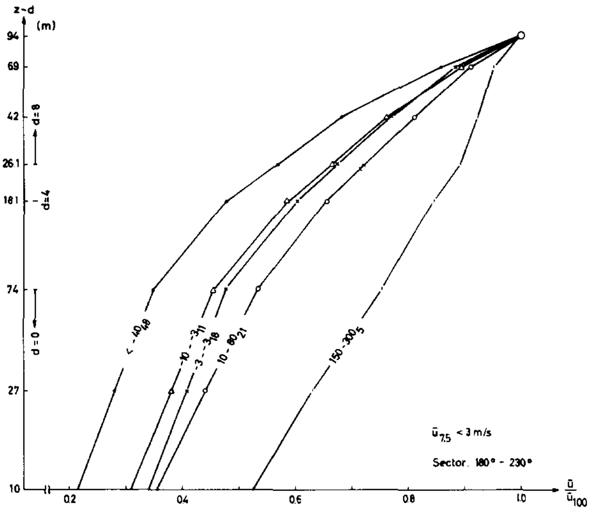


Fig. 7. Relative mean wind profiles from Gränby for 7.3-m winds less than 3 m s^{-1} for the sector 180°–230°. Figures on the profiles give net radiation (Wm^{-2}) and number of individual hourly profiles. See also Figure 5.

low wind speed group. The figures on the curves indicate net radiation ranges. The general trend of the curves is as expected for an 'ideal' site, but convex curvature occurs only with the very unstable cases, the slightly unstable ones having more the shape of the stable curves.

5.2. HUMIDITY PROFILES

The humidity profiles have not yet been the subject of a systematic study. Figure 8 shows just an interesting example of simultaneous humidity and temperature profiles. The wind is southerly, i.e., from the city. The presence of internal boundary layers at the same height in the two profiles is evident.

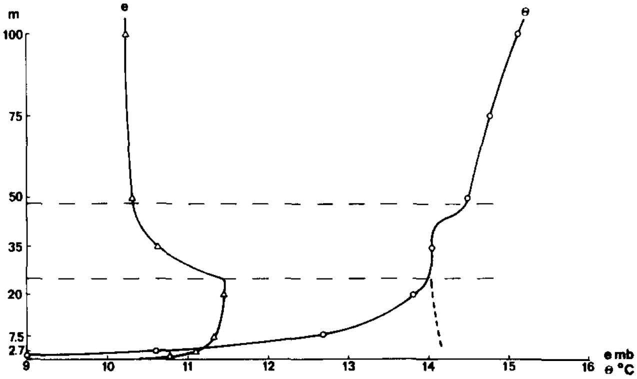
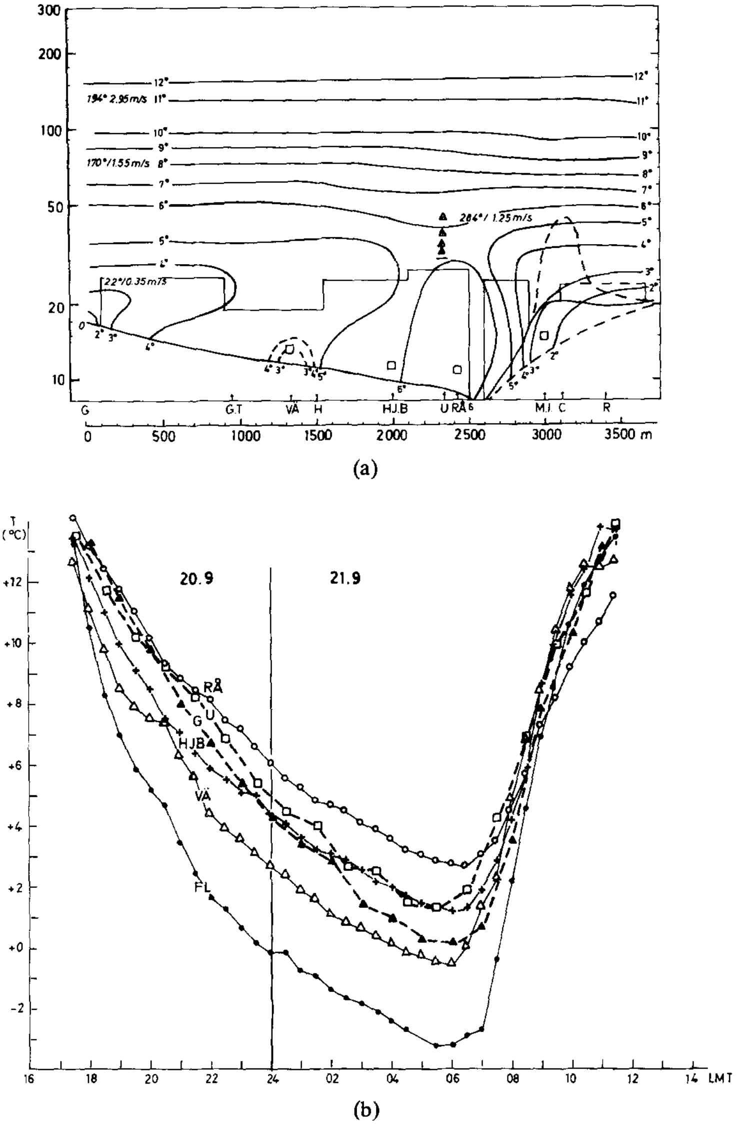


Fig. 8. Humidity and temperature profiles for the half hour beginning 22:25 12 August 1974. Winds from the city area.

5.3. THREE-DIMENSIONAL HEAT-ISLAND STUDIES

As a special investigation, the transition between the urban canopy layer and the layer above roof-level is being studied. The distinction between the urban canopy-layer and the urban boundary-layer has been pointed out by Oke* (1976). The



(a)

(b)

Fig. 9. Development and structure of the urban heat island during the night 20–21 September, 1976. The symbols indicate measuring stations; see Figure 1. (a) Vertical distribution of potential temperature at 23:30 LMT along 210°. Also given is wind direction and speed at three levels in Gränby (symbol G) and one level at the roof-top station (U). (b) Screen temperatures for various sites.

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* The present study was directly inspired by Tim Oke, who spent three months as a visiting scientist in Uppsala in 1975.

fixed and mobile measurements described in Section 2 will be analyzed first in order to study the three-dimensional thermal structure of the urban atmosphere and the time development of the urban heat island. In Figure 9a, b, results are presented from one night. The heat island in this case obviously was confined to a shallow layer not reaching much above roof-top level. The same general result is also brought out by the measurements from most of the 13 nights. On some occasions, distinct cross-overs between the Gränby- and city center profiles occur. This feature seems to be particularly well developed during the daytime, when the air above roof-level has been found to be 2–3 °C cooler than the air in Gränby at the same level.

The measurements also permit some approximate analyses of urban-rural differences in wind speed and direction in and immediately above the urban canopy. Preliminary results show cases with considerable urban-induced convergence above roof-level associated with inflow towards the heat-island center in the canopy-layer. Subsequent analyses will be undertaken to estimate the magnitude of the different terms in the thermal energy balance equation for the lower part of the urban atmosphere in order to assess the importance of various processes contributing to the formation of the urban thermal structure.

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