How to measure the energy balance of a road surface

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Summary

In Road Climatology great emphasis is put on predicting the surface temperature of a road. Good predictions will give information of the road conditions and warn for risk of slipperiness. Thereby accidents can be avoided by maintaining the road. In this study the emphasis is put on validating the models, not only with surface temperature, but also by studying the various heat fluxes to and from the road surface. Radiation and ground heat flux can be measured with well known techniques, but the turbulent latent and sensible heat flux is very difficult to measure for a road surface. In order to measure the turbulent fluxes it is necessary to get very close to the road surface, so that influence from the surroundings is minimized. Various techniques from micrometeorology have been tested at a test site outside Göteborg in south western Sweden. The Eddy covariance technique seems to underestimate the flows, but the Bowen-ratio technique seemed to work under good conditions.

1 Introduction

Many road ice prediction models are energy balance models. The results are normally verified by comparing the observed and the modelled surface temperature. In this study the energy fluxes are measured and compared to the output of an energy balance model. Measuring the energy balance of a road surface is a very demanding task. Normal micrometeorological techniques cannot be applied. It is necessary to understand the properties of the internal boundary layer (IBL) of the road. The internal boundary layer has been thoroughly investigated by many researchers (Garratt, 1990), (Antonia et al., 1977). The road surface can be seen as an anomaly in a larger landscape, where the larger scale climate is determined by the surroundings. The climate of the road itself is then defined by the IBL forming after a step change in surface roughness or surface heat flux. The IBL of the road will develop from the edge of the road and grow with increasing fetch length. Within the IBL there is an equilibrium boundary layer (EBL), sometimes called fully flux adjusted layer. This is defined as the height where 90 % of the energy fluxes are adjusted to the new surface. In order to do energy balance measurements one needs to get within the EBL. These features have been investigated in Almkvist et al. (2003) and it was found that the road has an EBL lower than 10 cm. Most micrometeorological measurements are done above 2 meters, so the instruments are constructed to measure

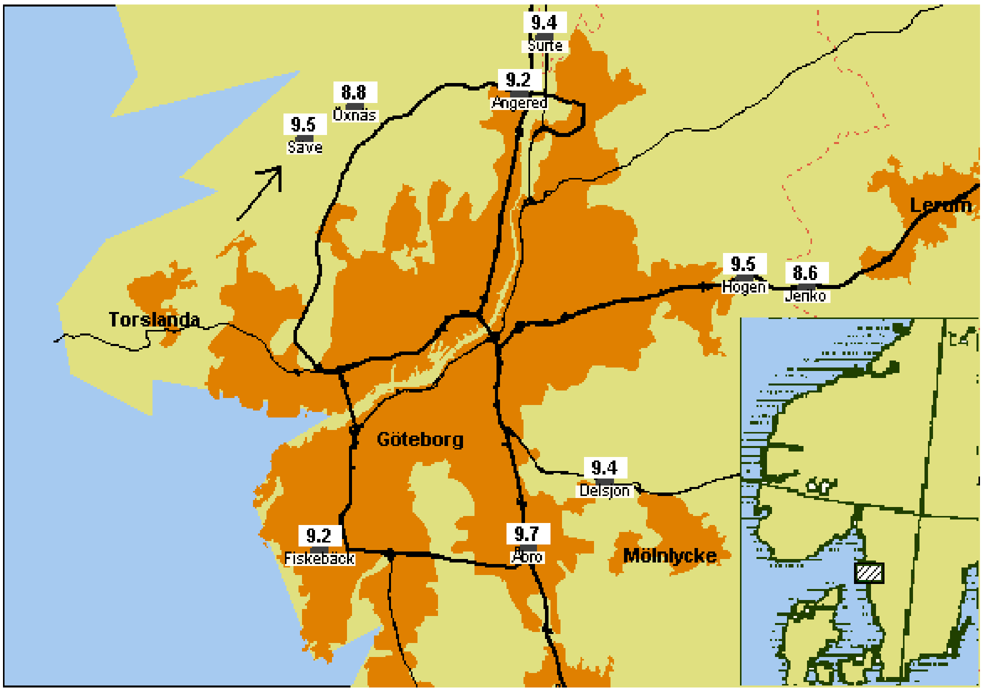

Figure 1: A map of the RWIS-stations in Gothenburg and its surroundings. The test site at Säve airport is indicated by an arrow. Scale 1:300 000.

at this level. If the measurements are done at the 10 cm level new techniques have to be used. In this article two methods are tested to measure the energy balance and surface fluxes: a traditional eddy covariance method using a sonic anemometer and an improved version of a Bowen ratio method where the temperature and humidity gradient below 12 cm is measured. The measurements are validated with an energy balance model.

2 Site and instrumentation

The test site is situated at Säve Airport 10 km north of Göteborg as seen in figure 1. The measurement area consists of a 24x24 m asphalt surface in an open area along a two lane road. There is a 2 m wide ditch that separates the road from the asphalt area. Two masts with instrumentation are situated at the west side of the asphalt area (figure 2). There is a workmen's cabin at the east side of the surface while the south and western sides are fenced. The main wind direction is western, so the influence from the cabin is normally small, but the fence will cause extra turbulence. The asphalt surface was built up to be representative of a normal Swedish road. It was therefore constructed with a top layer of 7 cm asphalt followed by 70 cm of crushed rock. A geotextile was placed to separate the crushed rock from the clay soil below.

The permanent instrumentation consists of a net radiometer, a heat flux plate, road temperature profile and an RWIS-station (Road Weather Information System)(table 1), which was developed for monitoring road conditions. The RWIS-stations measure air temperature, road surface temperature, relative humidity, wind speed and precipitation. At this site the road surface temperature was measured at the test area and not at the road. The net radiometer measured upward and downward short- and longwave radiation. The heat flux plate was self calibrating to account for differences in conductivity of the asphalt and the plate. The validation variables are used to test the model. For the Bowen ratio method, thermocouples were used to measure the temperature and an infrared gas analyzer was used to measure the humidity (table 2). The heights were reversed every 5 minutes to account for differences due to instrumental errors.

Figure 2: The asphalt surface at Säve as seen from the north-west. The RWIS-station is mounted on the left tower, while the instrument measuring the radiation components is on the right tower. The road is seen as a grey line in the foreground.

Table 1: The instrumentation at the test site.

Variable	Location	Instrument	Comments
Climate variables			
Air temperature [°C]	2 m	Pt-100	RWIS
Relative humidity [%]	2 m	Capacitive	RWIS
Global radiation [$W \cdot m^{-2}$]	2.5 m	Pyranometer	Kipp & Zonen
Wind speed [$m \cdot s^{-1}$]	10 m	3-cup anemometer	RWIS
Precipitation [mm]	10 m	IR-sensor	RWIS
Validation variables			
Net radiation [$W \cdot m^{-2}$]	2.5 m	Pyrano/Pyrgeometer	Kipp & Zonen
Road temperature [°C]	0 cm	Pt-100	RWIS
Asphalt temperature [°C]	6 levels, 0-100 cm	Pt-100	
Asphalt heat flux [$W \cdot m^{-2}$]	4 cm depth	Heat flux plate	Hukseflux
Sensible heat flux [$W \cdot m^{-2}$]	15 cm	Sonic anemometer	USAT-1
Latent heat flux [$W \cdot m^{-2}$]	12-15 cm	Infrared	Licor 7000

Table 2: The instrumentation for the Bowen ratio measurements.

Variable	Location	Instrument	Comments
Air temperature [°C]	4 and 12 cm	Thermocouples	Copper-Constantan
Absolute humidity [$kg \cdot m^{-3}$]	4 and 12 cm	Infrared	Licor 7000

3 Measurements

The measurements at the test site have been running since March 2003, but for this study measurements from the period 2-April to 11-April. Temporary measurements of sensible and latent heat flux with the sonic anemometer were made from 2-April to 10-April. The Bowen ratio measurements were made 3 April.

In order to get sufficient fetch on a road surface one needs to measure very close to the surface. This can be a problem since the eddies close to the surface are smaller, dissipate faster and therefore require a faster sampling rate than when measuring at a higher level. The measurements were made at both 10 Hz and 48 Hz. The sonic was placed 15 cm above the surface at the center of the test site. Thereby a fetch of at least 10 m was achieved. A simple estimate of the height for the fully flux adjusted layer or Equilibrium Boundary Layer (EBL), is 1/100 of the fetch length (Blackadar, 1997). This gives a height of the EBL of 10-14 cm, which suggests that the sonic was slightly influenced from the surroundings. The sensible heat flux was calculated from the covariance between the vertical wind-speed and the temperature. The temperature measured by the sonic anemometer is nearly equal to the virtual temperature, which can introduce an error of about 10-20% when calculating the sensible heat flux (Schotanus et al., 1983). This error was neglected in this study since these measurements mainly aim at testing the eddy covariance method for a road surface. Other errors can be more significant.

4 Analysis

The model used in this work, the COUP-model, was originally constructed as a heat and mass transfer model for the soil-vegetation-atmosphere systems. The model allows for a great deal of flexibility and was here parameterized to resemble the soil-road-atmosphere system. The first version of the model was presented by Jansson and Halldin (1979) and a detailed model description is available by Jansson and Karlberg (2001). The model was run on hourly values of global radiation, air temperature, vapour pressure and wind speed. More information of the model runs can be found in Jansson et al. (2003). Important parts of the model as it was used in this study can also be found in Alvenäs and Jansson (1997).

5 Results and Discussion

The net radiation and ground heat flux can be measured by traditional methods. These variables agree well with model results as seen in figure 3 and 4. The model was run on tabular values for asphalt properties. The accuracy of the results could be improved further by fine tuning the model. The turbulent fluxes are both more difficult to model and to measure. The results are shown in figure 5 and 6. The sensible and latent heat fluxes are underestimated by the measurements compared to the model. In order to close the energy balance, the sensible heat flux needs to be about the same order of magnitude as the modelled flux. Therefore the modelled sensible heat flux is more likely to be correct than the measured flux. The eddy covariance technique is designed for measurements above 2 m, so the problems arrive since the small eddies are not resolved by the sonic at 15 cm. The path length of the sonic is probably too large to measure at this low level. The latent heat flux was difficult to model. During the first day the surface was wet and evaporation should be present. The other days were dry, so the modelled latent heat flux is probably unphysical. In figure 7 the results from the Bowen ratio method are shown. The results seem to be reasonable. There was a clear temperature and humidity gradient that gives the fluxes of sensible and latent heat. The measurements were made immediately after a rainfall, so there should be fluxes of water vapor present. There occurred problems with dew formation in the tubing leading to the gas analyzer during the days following the 3 April. To avoid this problem, the tubes should be heated.

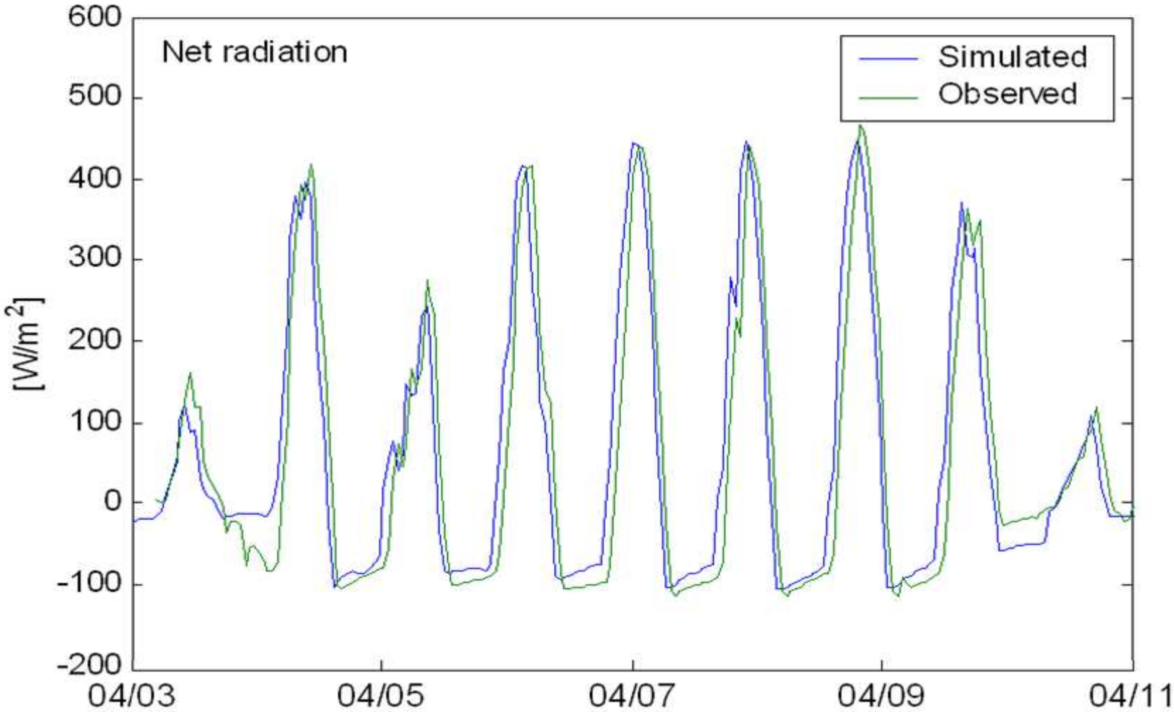

Figure 3: The measured energy flux compared to the modelled energy flux. The data is from the 3-11 April, 2003.

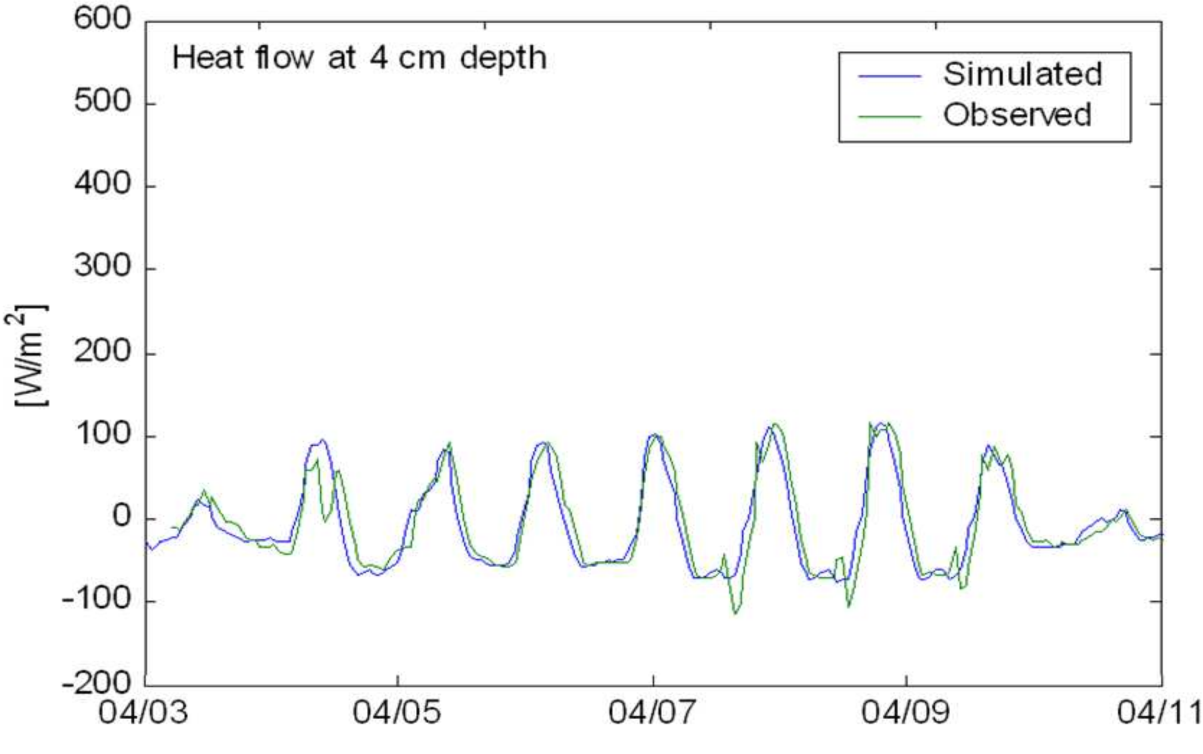

Figure 4: The measured energy flux compared to the modelled energy flux. The data is from the 3-11 April, 2003.

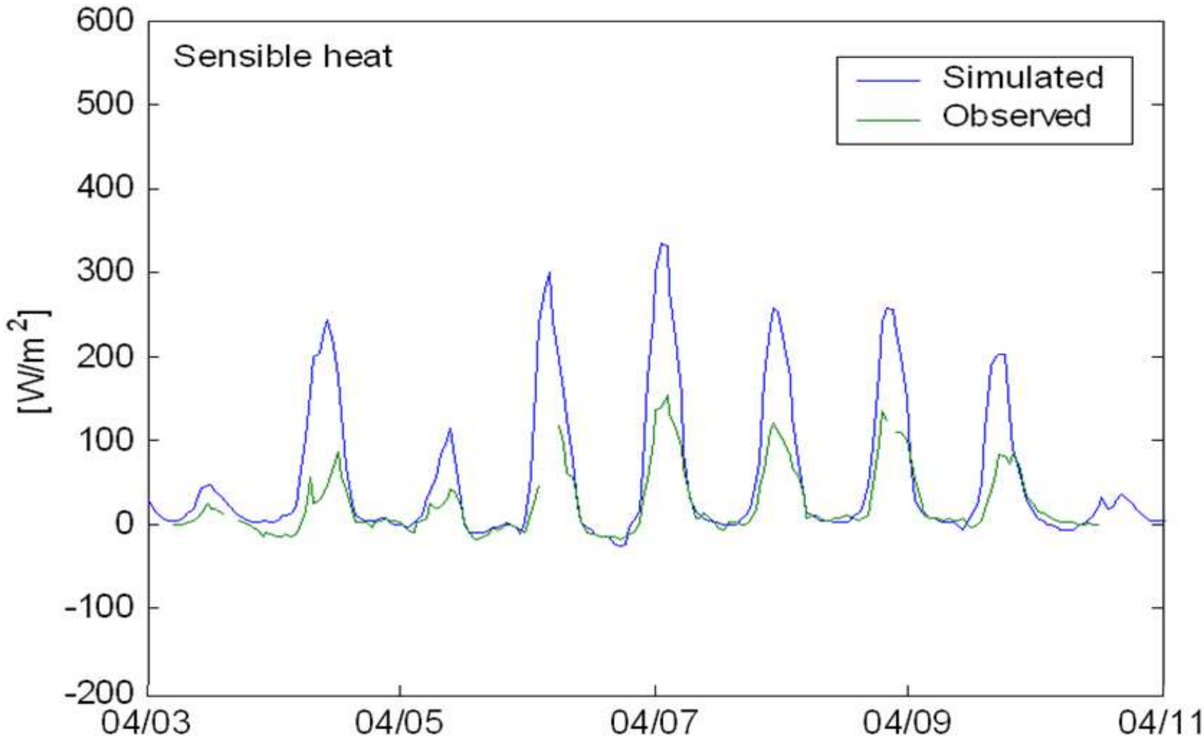

Figure 5: The measured energy flux compared to the modelled energy flux. The data is from the 3-11 April, 2003.

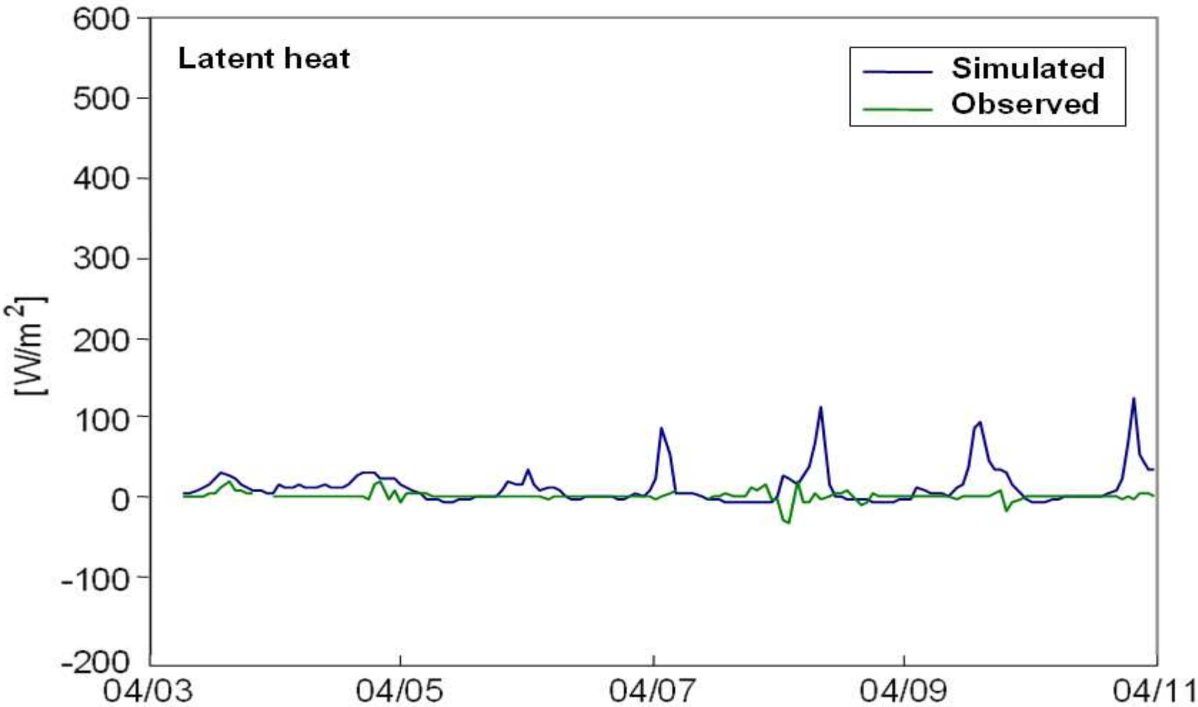

Figure 6: The measured energy flux compared to the modelled energy flux. The data is from the 3-11 April, 2003.

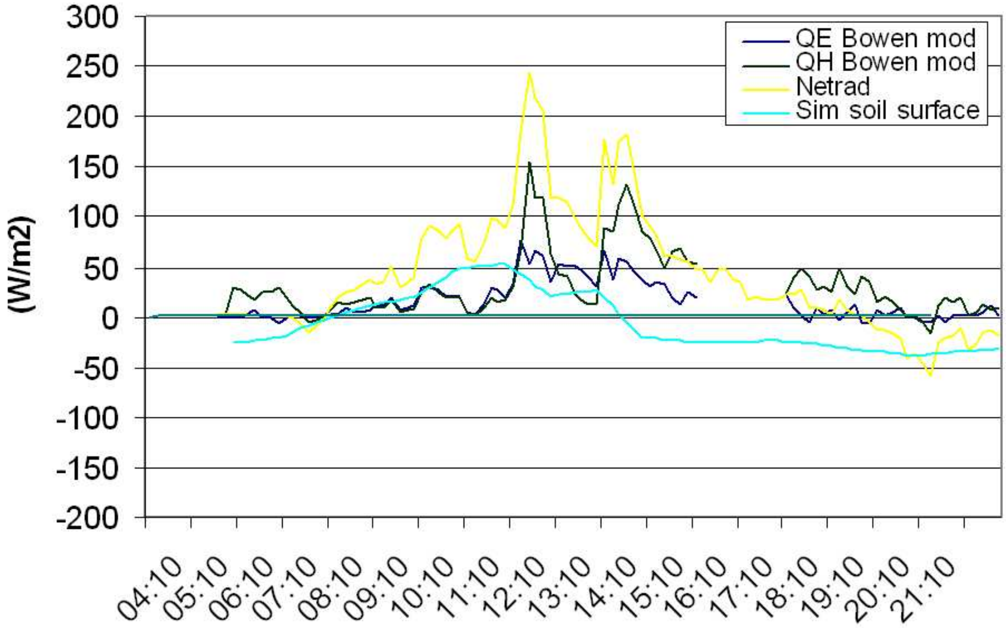

Figure 7: The energy fluxes measured using the Bowen ratio method. The data is from the 3 April, 2003.

6 Conclusions and future research

The results show that measurements of net radiation and ground heat flux are useful to validate the energy balance model. The eddy covariance method is difficult to apply, but the Bowen ratio method can be useful if care is taken to avoid instrumental errors. For frost events the latent heat flux is very important. By studying the humidity gradient and latent heat flow with the Bowen ratio method, valuable information about frost processes can be found. More measurements will be made during the winter 2004 which hopefully will give some good results that can be presented at the SIRWEC meeting.

References

Almkvist, E., Gustavsson, T., and Bogren, J.: 2003, An attempt to define the road climate room, *Submitted to Meteorological applications*

Alvenäs, G. and Jansson, P.-E.: 1997, Model for evaporation, moisture and temperature of bare soil: calibration and sensitivity analysis, *Agricultural and Forest Meteorology* **88**, 47–56

Antonia, R. A., Danh, H. Q., and Prabhu, A.: 1977, Response of a turbulent boundary layer to a step change in surface heat flux, *Journal of Fluid Mechanics* **80**, 153–177

Blackadar, A. K.: 1997, Turbulence and diffusion in the atmosphere : lectures in environmental sciences, *Berlin : Springer, cop.* p. 185p

Garratt, J. R.: 1990, The internal boundary layer - a review, *Boundary-Layer Meteorology* **50**, 171–203

Jansson, C., Almkvist, E., and Jansson, P.-E.: 2003, Heat balance of an asphalted road: Observations and physical based simulations, *Manuscript in licentiate thesis: Water and Heat Balances for Urban Surfaces*, (ftp://www.lwr.kth.se/Common/Christer%20Jansson/KappaLic.pdf)

Jansson, P.-E. and Halldin, S.: 1979, Model for the annual water and energy flow in a layered soil. in: Comparison of forest and energy exchange models (ed. s. halldin), *Division of Land and Water Resources, KTH, Stockholm. 320pp.* pp 145–163, (http://www.lwr.kth.se/vara%20datorprogram/CoupModel/index.htm)

Jansson, P.-E. and Karlberg, L.: 2001, Coupled heat and mass transfer model for soil-plant-atmosphere systems, *International Society for Ecological Modelling, Copenhagen* pp 145–163

Schotanus, P., Nieuwstadt, F. T. M., and DeBruin, H. A. R.: 1983, Temperature measurement with a sonic anemometer and its application to heat and moisture fluctuations, *Boundary-Layer Meteorology* **26(1-2)**, 81–93