12.7 APPLICATION OF SURFACE LAYER SIMILARITY THEORY TO CARBON DIOXIDE, MOISTURE AND TEMPERATURE

J. Vilà-Guerau de Arellano *
Meteorology and Air Quality Group, Wageningen University, Wageningen, The Netherlands
O. Hartogensis
Meteorology and Air Quality Group, Wageningen University, Wageningen, The Netherlands
A.T. Vermeulen
ECN, The Netherlands
F. C. Bosveld and W. Kohsiek
KNMI, The Netherlands
A. A. M. Holtslag
Meteorology and Air Quality Group, Wageningen University, Wageningen, The Netherlands

1. INTRODUCTION

Surface layer similarity theory is applied to measurements (temperature, specific humidity and CO_2) taken at Cabauw (The Netherlands) during the summers of 1995 and 2001. It is generally assumed that the same similarity functions and their dependence on the stability parameter $\xi = z/L$ (z is height and L is the Monin-Obukhov length scale) hold for the three scalars, and in particular for the flux-gradient relationships (ϕ). However, the role of advection, correlation among the variables and sources and sinks could lead to divergences in the $\phi-$functions. So far, there have been few attempts to estimate the flux-gradient relationships for carbon dioxide (ϕ_c) over relativately flat surfaces where canopy effects are almost negligible and to compare these relationships with the values for heat and moisture. Under near-neutral conditions (-0.1< ξ <0) and above land covered with irrigated water (paddy fields) Ohtaki (1984) found that (ϕ_c) follows the function $(1 - 16\ \xi)^{-1/2}$, just like the flux-gradient ralation for heat.

We now extend our study to more convective conditions and compare simultaneously the $\phi-$functions for temperature, moisture and carbon dioxide. By deriving the governing equation for the $\phi-$functions, we are able to discuss under what conditions one should expect differences in the ϕ-functions for the three scalars. In addition, and prior to the flux-gradient relationship calculations, we investigate whether the three scalar fluxes can be averaged over the same time interval by calculating the ogive functions from the co-spectra of the fluxes (Oncley *et al.*, 1996).

2. THEORETICAL BASIS

First of all, we discuss under what conditions one would expect to have similar functions of the scalar flux-gradient relationships. In absence of sources and sinks and assuming a steady-state flow, the budget of a scalar (S) flux (where S stands for temperature, moisture or CO_2) over a horizontally homogeneous surface reduces to

$$-\overline{w^2}\frac{\partial S}{\partial z} - \frac{1}{\rho_0}\left[\overline{s\frac{\partial p}{\partial z}}\right] + \frac{g}{\theta}\,\overline{\theta s} \approx 0, \qquad (1)$$

where the left-hand-side terms represent the gradient production, the buoyant production/destruction and the pressure-covariance destruction, respectively. Third-order covariance terms (turbulence transport) are neglected in this analysis.

In eq (1), we approximate the pressure-covariance term by recognizing three contributions: (1) the tendency of turbulence to become less anisotropic as it decays, i.e. the "return-to-isotropy" (Rotta,1951), (2) the mean shear-turbulence interactions and (3) the buoyancy-turbulence interactions (for the last two contributions see Launder *et al.*, 1975). By introducing this closure and making eq (1) dimensionless by means of a length scale (z), the friction velocity (u_*) and a scalar scale ($s_* = -\overline{ws}/u_*$), we obtain the following expression for the dimensionless scalar flux (Yamada 1985, Vilà-Guerau de Arellano *et al.*, 1995)

$$-r_{33}\phi_s + C\frac{\phi_\epsilon}{e_t} - \frac{1}{5}r_{1s}\phi_m + \frac{2}{3}\xi r_{\theta s} \approx 0. \qquad (2)$$

Here now the first term accounts for the gradient production, the second and third terms describe the pressure-covariance term (including the return-to-isotropy and the mean shear-turbulence interactions) and the last term represents the buoyancy effects (including the contribution (3) of the pressure-covariance term). Equation (2) can be solved to obtain ϕ_s if one couples this equation to the other second-order governing equation for momentum, heat and moisture (Yamada 1985, Vilà-Guerau de Arellano *et al.*, 1995).

The dimensionless quantities in equation (2) are defined as follows:

a) Flux-gradient relationships

$$\phi_m = \frac{\kappa z}{u_*}\left(\frac{\partial U}{\partial z}\right) \qquad \phi_s = \frac{\kappa z}{s_*}\left(\frac{\partial S}{\partial z}\right) \qquad (\kappa = 0.4) \qquad (3)$$

* *Corresponding author address:* Jordi Vilà-Guerau de Arellano, Meteorology and Air Quality Group, Wageningen University, Duivendaal 2, 6701 AP Wageningen, The Netherlands; e-mail: jvila@hp1.met.wau.nl

b) Dissipation rate (accounts for the return-to-isotropy term)

$$\phi_\epsilon = \frac{\kappa z}{u_*^3}\epsilon \tag{4}$$

c) Co-variances

$$r_{33} = \frac{\overline{w^2}}{u_*^2} \quad r_{1s} = \frac{\overline{us}}{u_* s_*} \quad r_{\theta s} = \frac{\overline{\theta s}}{\theta_* s_*} \tag{5}$$

d) Turbulent kinetic energy and length scales

$$e_t = \frac{e}{u_*^2} \quad \xi = \frac{z}{L}. \tag{6}$$

Before discussing the implications of eq. (2), we consider it important to mention that although we have derived the equation under horizontally homogeneous conditions, an advective term (r_{1s}) appears in the equation due to the contribution (2) of the pressure-covariance term. From eq. (2), we deduce that the ϕ_s-functions have a similar dependence on ξ if the co-variance terms r_{1s} (advective term) and $r_{\theta s}$ (buoynacy term) have similar values. For the scalars moisture and temperature, earlier numerical (Wharaft, 1976; Hill, 1989) and observational studies (De Bruin *et al.*,1999) showed differences between ϕ_t and ϕ_q. In particular, these deviations are larger under conditions of low correlation among the scalars ($\rho_{\theta q} < \pm 1$). Note that the correlation coefficient is related to the non-dimensional covariance term $r_{\theta s}$. In future experiments therefore it will be useful to measure and compare the dimensionless covariances to determine possible deviations from the assumption $\phi_h = \phi_q = \phi_c$.

3. OBSERVATIONS

Two sets of observations collected in 1995 and 2001 were analyzed for this study. The first set was taken during the summer 1995. It is more suitable for calculating the flux-relationships of the three scalars. In 1995, CO_2 concentration measurements were taken with higher vertical resolution in the surface layer (3 levels) compared to the campaign in 2001 (only one point measurement in the surface layer). The second observational experiment was performed during the summer 2001. It allow us to address certain research questions that we can not discuss with the 1995 data set. In particular, the 2001-data set let us to calculate the (co)-variances among the scalars and use raw data to estimate possible differences in the time averaging in order to calculate second-order moments. It is our intention to use all the experience we have gained during the current analysis of these two experiments and to carry out a complete experiment during the summer of 2002.

In the summer of 1995, temperature and specific humidity measurements were taken at Cabauw (land surface covered with grass) at 0.6, 2, 10, 20, 40, 80, 140 and 200 m and carbon dioxide concentrations were measured at 1, 2, 10 and 200 m. In addition, momentum and sensible heat flux were measured by a sonic instrument and moisture and CO_2- fluxes were observed with an open path instrument at 5 m (Kohsiek, 1991). From these measurements, we selected two days characterized by convective conditions and absence of clouds. The tower and flux measurements were averaged every 30-minutes. Similar to Oncley *et al.* (1996) we used a least-square interpolation method to fit the vertical profiles since visual inspection of the data clearly showed logarithmic profiles. From these fitted expressions, we calculated the flux-gradients at the height of the fluxes.

4. RESULTS and DISCUSSION

In the absence of the data (for the 1995 experimental campaign) and in order to find out whether the same time-averaging could be used to calculate the flux of heat, moisture and carbon dioxide; we use the observations collected at Cabauw under similar surface layer conditions (-0.5< ξ <0) during 2001. Figure 1 shows the cumulative integral of the co-spectra (ogive) of the vertical velocity and the three scalars. The convergence frequency of the three fluxes is very similar ($f \approx 0.001$), which indicates that a similar time-averaging value ($\tau \approx 15\ min$) can be used to estimate the second-order moments for this situation. In future campaigns, we will apply the ogive method sistematically and we will analyze the cause of possible differences on the time-averaging value to calculate the scalar fluxes.

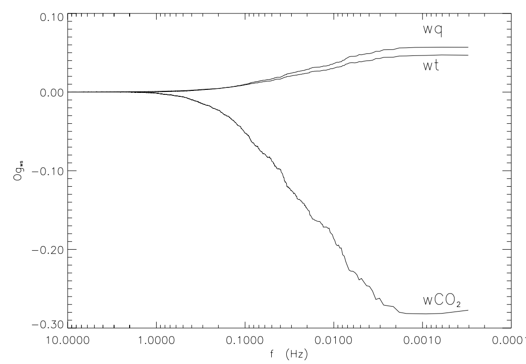

FIG. 1: Ogives for the co-spectra of wt,wq and wCO_2 calculated from measurements taken on 22 August 2002 at 13 UTC.

The choice of appropriate time-averaging is particularly important in the calculation of scalar fluxes. Short time-averaging could lead to an underestimate of the scalar fluxes. For instance, in a recent paper, Sakai *et al.* (2001) found out that the CO_2-flux can be $10\% - 40\%$ lower if low contributions are filtered during the flux calculation.

As mentioned earlier, the data collected in 1995 are more suitable for our purpose, namely to calculate the flux-gradient relationships. Figure 2 shows the $\phi-$functions for heat, moisture and carbon dioxide as a function on the stability parameter ξ. To diminish the effect of the scatter, we have grouped and averaged the data in bins of $\xi = 0.05$. In spite of the typical scatter in most surface layer experiments, the results show that the heat and moisture functions agree rather well the experimental fitted function $\phi = (1 - 16\ \xi)^{-1/2}$. The values for CO_2 shows larger unsystematic differences. For instance, in the range -0.3< ξ <-0.1, a slight underestimation is found, but there is a good agreement with the ϕ values for heat and moisture. However, in the range -0.3> ξ, the values for CO_2 clearly overestimate the values for heat and moisture.

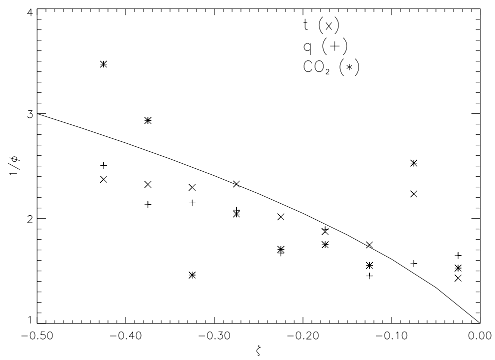

FIG. 2: Flux-gradient relationships for heat, moisture and carbon dioxide versus the stability parameter ξ. The measurements were gathered on 30 July and 1 August 2001. The continuous line shows the experimental fitted ϕ-function, $\phi = (1 - 16\ \xi)^{-1/2}$
.

These preliminary results clearly show that in order to study the validity of surface layer similarity theory for scalars, it is necessary a more complete experiment which combines high vertical resolution measurements of first- and second-order moments for heat, moisture and carbon dioxide. The analysis will have to include a proper calculation of the time-averaging for the second-higher order moments for the scalars and discuss the possible difference of the $\phi-$ functions which can arise from the differences in the values of the co-variances r_{1s} and $r_{\theta s}$.

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