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Profile Measurements for Dispersion Calculations

by

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Note

1 Introduction

Modern dispersion models use empirical similarity relationships to estimate the turbulence parameters that determine plume spread (e.g. Gryning (1987)). For these similarity relationships to be used it is necessary to make estimates of the surface friction velocity and the surface sensible heat flux. There are a number of schemes, based on assumptions about the surface energy balance, that use standard meteorological observations to obtain estimates of these parameters. An alternative is to determine these parameters directly. There are two methods that can be used, the profile method, which will be discussed here, and the eddy correlation technique. The advantage of a direct determination of the sensible heat flux, over an estimate based on a surface energy balance, is that there is no need to know the ground state, which determines the partitioning of the available energy between the sensible and latent heat fluxes. Profile methods are considered more attractive than eddy correlation methods because they do not require fast response temperature measurements. Thermometers having the response required for eddy correlation measurements are usually fragile, and would not be suitable for routine use. However, sonic anemometers can be used to provide fast response temperature measurements, in addition to the wind vector. Since the prices of sonic anemometers have fallen considerably in recent years it is possible that the use of routine eddy correlation measurements may become more common in the future.

2 The profile method

An important result from Monin-Obukhov similarity is the relationship between surface fluxes and mean gradient. These relationships can be used to obtained the flux of a quantity from a measurement of its vertical gradient and the windspeed at some height. For windspeed and potential temperature the relationships are:

$$\frac{\partial U}{\partial z} = \frac{u_*}{\kappa z}\phi_m\left(\frac{z}{L}\right) \quad (1)$$

$$\frac{\partial \theta}{\partial z} = \frac{\theta_*}{\kappa z}\phi_h\left(\frac{z}{L}\right) \quad (2)$$

where

u_* = Friction velocity

t_* = $H/(\rho C_p u_*)$

H = Sensible Heat Flux

C_p = Specific heat at constant pressure

ρ = Density

κ = Von Karman's constant

z = Height above zero-plane

L = Monin-Obukhov Length

$\phi_{m,h}$ = Non-dimensional gradients

The functions ϕ_m and ϕ_h have been determined from the results of a number of field experiments.

Equations 1 and 2 can be integrated to give:

$$U(z) = \frac{u_*}{\kappa}\left(\ln\left(\frac{z}{z_o}\right) - \psi_m\left(\frac{z}{L}\right)\right) \quad (3)$$

$$\theta(z_2) - \theta(z_1) = \frac{\theta_*}{\kappa}\left(\ln\left(\frac{z_2}{z_1}\right) - \psi_h\left(\frac{z_2}{L}\right) + \psi_h\left(\frac{z_1}{L}\right)\right) \quad (4)$$

where the functions $\psi_{m,h}$ are given by,

$$\psi_{m,h}(x) = \int_0^x \frac{1-\phi_{m,h}(\zeta)}{\zeta} d\zeta$$

Given a measurement of the windspeed at a height z, the difference in temperature between heights z_1 and z_2 and an estimate of the surface roughness length Equations 3 and 4 can be used to estimate the friction velocity and the sensible heat flux. The need for an estimate of the surface roughness length can be eliminated if the windspeed is also measured at two levels, Equation 3 would then be replaced by;

$$U(z_2) - U(z_1) = \frac{u_*}{\kappa}\left(\ln\left(\frac{z_2}{z_1}\right) - \psi_m\left(\frac{z_2}{L}\right) + \psi_m\left(\frac{z_1}{L}\right)\right) \quad (5)$$

However, in inhomogeneous areas there may be advantages in using Equation 3, so only the combination of windspeed and temperature difference data will be considered here.

3 Results

Dispersion is often assessed using the Pasquill stability classification. Figure 1 shows Pasquill stability class boundaries and the sensible heat flux as a function of the temperature difference from 5m to 10m and the windspeed measured at 10m. The roughness length was taken to be 0.5m. The Pasquill stability classes were determined using the method described by Thomson and Tonkinson (1992).

The hatched areas in Figure 1. are regions where the calculated heat flux exceeds 400Wm^{-2}. Such conditions are unlikely to occur very frequently in the UK. From this plot it is apparent that even under very convective conditions the difference in temperature between 5m and 10m will usually be less than 0.5°C. For windspeeds below 3ms^{-1}, where stability effects become more marked, the Pasquill stability classes are less than 0.2°C wide. To distinguish different stability classes temperature measurements with an accuracy better than ±0.1°C are necessary. (It is assumed that there are significant differences in plume dispersal in different stability classes which the temperature measurements would have to distinguish.)

Figure 2 shows the standard deviation of the vertical velocity component (σ_w) at 100m as a function of windspeed and temperature difference. The standard deviation of the vertical wind was calculated from:

$$\sigma_w = 1.25u_* \left(1.0 - 3.0\frac{z}{L}\right)^{1/3}$$

which is a commonly used formula (Panofsky et al (1977)).

Given temperature measurements with sufficient accuracy to resolve different Pasquill stability classes it should be possible to estimate σ_w at 100m to within about 20%, which should be adequate for dispersion calculations.

The results in Figures 1 and 2 show that for the profile method to be useful the temperature difference (between 5m and 10m in this case) needs to be measured to an accuracy of better than ±0.1°C. If independent thermometers are used to measure the temperature difference this implies the accuracy of the individual temperature measurements must be better than ±0.07°C. Temperature measurements with this accuracy are quite difficult to make, particularly in continuous unattended operation. It is usually considered that, with care, temperature measurements using platinum resistance thermometers can be made with an accuracy of ±0.05° in the atmosphere (Kaimal (1986)). The main limitation on the accuracy of temperature measurements in the atmosphere are uncertainties introduced by the radiation shielding and aspiration of the thermometers. Systematic biases between thermometers can be detected and removed by regular intercomparison of thermometers. The accuracy requirements could be reduced by reducing the height of the lower thermometer, which would increase the temperature difference to be measured. For example, for a lower height of 2m, instead of 5m, the temperature differences in Figures 1 and 2. would cover a range of 1°C. However, as discussed below there are problems with using a thermometer at a low height.

4 Limitations to the profile method

In addition to the stringent accuracy requirements there are a number of other problems that need to be considered when using the profile method.

1. Monin-Obukhov similarity is only applicable for flow over flat homogeneous terrain. In practice few sites of interest are likely to satisfy these criteria. Beljaars (1982) has shown that for Cabauw in Holland it is possible to obtain reasonable estimates of the friction velocity and sensible heat flux over heterogeneous surfaces using temperature profiles and an effective roughness length (see Wieringa (1976) for a discussion of the effective roughness length and its determination). This result is based on a limited amount of data, and although a qualitative justification is given, it is not clear how generally applicable this method is.

2. Monin-Obukhov similarity only holds at a sufficiently large height above the surface (or zero-plane displacement). Measurements over rough surfaces indicate that the standard Monin-Obukhov similarity profiles are valid for heights greater that 30-50z_o. For a typical urban roughness length of 0.3m this suggests that the lowest measurement height should be above 9m.

3. Because they are empirically derived the Monin-Obukhov functions are only strictly valid over the stability range for which they have been determined from observations. This restricts the use of profile relationships to $-z/L \geq 2$.

4. Profile measurements are local and the parameters derived from them represent the effect of the surface some distance upwind of the mast. In practice the turbulent parameters that affect the dispersion of a plume may be determined by the characteristics of the surface over a much larger area. If the local surface characteristics are significantly different from the characteristics of the larger area then the fluxes derived from the profile measurements may not be representative.

5 Conclusions

A great deal of care is required to use the profile technique to estimate surface fluxes. The accuracy with which the air temperature needs to be determined is high and likely to be difficult to achieve on a routine basis. In addition the assumptions underlying the profile method need to be satisfied if the derived fluxes can be used with any confidence.

6 References

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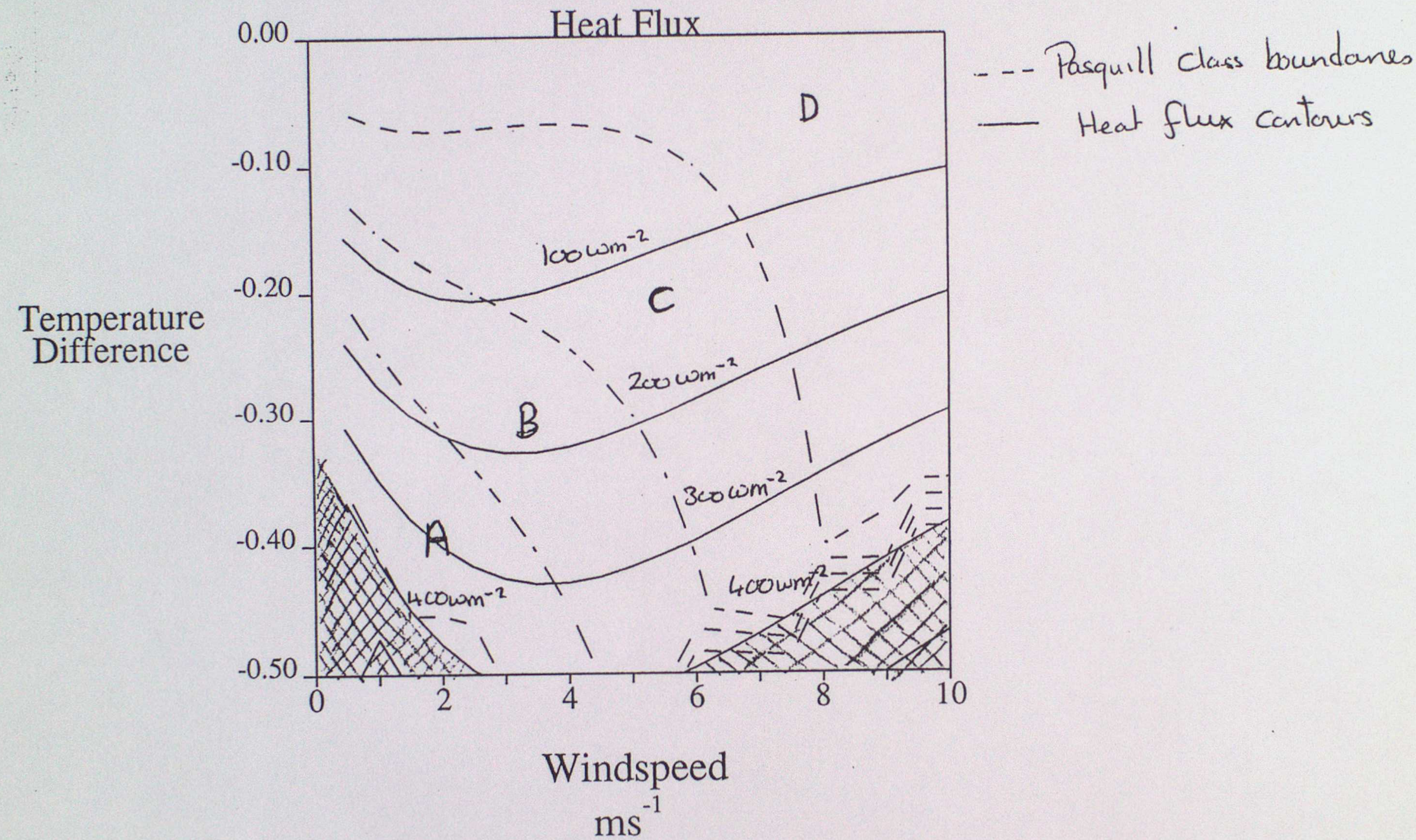
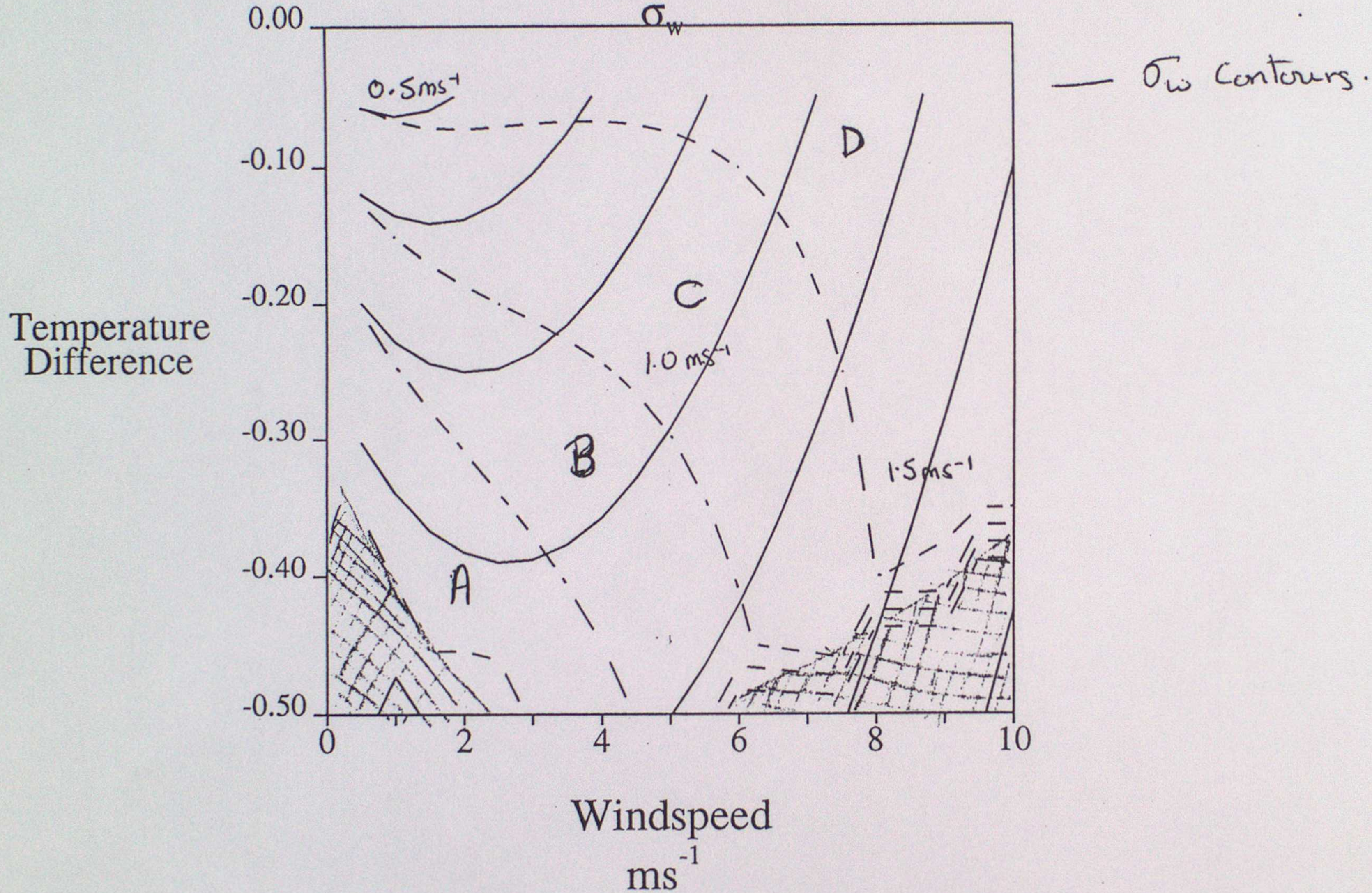
Fig 1



Heat Flux
0.00
-0.10
-0.20
-0.30
-0.40
-0.50
Temperature Difference
0
2
4
6
8
10
Windspeed ms-1
100 wm-2
200 wm-2
300 wm-2
400 wm-2
400 wm-2
A
B
C
D
- - - Pasquill class boundaries
— Heat flux contours

Fig 2.



σw
— σw contours.
0.5ms-1
1.0 ms-1
1.5ms-1
A
B
C
D
Temperature Difference
0.00
-0.10
-0.20
-0.30
-0.40
-0.50
0
2
4
6
8
10
Windspeed
ms-1