PRELIMINARY ANALYSIS OF TURBULENT TRANSFER CHARACTERISTICS IN THE SURFACE LAYER OVER GUANGZHOU REGION

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ABSTRACT

On the basis of the Monin-Obukhov similarity theory, a semi-empirical expression of universal functions is fitted by means of the iteration method, using the gradient observation data of wind and temperature in the surface layer. The characteristics of bulk transfer coefficient are studied and some empirical relationships among the bulk transfer coefficient, the wind speed and temperature are obtained. The applicability of the results is investigated using observation data.

Key words: bulk transfer coefficient, universal function, air-land interaction

I. INTRODUCTION

The core in solving the land processes in the transfer and exchange of energy and mass between the underlying surface and the atmosphere. In determining with observational data the exchanges of momentum, heat and water moisture between them, the usual way is employing a parameterization scheme expressed by bulk transfer coefficients (Eageleson, 1981). The issue has thus been reduced to·one that determines the coefficient that describes the bulk transfer of matter and energy between the land and atmosphere. Much work has been done on this aspect (Chen and Reng, 1984; Ma, 1990; Lu, 1989 and Zuo and Hu, 1992). With the bulk transfer coefficient, the momentum, sensible heat and water vapor flux are determined with the wind speed in the near-surface layer and vertical distribution of temperature and humidity given by the model. There has been not much work on the issue for the area of Guangzhou due to insufficient knowledge of the coefficient, incomplete research with different underlying surfaces, and limitation of observational data. Based on gradient observations in Guangzhou, preliminary discussions are conducted here to study the universal function and bulk transfer coefficient for understanding of patterns of turbulence near the surface.

II. BASIC THINKING AND ALGORITHM OF PP

The data used in the work is part of the observed heat equilibrium in Guangzhou in 1958. The observation site is flat and open, with great degree of horizontal homogeneity. The terms of observation include air temperature, water vapor pressure and wind speed at heights of 0.5 m and 2.0 m and accuracy of 0.1℃, 0.1 hPa and 0.1 m/s, respectively. The observation was taken at 0100, 0700, 1000, 1300, 1600 and 1900 (Local time). Details of instrumentation and observation

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are referred to Chen et al.(1982).

III. METHOD OF ANALYSIS

Following the Monin-Obukhov similarity theory, dimensionless gradient of wind speed and temperature are written as follows for the near-surface layer with homogeneously even underlying surface:

$$\frac{\partial U}{\partial Z}=\frac{U_*}{kZ}\Phi_m(\zeta) \tag{1}$$

$$\frac{\partial T}{\partial Z}=\frac{T_*}{kZ}\Phi_t(\zeta) \tag{2}$$

where U_* is the frictional speed, T_* the characteristic temperature and $\zeta=z/L$ the dimensionless height. k is the Fencarmen constant (taken as k=0.4), and Φ_m, Φ_t are dimensionless wind speed and temperature. It is then clear that the study of wind temperature profile can be reduced to that of the universal function $\Phi(\zeta)$, whose empirical function takes on the form that is determined by experimental data. By the following expression,

$$L=U_*^2T/(kgT_*) \tag{3}$$

is determined, in which T is the mean temperature for the near-surface layer, g=9.8 m/s^2 the gravitational acceleration. Much experimental data (Haugen, 1973) have shown that

$$\Phi_m(\zeta)=1+\beta_m\zeta \qquad \Phi_t(\zeta)=1+\beta_t\zeta \qquad \zeta\ge 0 \tag{4}$$

$$\Phi_m(\zeta)=(1-\gamma_m\zeta)^{-1/4} \qquad \Phi_t(\zeta)=(1-\gamma_t\zeta)^{-1/2} \qquad \zeta\le 0 \tag{5}$$

where $\beta_m, \beta_t, \gamma_m, \gamma_t$ are parameters to determine. Integrating Eq.(1) from height Z_1 and Z_2 yields

$$U(z_2)=U(z_1)=U_*\psi_m/k \tag{6}$$

$$T(z_2)=T(z_1)=T_*\psi_t/k \tag{7}$$

where ψ_m, ψ_t are the functions of integral approximation, which, following Paulson (1983?), can be expressed as:

$$\psi_m=\ln(Z_2/Z_1)+\beta_m(Z_2-Z_1)/L \qquad \zeta\ge 0$$

$$\psi_t=\ln(Z_2/Z_1)+\beta_t(Z_2-Z_1)/L \qquad \zeta\ge 0 \tag{8}$$

$$\psi_m=\ln\left(\frac{z_2}{z_1}\right)+\ln\left(\frac{(x_1^2+1)(x_1+1)^2}{(x_2^2+1)(x_2+1)^2}\right)+2(\tan^{-1}x_2-\tan^{-1}x_1) \qquad \zeta\le 0$$

$$\psi_t = \ln\left(\frac{z_2}{z_1}\right) + 2\ln\left(\frac{y_1+1}{(y_2+1)}\right) \qquad \zeta \le 0 \tag{9}$$

where $x_1 = (1-\gamma_m z_1/L)^{1/4}$, $x_2 = (1-\gamma_m z_2/L)^{1/4}$, $y_1 = (1-\gamma_t z_1/L)^{1/2}$, $y_2 = (1-\gamma_t z_2/L)^{1/2}$.

The gradients for temperature and wind speed are exactly determined using the formulae of logarithmic interpolation as in

$$\frac{\partial U}{\partial t} = \frac{U(z_2)-U(z_1)}{Z(\ln(z_2-z_1))} \qquad \frac{\partial T}{\partial z} = \frac{T(z_2)-T(z_1)}{Z(\ln(z_2-z_1))} \tag{10}$$

where $Z=\sqrt{z_1 z_2}$. Substituting Eq.(10) into Eqs.(1) and (2), we have

$$\Phi_m(Z/L) = k(U(z_2)-U(z_1))/(U_* \ln(z_2/z_1)) \tag{11}$$

$$\Phi_t(Z/L) = k(T(z_2)-T(z_1))/(T_* \ln(z_2/z_1)) \tag{12}$$

By substituting Eqs.(6), (7) into Eqs.(11), (12), we have

$$\Psi_m = \ln(z_2/z_1)\phi_m(z/L) \tag{13}$$

$$\Psi_t = \ln(z_2/z_1)\phi_t(z/L) \tag{14}$$

Using Eqs.(13), (14), the coefficients in Eqs.(4) and (5) are obtained.

Following Yokoi (1991), dimensionless height ζ is related to the Richardson number R_i for the gradient as

$$z/L = R_i/(1-5R_i) \qquad \zeta \ge 0 \tag{15.1}$$

$$z/L = R_i \qquad \zeta \le 0 \tag{15.2}$$

where R_i is derived in

$$R_i = \frac{g}{T}\left[\frac{\Delta T}{\sqrt{z_1 z_2}(\ln(z_2/z_1))} + \gamma_d\right]\left[\frac{\sqrt{z_1 z_2}(\ln(z_2/z_1))}{\Delta u}\right]^2 \tag{16}$$

As there is a relationship of non-linear implicit function in Eqs.(3), (6), (7), (13) and (14), solutions have to be sought by means of iteration as in:

(1) With the wind speed and temperature observations at the two heights, R_i is obtained from Eq.(16) and the initial value of the Monin-Obkhov length L is derived by substitution of Eq.(15);

(2) With the initial profile parameters $\beta_m^{(0)}, \beta_t^{(0)}, \gamma_m^{(0)}, \gamma_t^{(0)}$ given, ψ_m, ψ_t are known from Eqs.(8) and (9) and $U_*^{(0)}, T_t^{(0)}$ are known with substitution of Eqs.(6) and (7). Then, Eq.(3) is used to obtain the 1st order approximated value of $L^{(1)}$ before making known the same approximations of $\beta_m^{(0)}, \beta_t^{(0)}, \gamma_m^{(0)}, \gamma_t^{(0)}$ for the profile parameters using Eqs.(4), (5), (13) and (14);

(3) By substituting $L(1)$ and $\beta_m^{(1)}, \beta_t^{(1)}, \gamma_m^{(1)}, \gamma_t^{(1)}$ into Eqs.(6) and (7), $U_*^{(1)}, T_t^{(1)}$ are known, which are then substituted into Eq.(3) for $L^{(2)}$; Eqs.(4), (5), (13) and (14) are used again to obtain $\beta_m^{(2)}, \beta_t^{(2)}, \gamma_m^{(2)}, \gamma_t^{(2)}$.

(4) Repeating the steps above, the computation does not stop until the result so obtained between two successive L in iteration meets the criterion of $\left|\left(L^{(n+1)}-L^{(n)}\right)/L^{(n+1)}\right| \leq 0.01$.

The flux of turbulence momentum is expressed by

$$\tau = \rho Cd(U_z - U_s)^2 \qquad (17)$$

where C_d is the bulk transfer coefficient of momentum flux, U_z the mean wind speed at the height of z above ground level, U_s the wind speed at the ground surface, which takes U_s=0 for the land. As a result, the bulk transfer coefficient is expressed by

$$Cd = U_*^2 / U_z^2 \qquad (18)$$

i.e. Eq.(18) is useful for determination of the bulk transfer coefficient for momentum flux.

IV. ANALYSIS OF RESULTS

1. *Universal function and M-O length L*

Based on the method and data above, the mean values and standard deviations of β_m, β_t, γ_m, γ_t are respectively 5.53, 5.53, 18.76, 10.63, 0.39, 0.39, 0.60 and 0.36. Then the semi-empirical expression for changes of the universal function with ζ becomes

$$\Phi_m(\zeta) = \phi_t(\zeta) = 1 + 5.53\zeta \qquad 0 \leq \zeta \leq 0.3 \qquad (19)$$

$$\Phi_m(\zeta) = (1 - 18.76\zeta)^{-1/4} \qquad -1.0 \leq \zeta \leq 0 \qquad (20)$$

$$\Phi_t(\zeta) = (1 - 10.63\zeta)^{-1/2} \qquad -1.0 \leq \zeta \leq 0 \qquad (21)$$

Additionally, another form of universal function, available with the least square fit and the Richardson number as the stability factor, is written as

$$\Phi_m(\mathrm{R_i}) = \Phi_t(\mathrm{R_i}) = 1 + 5.95\zeta \qquad 0 \leq \mathrm{R_i} \leq 0.2 \qquad (22)$$

$$\Phi_m(\mathrm{R_i}) = (1.03 - 15.66\mathrm{R_i})^{-1/4} \qquad -1.0 \leq \mathrm{R_i} \leq 0 \qquad (23)$$

$$\Phi_m(\mathrm{R_i}) = (1 - 8.62\mathrm{R_i})^{-1/2} \qquad -1.0 \leq \mathrm{R_i} \leq 0 \qquad (24)$$

It is known from the discussion above that the computation for determining L is too complicated to apply in practice. Based on observed gradients, the empirical relationship expression between L and land-atmosphere difference and wind-speed difference is shown as

$$L = 23.764(T_0 - T_2)^{-0.962}(U_2 - U_1)^{1.921} \qquad T_0 - T_2 > 0 \qquad (25)$$

$$L = -18.812(T_2 - T_0)^{-1.041}(U_2 - U_1)^{2.080} \qquad T_0 - T_2 > 0 \qquad (26)$$

where T_0 is the temperature of land surface, T_2 the air temperature at the height of 2 m and U_1 and U_2 the wind speed at 0.5 m and 2.0 m, respectively. In conventional computation, L can be decided through Eqs.(25) and (26) before substitution into Eqs.(6) and (7) for U^* and T^*, and further on for sensible heating etc. Comparing the results of Φ_m, Φ_t, L as derived in Eqs.(22) –

(26) with those obtained by the profile method, we find that the correlation coefficients and mean standard deviations become 0.99, 0.99, 0.99, 0.67, 0.78 and 0.83×10^{-4}, 0.29×10^{-2}, 0.46×10^{-2}, 0.12×10^{3}, 0.11×10^{3}, respectively. It suggests good fitting for each of the expressions above.

2. *Characteristics of bulk transfer coefficient*

Fig.1 gives the diurnal variations of C_d and U_2 for January and July in 1958. It is shown that C_d decreases as U_2 increases but increases as C_d decreases. The figure shows a clear correlation between C_d and U_2 in which U_2 and U_2 vary by the same magnitude of amplitude.

Fig.2 shows the relationship between the bulk transfer coefficient and the wind speed at 2.0 m. It is obvious that in any stratification condition the bulk transfer coefficient decreases as the wind speed increases, being consistent with Fig.1. When the mean wind speed is small ($R_i>0$), $U_2<1.8$ m/s; with $R_i<0$, $U_2>1.6$ m/s. In other words, the coefficient is sensitive to the change in wind speed in a manner that is non-linear and discrete. It may be accountable by the fact that small magnitude of wind speed is favorable for the stratification to develop towards convection so that the superadiabatic process and exchange of turbulence become stronger in the

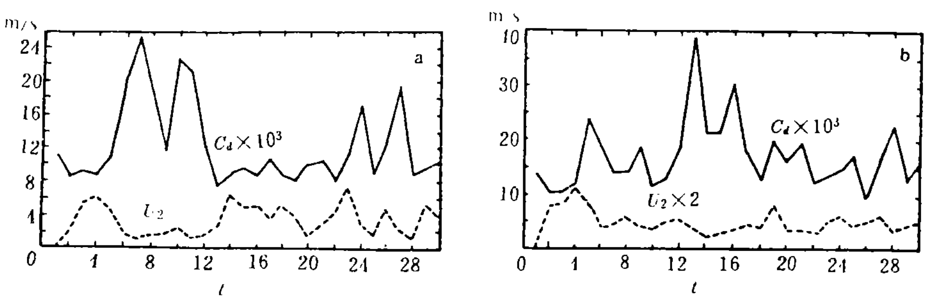

Fig.1. Day-to-day changes of bulk transfer coefficient c_d and wind speed u_2 in (a) January and (b) July.

near-surface layer. On the other hand, as the wind gets stronger, the bulk transfer coefficient decreases and becomes closer to constant, because the stratification tends to be neutral or near it as the wind increases. With the condition of stable stratification and $U_2>4.2$ m/s, the coefficient is within the constant region of 11.6×10^{-3}; the unstable stratification with $u_2>4.2$ m/s moves a bulk transfer coefficient to a constant region of 12.1×10^{-3}. With statistic analysis of computed results for the year of 1958, the bulk transfer coefficient is found to relate to wind speed and difference between land and atmosphere by the following way.

$$C_d\times10^3=14.4-3.33U_2+0.65U_2^2 \tag{27}$$

$$C_d\times10^3=23.36U_2^{-0.52} \tag{28}$$

$$C_d \times 10^3 = 25.51U_2^{-0.58}(T_0 - T_2)^{-0.05} \qquad T_0 - T_2 > 0 \tag{29.1}$$

$$C_d \times 10^3 = 15.80u_2^{-0.12}(T_2 - T_0)^{-0.02} \qquad T_0 - T_2 < 0 \tag{29.2}$$

where U_2 is the wind speed at 2 m, T_2 the temperature at ground surface and T_2 that at 2 m.

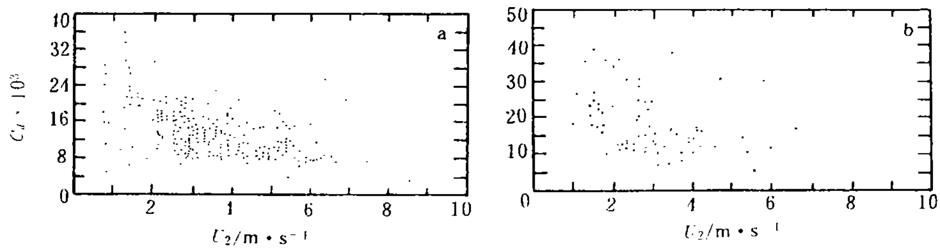

Fig.2. Relationship between bulk transfer coefficient c_d and wind speed at the 2.0 m level with $R_i > 0$ (a) and $R_i < 0$.

3. *Tests of applicability for the expression of the fitting relation for bulk transfer coefficient*

Fig.3a, b, c show in comparison the flux of turbulence momentum as derived from Eqs.(27), (28), (29) and (17) [denoted by subscript "est"]and that which is obtained by the profile approach (denoted by subscripts "obs"). It is seen that good correlation exists between the flux of turbulence momentum by both methods, the correlation coefficients being 0.81, 0.92 and 0.92, and the relative error being 0.26, 0.16 and 0.15, respectively. From the fitting expressions of Eqs.(27), (28) and (29), we know that the drag effects of turbulence friction are expressed by the bulk transfer coefficient of the momentum flux and dependent on kinetics, but Eq.(29) seems to fit the bulk transfer coefficient best when the thermodynamics term is included to account for the close relation between C_d and the stratification. The analysis above indicate that Eqs.(28) and (29) have good applicability.

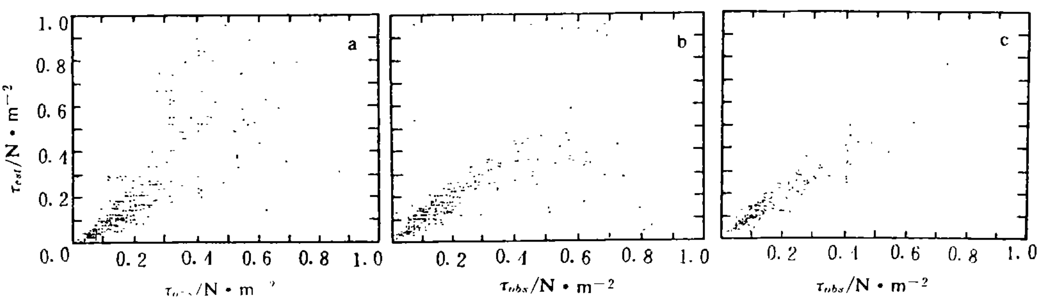

Fig.3. Comparison between the estimated momentum flux by the empirical expression and calculated momentum flux by the profile method.

V. CONCLUSIONS

a. A semi-empirical expression of universal function is derived in this work that is applicable for the area of Guangzhou and an empirical expression is obtained for the relation between wind/temperature gradient and Monin-Obukhov length L.

b. The bulk transfer coefficient decreases as the wind increases while it largely becomes a constant when the wind is getting stronger.

c. An empirical expression is obtained for relation between the bulk transfer coefficient and mean wind speed and land-atmosphere temperature difference, which is shown to have good applicability.

The results above are of some reference value for the parameterization of land surface processes.

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