Estimation of boundary layer parameters for dispersion calculations using outputs from numerical weather prediction models

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Key words: surface flux, dispersion model, numerical weather prediction model

1 Introduction

Atmospheric boundary layer parameters, such as friction velocity, surface sensible heat flux and Monin-Obukhov length scale, are needed for many applications in the field of meteorology and environmental science. They can be estimated by using standard meteorological observations from synoptic stations or at a few places from meteorological mast data (COST Action 710). Alternatively output from numerical weather prediction models can be used. Numerical weather prediction models are power-full tools for getting meteorological data, particular in areas of irregular spatial distributions of synoptic stations, or in areas lacking observational data. However boundary layer parameters are not always given as direct outputs from these models. They therefore often need to be calculated in a post-processing step.

In this study a data comparison will be presented between output from the numerical weather prediction model Hirlam (HIgh Resolution Limited Area Model), an operational mesoscale analysis system based on optimal interpolation technique (MESAN) and data from a meteorological mast in Sweden. The models have been used for producing meteorological inputs to two different methods for calculations of surface fluxes.

2 Meteorological models

The Hirlam model is a limited area, short-range weather forecasting and analysis system (Källen,1996). The version of Hirlam used in this study has a horizontal resolution of 22 km and 24 vertical levels and covers the northern part of Europe. Surface fluxes are calculated in the model but not given as output. They need therefore to be calculated in a post-processing step using wind and temperature differences from the lowest model level and the surface. The lowest model level is located at approximately 30 m above the ground.

The Mesan system (Häggmark et. al, 2000) is an operational objective analysis system based on the optimal interpolation technique. The basic idea for the system is to produce gridded information of variables that are normally not available directly from numerical weather prediction models, but also to improve model variables using latest possible information. Examples of parameters are precipitation, 2-m temperature and humidity, wind at 10 m level, visibility and clouds. Observations from synoptic and automatic stations, radar and satellites are used. The background field (or first guess) is a six-hour forecast from the Hirlam model with 22-km horizontal resolution.

3 Surface fluxes

In the present study data from the operational Hirlam version at the Swedish Meteorological and Hydrological Institute (SMHI) have been used for the period when the observation data were taken. The calculations of surface fluxes in Hirlam are based on a drag coefficient formulation, using Monin-Obukhov similarity theory for the atmospheric surface layer. These parameters are however not given as direct output from the model, therefore they are calculated in a post-processing step in the similar way as done in the model. The surface turbulent fluxes are calculated from mean model parameters at the lowest model level using bulk formulations:

$$\begin{aligned} \tau &= \rho C_D u_{nlev}^2 \\ H &= \rho C_p C_H u_{nlev} (\theta_s - \theta_{nlev}) \end{aligned} \qquad (1)$$

where τ and H are the vertical turbulent fluxes of momentum and sensible heat flux, ρ is the air density, C_p the specific heat capacity of air. The mean wind and potential temperature at the lowest model level are denoted u_{nlev} and θ_{nlev} .θ_s is the potential temperature at the surface. C_D and C_H are the transfer coefficients for momentum and heat. They are dependent on stability based on Monin-Obukhovs similarity theory. To avoid iterative calculations, analytic formulas are used (Louis et. al., 1982).

For the Mesan system surface fluxes are calculated by the method from van Ulden and Holtslag (1985). This method is fairly pragmatic, using only windspeed (u_{10m}), temperature (T_{2m}) and total cloud cover (N_{tot}) as meteorological data for estimation of surface flux parameters. Several empirical constants are therefore used to simplify the rather complicated physics involved.

4 Data

Meteorological data from a 24 meters high mast in Högdalen (59.26 N, 18.06 E) near Stockholm, Sweden was used in this study. Measurements of wind where done at one level (20 metre) and temperature at two levels (5 and 20 metres). These data was used as input for calculation of surface parameters by the profile method presented by Berkowitz and Prahm (1981). The roughness parameter (z_0) was estimated by analysing the standard deviation of wind direction (σ_θ) according to Beljaars and Holtslag (1991). For near-neutral conditions the following relations were used

$$\sigma_v / u_* = 1.75, \quad \sigma_v = u\sigma_\theta \tag{2}$$

$$\frac{u}{u_*} = \left(\frac{1}{k}\right)\ln\left(\frac{z}{z_0}\right) \tag{3}$$

where σ_v is the standard deviation of velocity fluctuations in y direction, u is the wind speed and z is the height.

The value 1.75 above was derived from the data. By this method the average surface roughness value was estimated to 0.53 m, which can be compared with 0.56 m using only equation (3).

5 Some results

In this section we illustrate the outputs from the two different models by comparing it with mast measurements from Högdalen (59.26 N, 18.06 E), Sweden. The comparison is done for one winter month. The roughness parameter in Hirlam for the gridpoint close to Högdalen is 0.49 m, which can be compared with 0.53 m estimated from observed data.

In figure 1 a comparison is done between outputs from the Hirlam model and measurements at Högdalen, Sweden for the period January 1997.

The figure shows that the Hirlam model overestimates the measured windspeed (1a) and the friction velocity (1b). For the sensible heat flux the Hirlam model tends to underestimate compared to mast measurements (1c). In figure 1d the relative frequency of the inverse of Monin-Obukhov length scale for the Hirlam model and the mast data are shown. The Hirlam model tends to overestimate near neutral conditions and underestimate stable conditions. This is an important difference, for air quality models, as stable conditions are often connected with high air-pollution concentrations.

In figure 2 similar comparison is done for the Mesan system. The agreement between measured and calculated windspeeds is here much better. The Mesan system surely improves the Hirlam output taken as first guess for the analysis. The windspeeds at the measure point is therefore more realistic described. As a consequence the friction velocity is also well estimated by the heat flux method used (figure 2b). For the sensible heat flux the results are reasonably good but with some scatter. The stability situations as described by the inverse of Monin-Obukhov length scale is very well calculated as shown in figure 2 d.

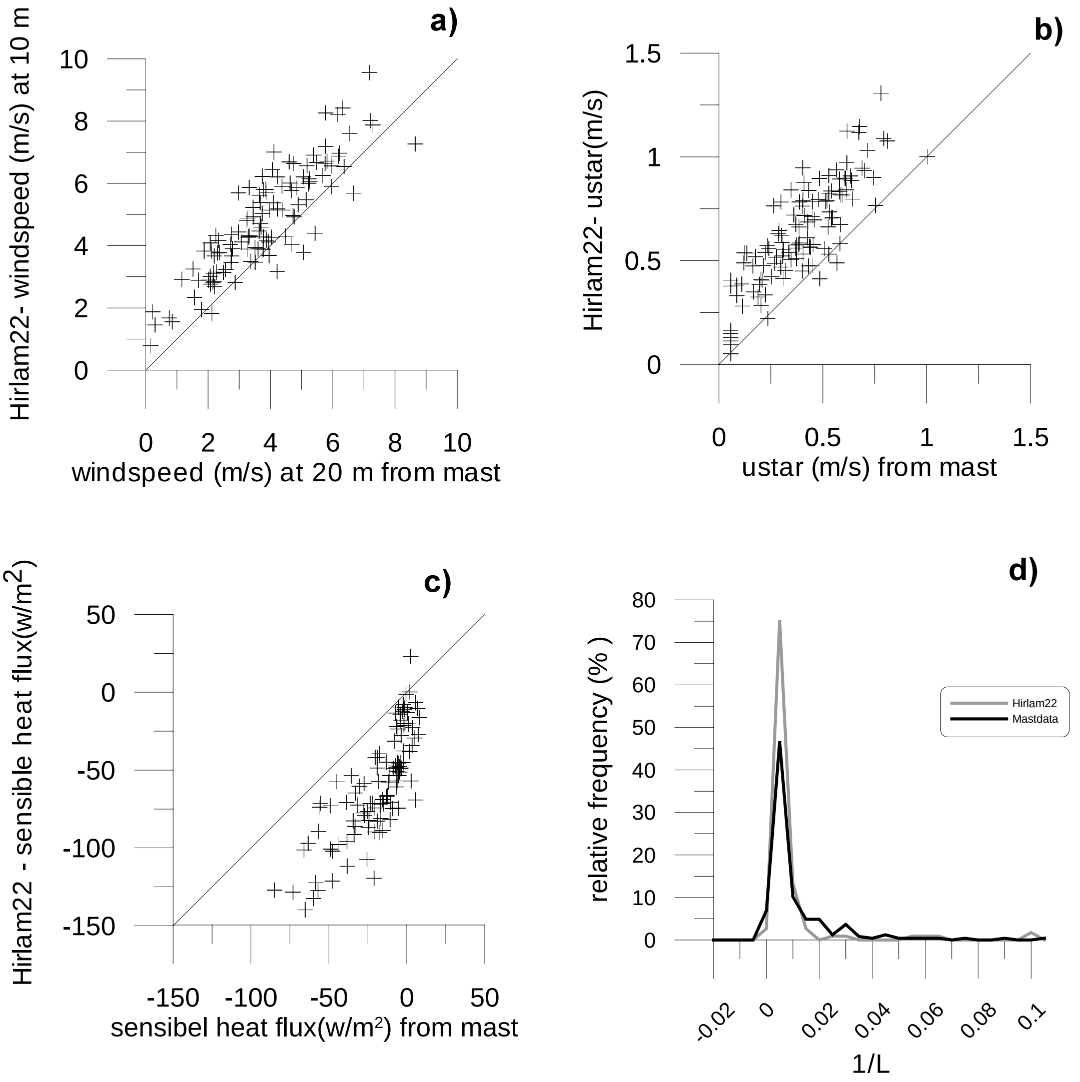

Figure 1 Comparison between outputs from the Hirlam model (with 22 km horizontal resolution) and measurements at Högdalen, Sweden for the period January 1997.

a) windspeed, b) ustar, c) sensible heat flux and d) the relative frequency of the inverse of Monin-Obukhov length scale.

The Monin-Obukhov length scale is defined by

$$L = -\frac{T_0}{g}\frac{u_*^3 \rho C_p}{\kappa H} \qquad (4)$$

where T_0 is the average surface layer temperature, g the constant of gravity, u_* the friction velocity, ρC_p is the specific heat capacity of air at constant temperature, κ is the von Karman constant and H the sensible heat flux. Obviously, L is highly correlated with u_* , and therefore the main meteorological parameter for L is the windspeed.

6 Summary

In this paper we have compared calculated surface layer parameters from meteorological models with mast data. Meteorological outputs from the numerical weather prediction model Hirlam (HIgh Resolution Limited Area Model) and the operational mesoscale analysis system MESAN have been used for one winter month. These models have been used for producing meteorological inputs to two different methods for calculations of surface fluxes. Before definitive conclusions can be drawn it is necessary to make comparisons for more than one single point and for a longer time period. However this study illustrates the importance of using meteorological models that are capable of calculating surface windspeeds rather accurate. Windspeed is the most important parameter for calculation of friction velocity and Monin-Obukhovs length scale. We have shown that if the windspeed is estimated well it is possible to calculate the atmospheric stability during stable conditions, as described by the inverse of Monin-Obukhov length scale, fairly well, which is important for dispersion model calculations.

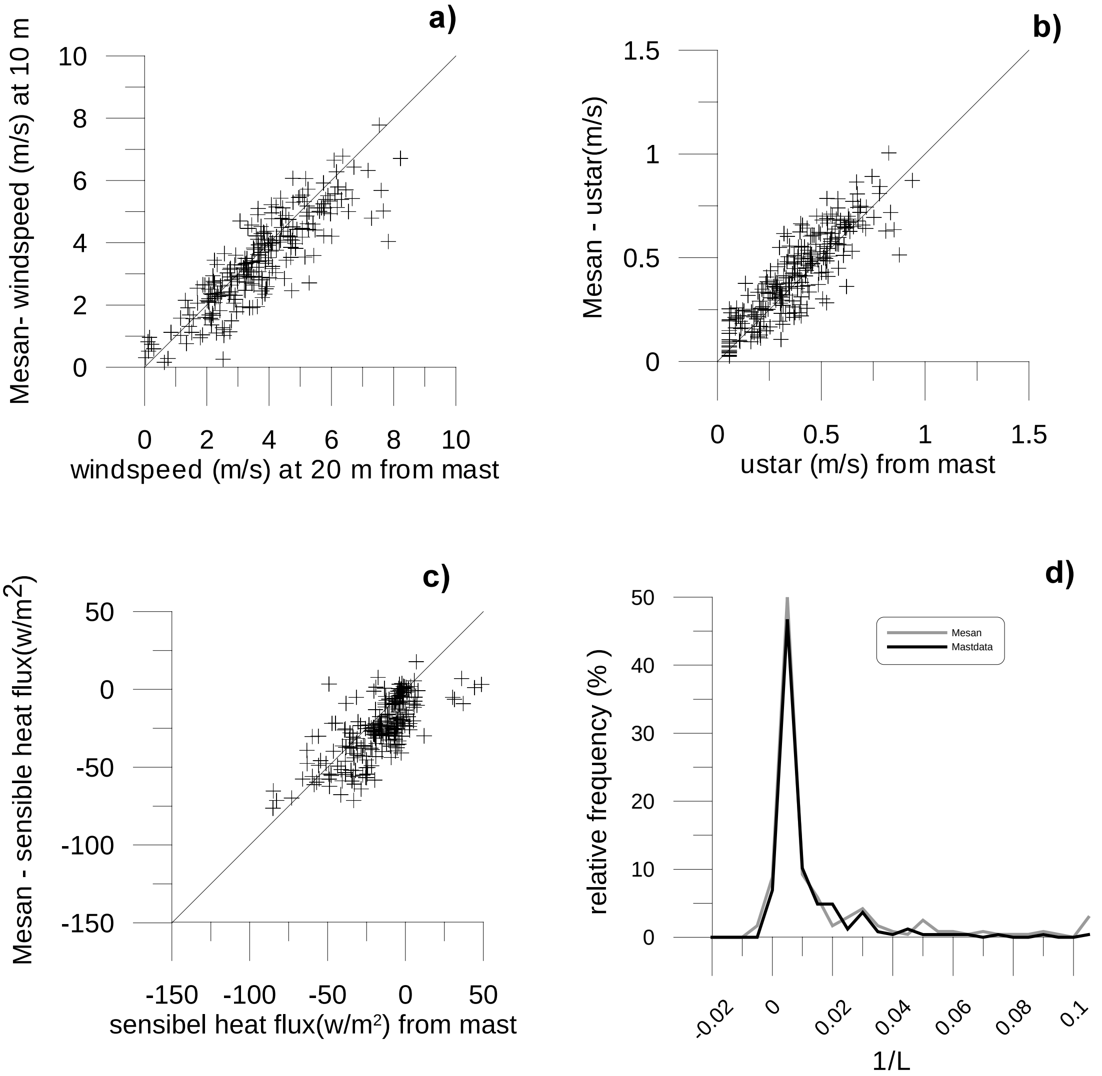

Figure 2 Comparison between outputs from the Mesan system and measurements at Högdalen, Sweden for the period January 1997
a) windspeed, b) ustar, c) sensible heat flux and d) the relative frequency of the inverse of Monin-Obukhov length scale.

Acknowledgements

I would like to thank my colleges Stefan Gollvik, Joakim Langner and Lennart Robertson for valuable discussions and help.

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