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Parameterization of the Atmospheric Boundary Layer for use in General Circulation Models: A Comparative Study

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This is an unreviewed manuscript, primarily intended for informal exchange of information among NMC staff members.

1. Introduction

Two distinct sublayers characterize the structure of the atmospheric boundary layer: The constant flux layer, and the so-called Ekman layer. The constant flux layer lies immediately above the surface to approximately 50 m. In this layer the vertical variations of momentum, heat, and moisture fluxes are negligible and the wind direction is essentially constant. The Ekman layer lies above the constant-flux layer; typically turbulent fluxes within this layer decreases upward.

An important role played by the planetary boundary layer in general circulation models (GCM) is the vertical exchange of fluxes of momentum, mass, heat and moisture. Accurate account of these turbulent fluxes has been the main focus in the boundary layer parameterization for GCM. Several schemes currently attempt to parameterize the boundary layer fluxes (sec. e.g. Bhumralkar, 1976). The simplest employ the usual bulk transfer relations with all the transfer coefficients for drag C_D and heat C_H assumed equal and prescribed a priśri (Cressman, 1960). In some cases different values are assigned for land and ocean surfaces and also some allowances made for various stability conditions.

Recently, schemes have been formulated from similarity considerations of the boundary layer. The basic assumptions underlying all similarity theories are that the boundary layer flow is horizontally homogeneous and quasi-stationary, a very restrictive assumption for many real atmospheric situations. As pointed out by Arya (1977), in a GCM, however, the variables are considered to be averaged horizontally over a fairly large grid area, and thus, the assumption of horizontal homogeneity is probably well justified.

There are two basic similarity theories: generalized similarity and Rossby Number similarity theories. The Rossby Number similarity theory assumes that boundary layer height is uniquely determined by a scale height which is a function of some internal parameters of the boundary layer, while in the generalized version, boundary layer height is considered an independent variable. Moreover, in the latter, the effects of complicated factors such as nonstationarity, diurnal heating, advection of heat and moisture, and large scale subsidence, etc. can be taken into account indirectly by specifying height of the boundary layer through a rate equation (Deardorff, 1974).

An alternative form of the similarity parametric relations originally proposed by Deardorff (1972) uses the layer-averaged wind, temperature and humidity. In this approach, the drag and heat transfer coefficients calculations are based on a set of nomograms in which surface fluxes of momentum and heat are estimated.

The purpose of this paper is to examine these boundary layer parameterization schemes (similarity theories, Deardorff scheme and Cressman method). We shall use observational data taken from the Wangara experiment (Clarke, et al., 1971). The Wangara experiment was conducted at Hay, Australia in 1968. Thus, the test results are relevant only for the land surface. The writer is in the process of conducting a similar test experiment using the Air Mass Transformation Experiment (AMTEX) data which was conducted over the ocean. The AMTEX experiment will be fully documented in a separate report.

2. Methods Tested

a. Similarity theory (Resistence Law)

The similarity theory parameterizes surface shear stress u_*^2, kinematic heat flux $u_*\theta_*$, and moisture flux u_*q_*, by the matching of mean profiles predicted by constant flux and Ekman layer similarity formulations (see Blackadar and Tennekes, 1968). The theory gives,

$$k u_h / u_* = -\left[\ln h/z_0 + A(\mu) \right]$$

$$k v_h / u_* = - B(\mu) \cdot \mathrm{sign}(f)$$

$$k(\theta_h - \theta_0)/\theta_* = -\left[\ln h/z_0 + C(\mu) \right]$$

$$k(q_h - q_0)/q_* = -\left[\ln h/z_0 + D(\mu) \right]$$

where u and v are the horizontal components of the mean velocity vector. The subscript h refers to the variables at the top of the boundary layer, while the subscript o to the variables at the surface. u_* is surface friction velocity, θ_* the scale temperature, and q_* the scale humidity. The surface shear stress $\tau_0 = u_*^2/\rho$, and surface heat flux $H_0 = \rho C_p u_* \theta_*$, can thus be determined. z_0 is the roughness length of the underlying surface f is Coriolis parameter, k is von Karman constant, ρ is air density, and C_p is specific heat at constant pressure. Empirical constants $A(\mu)$, $B(\mu)$, $C(\mu)$ and $D(\mu)$ are the so-called similarity funcitons which are functions of atmospheric stability parameter $\mu = h/L$, where h is the height of boundary layer and L is surface Monin Obukhov length.

Thus, if the height of the boundary layer h is known, and the external parameters u, v, θ and q at $z=h$ are given, the internal parameters u_*, θ_* and q_* may be determined. For this study, we used observed data taken from the Wangara experiment (Clarke, et al., 1971). In particular, the days of the Wangara experiment as chosen by Melgarejo and Deardorff (1974), were selected for analyses. Wind and temperature data at the observed boundary layer height h, defined as the height to which significant cooling has extended as judged both from individual profiles and their evolution in time, were used to compute the surface fluxes of heat and momentum. This case may be referred to as the generalized similarity theory. Based on the similarity theory, we also used wind and temperature at two fixed values of h, i.e., h=1000 m and h=500 m. This approach is simple for use in general circulation models. The latter two cases may be referred to as the Rossby Number similarity theory.

The functional forms of the similarity functions $A(\mu)$, $B(\mu)$, $C(\mu)$ are taken from Yamada (1976). The procedure for determining the similarity functions in terms of a bulk Richardson number is given in Appendix I.

b. Deardorff (1972) approach

We parameterize the surface heat flux and shear stress using a version of the bulk aerodynamic method (Deardorff, 1972). Following Deardorff's notation, we write $H_0/\rho C_p = C_\theta u_* (\theta_s - \theta_m)$ for surface heat flux, where C_θ is the heat transfer coefficients, θ_s is the surface temperature, and θ_m is mean potential temperature of the atmospheric boundary layer. The surface stress can be parameterized by $u_* = C_u U_m$, where $U_m = (u^2+v^2)^{1/2}$ is the mean velocity within the boundary layer, and C_u is surface drag coefficient.

The bulk transfer coefficients C_θ and C_u are expressed as functions of the bulk Richardson number R_{iB} given by

$$R_{iB} = gh(\theta_m - \theta_s)/T_m U_m^2$$

then, C_θ and C_u are written as

$$C_u^{-1} = C_{un}^{-1} - 25\exp(0.26\zeta - 0.030\zeta^2)$$

$$C_\theta^{-1} = C_{\theta n}^{-1} + C_u^{-1} - C_{un}^{-1}$$

where $$\zeta = \log_{10}(-Ri_B) - 3.5 \quad , \quad Ri_B < 0$$

The neutral transfer coefficients C_{un} and $C_{\theta n}$ are given by

$$C_{un} = \left[\ln(0.025\, h/z_o)/k + 8.4 \right]^{-1}$$

$$C_{\theta n} = \left[0.74 \ln(0.025\, h/z_o)/k + 7.3 \right]^{-1}$$

For the stable case, C_u and C_θ are written as

$$\left.\begin{aligned} C_u &= C_{un}\,(1 - Ri_B/Ri_c) \\ C_\theta &= C_{\theta n}\,(1 - Ri_B/Ri_c) \end{aligned}\right\} \quad 0 \leq Ri_B < Ri_c = 3.05$$

c. Cressman (1960) method

Surface heat flux is given by

$$H_o/\rho C_p = |V_m|\, C_D\, (\theta_m - \theta_s)$$

Momentum flux is parameterized by

$$\tau_o/\rho = u_*^2 = C_D\, |V_m|^2$$

where the drag coefficient C_D is specified for this study as $C_D = 2.3 \times 10^{-3}$.

3. Test Results

The surface friction velocity u_* and kinematic heat flux $H_o/\rho C_p$ calculated by various methods for the Wangara data are tabulated in Appendix II and III. The results are summarized in Tables 1 and 2. In addition, the values calculated by Yamada (1976) and Melgarejo and Deardorff (1974) are included for comparison. Note that their values were calculated by flux-profile relationships of Businger, et al., (1971). Since the profile-flux relationships were deduced from a carefully designed field experiment, use of the results of

Yamada (1976) and Melgarejo and Deardorff (1974) is well justified. From Tables 1 and 2, we see that values of u_* and $H_o/\rho C_p$ calculated by Yamada (1976) are in good agreement with those of Melgarejo and Deardorff (1974). Thus, for this study, the root mean square errors (RMSE) for various methods were calculated with respect to the values of Melgarejo and Deardorff (1974) (hereafter referred to MD).

Under unstable conditions, Table 1 shows that mean friction velocity calculated by various methods are satisfactory when compared with those of MD. Moreover, values calculated by similarity theories are in better agreement with those of MD than either Deardorff's (1972) approach or Cressman's method. Furthermore, the RMSE values for the generalized similarity theory are not much different from those for the Rossby Number similarity theories. This suggests that during the unstable period, the Rossby Number similarity theory is equally valid as the generalized similarity theory. This may be due to wind and temperature profiles that are typically well mixed throughout the entire boundary layer. As a consequence, little difference is expected between the two similarity theories.

During the stable periods, Table 1 shows a large variability in mean friction velocity calculated by different methods. Values of u_* calculated by the generalized similarity theory and Cressman (1960) method are much too large when compared to those of MD. Values of u_* calculated by the Rossby Number similarity theory are slightly better than those of the generalized similarity theory. This may be caused by boundary layer heights that are somewhat indeterminate at stable hours (see Yu, 1978). As a result, parameterization of momentum flux based on the generalized similarity theory is subject to large errors. Based on the RMSE values, we see that Deardorff (1972) method performs just as well as the Rossby Number similarity theory.

Table 2 summarizes kinematic heat fluxes calculated by various methods for the Wangara data. Under the unstable conditions, as pointed out previously, since the wind and temperature profiles are well mixed, heat fluxes calculated by the Rossby Number similarity theory are not much different from those calculated by the generalized similarity theory. However, the values calculated by the similarity theories are much too large when compared to those of MD. Although both Deardorff's (1972) approach and Cressman's (1960) method underestimate surface heat flux, they are in better agreement with the values of MD.

During the stable conditions, the values of kinematic heat fluxes (Table 2 and Appendix III) calculated by the generalized similarity theory are least satisfactory. Although the Deardorff (1972) method performs slightly better, none of the methods tested are reliable.

4. Concluding Remarks

This study compares several boundary layer parameterization schemes for use in large scale general circulation models. These methods include the generalized similarity theory, the Rossby Number similarity theory, Deardorff's (1974) and Cressman's (1960) methods. The following conclusions may be drawn:

(1) Parameterization of the boundary layer fluxes of momentum and heat shows little difference between the generalized and the Rossby Number similarity theories.

(2) Under the unstable atmospheric stability conditions, all the methods tested are satisfactory in the surface friction velocity, and hence momentum flux parameterization. We especially recommend the generalized similarity

theory for use in GCM during the unstable condition. Although the Rossby Number similarity theory performs equally well as the generalized theory, the former may not be applicable near the tropics where the determination of the boundary layer height by a scale height parameter such as u_*/f is no longer valid.

(3) Under the stable atmospheric conditions, however, similarity theories show great sensitivity to the height of the boundary layer. As a consequence, parameterization of boundary layer fluxes by similarity theories are unreliable unless the height of boundary layer can be determined with more certainty. Though none of the methods tested are satisfactory, we recommend Deardorff's (1972) scheme for its simplicity and its relatively slightly better performance as compared to others.

(4) In spite of its crudeness, Cressman's (1960) method is comparable with all the other more sophisticated schemes. The main disadvantage of the scheme, however, lies in its arbitrariness on the specification of the drag coefficient.

Finally, it is of importance to know how much the errors in parameterizing the boundary layer fluxes due to different methods contribute to the change in wind speed and temperature. Let us consider the following,

$$\frac{\partial u}{\partial t} = \cdots + \frac{1}{\rho}\frac{\partial \tau_x}{\partial z}$$

$$\frac{\partial v}{\partial t} = \cdots + \frac{1}{\rho}\frac{\partial \tau_y}{\partial z}$$

$$\frac{\partial \theta}{\partial t} = \cdots - \frac{1}{\rho C_p}\frac{\partial H}{\partial z}$$

Let us further assume that the first level of a GCM is at h=1000 m where the boundary layer fluxes of momentum and heat are negligibly small as compared to the surface values. Then, we have

$$\frac{\partial u}{\partial t} = \cdots - u_*^2 \cos\phi / h$$

$$\frac{\partial v}{\partial t} = \cdots - u_*^2 \sin\phi / h$$

$$\frac{\partial \theta}{\partial t} = \cdots + \frac{1}{\rho C_p} H_o / h$$

Based on Tables 1 and 2, we assume errors of u_* and $H_o/\rho C_p$ respectively to be 30 cm/sec and 30 cm °K/sec which can occur at stable conditions. For a surface cross isobaric angle of $\phi = 30^\circ$, we find

$$\frac{\partial u}{\partial t} = -7.48 \times 10^{-5} \; m/sec^2$$

$$\frac{\partial v}{\partial t} = -4.50 \times 10^{-5} \; m/sec^2$$

$$\frac{\partial \theta}{\partial t} = -1.1\,^\circ K/hour$$

Thus, we see that due to different parameterization schemes, a substantial effect on the changes in air temperature may result. The effect on the change of wind speed is relatively smaller however. This suggests that improvement in the parameterization of boundary layer heat flux is far more important than that in the momentum flux parameterization.

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Arya, S. P. S., 1975: Geostrophic drag and heat transfer relations for the atmospheric boundary layer. Quart. J. Roy. Meteor. Soc., 101, 147-161.

Arya, S. P. S., 1977: Suggested revision to certain boundary layer parameterization schemes used in atmospheric circulation models. Mon. Wea. Review, 105, 215-227.

Arya, S. P. S., 1978: Comparative effects of stability, baroclinicity, and the scale-height ratio on drag laws for the atmospheric boundary layer. J. Atmos. Sci., 35, 40-45.

Bhurmalkar, C. M., 1976: Parameterization of the planetary boundary layer in atmospheric general circulation models. Review Geophy. Space Phys., 14. 215-226.

Blackadar, A. K., and H. Tennekes, 1968: Asymptotic similarity in neutral barotropic planetary boundary layers. J. Atmos. Sci., 25, 1015-1020.

Businger, J. A., J. C. Wyngarrd, Y. Izumi, and E. G. Bradley, 1971: Flux-profile relationships in the atmospheric surface layer. J. Atmos. Sci., 28, 181-189.

Clarke, R. H., A. J. Dyer, R. R. Brook, D. G. Reid, and A. J. Troup, 1971: The Wangara Experiment: Boundary Layer Data. Commonwealth Scientific and Industrial Research Organization, Australia, 1971. 349 pp.

Cressman, G. P., 1960: Improved terrain effects in barotropic forecasts. Mon. Wea. Review, 88, 327-342.

Deardorff, J. W., 1972: Parameterization of the planetary boundary layer for use in general circulation models. Mon. Wea. Review, 100, 93-106.

Deardorff, J. W., 1974: Three-dimensional numerical study of the height and mean structure of a heated boundary layer. Boundary Layer Meteor., 7, 81-106.

Melgarejo, J. W., and J. W. Deardorff, 1974: Revision to "Stability Functions for the boundary-layer resistance laws based upon observed boundary-layer height." J. Atmos. Sci., 32, 837-839.

Yamada, T. 1976: On the similarity functions A, B, and C of the Planetary boundary layer. J. Atmos. Sci., 33, 781-793.

Yu, T. 1978: Determining height of the nocturnal boundary layer. J. Appl. Met., 17, 28-33.

APPENDIX I

Determination of the Similarity Functions

The purpose of this appendix is to show that similarity functions A, B, C, and D can be determined in terms of a bulk Richardson number. In theory, these similarity functions are functions of atmospheric stability $\mu = h/L$, where h is height of the boundary layer and L is surface Monin-Obukhov length defined as $L = \bar{\theta} u_*^2 / k g \theta_*$. Noting that L is related to the internal parameter u_* and θ_* which are yet to be determined by the similarity theory, it is not practical to determine the similarity functions in terms of L.

Recently, Yamada (1976) reexamined the similarity functions based on the Wangara data. Both in the stable and unstable conditions, his proposed similarity functions show substantial improvement when compared with the observed data over the previous work by Deardorff and Melgarejo (1975) and Arya (1974). By formulating the similarity functions in terms of bulk Richardson numbers based on Yamada's work (1976), we note that the bulk Richardson number R_{iB} is related to the similarity functions by

$$R_{iB} = 0.74 \frac{h}{L} \frac{\ln(h/z_0) - C(\mu)}{[\ln(h/z_0) - A(\mu)]^2 + B^2(\mu)}$$

The similarity functions are defined as in Yamada (1976),

$$A = \begin{cases} 1.855 - 0.380\, h/L, & 0 < h/L \le 35 \\ -2.94\,(h/L - 19.94)^{1/2}, & 35 < h/L \end{cases}$$

$$B = \begin{cases} 3.020 + 0.300\, h/L, & 0 < h/L \le 35 \\ 2.85\,(h/L - 12.47), & 35 < h/L \end{cases}$$

$$C = \begin{cases} 3.665 - 0.829\, h/L, & 0 \le h/L \le 18 \\ -4.32\,(h/L - 11.21)^{1/2}, & 18 < h/L \end{cases}$$

Under the unstable conditions,

$$A = 10.0 - 8.145\left(1.0 - 0.008376\ h/L\right)^{-1/3}$$

$$B = 3.020\left(1.0 - 3.290\ h/L\right)^{-1/3}$$

$$C = 12.0 - 8.335\left(1.0 - 0.03106\ h/L\right)^{-1/3}$$

It follows that for a given set of values of $\zeta = h/L$ and roughness parameter z_o, the corresponding values of A, B, and C are readily determined.

Now for given values of R_{iB} and z_o, we want to determine h/L and thus A, B, and C. For this, the Newton-Ralphson method proves useful for stable cases,

$$\zeta_{i+1} = \zeta_i + \left[R_{iB} - f(\zeta_i)\right] / f'(\zeta_i)$$

where $$f(\zeta) = 0.74\,\zeta(\alpha - c) / \left[(\alpha - A)^2 + B^2\right]$$

and $$f'(\zeta) = f(\zeta)\left[\zeta^{-1} - c'/(\alpha - c) - 2\left(AA' - \alpha A' + BB'\right)/\left((\alpha-A)^2 + B^2\right)\right]$$

where $\zeta = h/L$ and $\alpha = \ln(h/z_o)$. The subscript i denotes the iteration index, and prime denotes derivatives with respect to ζ. The Newton-Ralphson method was tested and found to converge within five iterations.

For unstable cases, a simple linear relationship exists between the bulk Richardson number and ζ i.e., $\zeta = R_{iB}\, f(C_N)$ where $C_N = k^{-1} \ln(h/z_o)$ and $f(C_N) = 0.75\, C_N - 1$.

Table 3 shows the values of A, B, and C calculated by two different methods. The values denoted with ( ) are those calculated with given bulk Richardson numbers; those without ( ) are calculated based on given h/L. The agreement between these two methods is certainly remarkable.

The geostrophic drag C_D and heat transfer coefficients C_H are defined as (Yamada, 1976),

$$C_D = k\left\{\left[\ln(h/z_0) - A(\mu)^2\right] + B(\mu)^2\right\}^{-1/2}$$

$$C_H = 1.35\, k\left\{\ln(h/z_0) - C(\mu)\right\}^{-1}$$

The calculated values of C_D and C_H, based on these two different methods are shown in Fig 1. Very close agreement in the values of C_D and C_H between these two methods is also well indicated.

APPENDIX II: Surface Friction Velocity (cm/sec): Wangara Data

Day	Hour	Generalized Similarity	Rossby h=1000	Rossby h=500	Deardorff (1972)	Cressman (1960)	Yamada (1976)	Melgarejo Deardorff (1976)
				STABLE PERIOD				
1	6	14.5	1.0	1.6	16.47	35.1	4.7	5.5
	18	31.1	6.5	14.1	21.03	37.3		11.0
	21	38.0	11.8	22.3	24.93	44.5	9.4	12.4
	24	47.5	8.6	44.2	33.46	62.8	16.8	16.5
4	3	46.7	11.4	45.5	29.33	56.0	11.7	14.2
	6	41.5	10.0	41.8	26.41	52.2	19.1	15.8
6	18	6.4	0.2	0.8	8.08	19.1		5.8
	21	10.1	0.4	1.4	15.78	35.9	6.6	3.8
7	3	7.5	3.9	5.7	12.14	39.7	5.0	3.9
	6	9.1	2.1	3.6	15.38	39.8	6.3	5.0
	18	5.6	1.5	3.0	9.84	22.0		4.7
	21	3.2	2.7	2.3	0	29.7	4.2	11.4
	24	8.3	2.3	3.9	12.93	39.3	6.9	10.4
10	24	6.4	0.3	0.7	7.90	15.3		0.8
[illegible]	24	39.8	1.7	7.7	30.29	56.1		12.9
[illegible]2	6	10.9	1.5	8.9	17.07	39.4	17.1	15.4
	9	33.7	4.2	7.8	24.48	37.8		21.6
	21	6.7	3.4	6.1	14.14	45.2	11.1	12.4
	24	18.3	4.6	7.9	22.90	47.8	10.9	10.6
13	3	41.3	2.7	50.0	28.36	47.8	10.1	4.1
	6	50.3	1.6	6.8	30.60	63.1	9.0	9.8
	18	31.7	5.0	10.9	18.67	36.6		4.4
	21	41.2	5.7	8.8	28.61	50.3	7.2	1.4
	24	45.4	2.8	12.8	26.67	50.1	6.8	6.7
14	3	41.4	1.4	8.1	27.20	45.1	12.0	7.8
	6	41.7	0.7	5.3	27.17	53.0	13.5	13.1
	21	13.4	4.5	4.2	14.86	31.2		5.0
	24	16.3	4.3	6.6	19.69	47.9		8.0
16	24	4.9	3.1	1.6	8.58	23.7		10.6
18	24	37.9	2.9	12.6	26.35	43.2		13.5
19	3	16.2	2.3	4.4	18.36	36.3	12.4	11.4
	6	9.7	1.6	2.5	14.13	31.6	12.1	10.0
25	21	11.4	0.9	3.0	14.48	32.4		3.4
26	6	4.2	1.4	1.6	7.05	21.2	5.6	3.8
	21	14.3	11.6	10.8	13.47	30.3	7.1	6.4
30	21	45.6	10.0	48.0	31.39	51.9	15.4	14.1
	24	50.4	11.2	47.0	33.07	59.9		19.3
31	3	45.9	7.0	17.9	30.28	56.5	14.6	12.5
	6	44.8	4.4	21.8	27.95	53.4	13.5	13.4
	21	12.0	3.5	4.7	14.17	32.4	5.0	9.0
	24	32.8	4.3	7.5	21.54	37.2	7.7	10.7

APPENDIX II Cont'd

Day	Hour	Generalized Similarity	Rossby h=1000	Rossby h=500	Deardorff (1972)	Cressman (1960)	Yamada (1976)	Melgarejo Deardorff (1976)
32	3	4.1	1.6	3.2	7.43	37.5	5.0	7.2
	6	3.8	0.7	2.7	4.38	36.0	4.4	4.6
	24	10.0	0.8	2.4	12.03	30.1	5.3	4.8
33	3	1.1	0.1	0.4	0	26.0	8.1	6.9
	18	5.9	1.5	3.0	8.10	23.8		8.1
	21	14.1	2.8	5.1	17.47	38.3	6.3	4.6
	24	8.1	3.5	6.4	14.67	48.9	7.0	4.9
34	3	8.0	2.4	5.9	18.23	54.7	7.3	7.3
	6	2.2	2.1	2.8	2.06	43.9	13.4	11.7
	18	36.2	13.7	35.1	24.57	43.8		15.2
	21	38.5	6.0	10.5	22.34	46.3	8.9	11.2
35	6	60.3	7.3	54.1	40.11	7.2	22.4	19.5
39	3	38.4	1.8	20.6	29.46	53.5	13.2	21.9
	24	0.7	0.6	0	0	7.2		2.0
40	3	0.3	0.1	0.1	0	5.2		7.7
42	21	6.1	1.1	1.9	13.32	28.9	6.2	15.1
	24	14.0	2.3	2.6	17.92	37.6	6.5	14.7
43	3	44.7	4.2	12.8	31.42	55.1	15.6	14.7
44	3	62.0	61.2	64.7	43.45	71.0	27.8	26.6
	6	69.1	65.8	69.0	47.51	80.0	28.2	27.0

UNSTABLE PERIOD

Day	Hour	Generalized Similarity	Rossby h=1000	Rossby h=500	Deardorff (1972)	Cressman (1960)	Yamada (1976)	Melgarejo Deardorff (1976)
1	15	25.7	25.9	24.3	18.51	32.0		24.8
6	15	10.5	7.1	9.9	4.73	7.7		7.2
7	12	27.7	27.4	29.9	19.48	30.7	23.1	24.6
	15	20.3	21.7	20.0	14.05	23.7	17.1	18.8
12	12	26.6	25.7	28.5	20.73	35.3	25.2	27.1
13	12	24.6	15.4	24.8	19.87	33.4	32.8	35.5
	15	27.3	28.3	25.0	19.71	33.6	27.6	32.7
14	15	19.2	24.3	16.4	11.43	19.0	16.0	17.5
25	15	29.3	30.1	28.8	22.07	38.1		34.2
26	12	28.3	20.8	29.4	22.33	36.3	25.8	27.2
	15	27.6	28.5	28.4	21.96	37.5	21.8	24.9
33	9	12.7	8.6	9.1	9.57	13.6		14.8
	12	17.5	17.5	14.5	7.99	13.5	14.3	14.0
	15	17.4	18.5	14.6	9.42	16.1	15.5	16.5
34	12	29.2	28.8	30.2	21.98	36.2	30.1	33.1
	15	28.6	30.1	29.5	22.33	37.3	28.4	31.5
35	12	37.2	36.9	36.9	29.92	50.8	41.8	43.2

APPENDIX III: Kinematic Heat Flux (cm s^{-1}): Wangara Data

Day	Hour	Generalized Similarity	Rossby h=1000	Rossby h=500	Deardorff (1972)	Cressman (1960)	Yamada (1976)	Melgarejo Deardorff (1976)
				STABLE PERIOD				
1	6	-7.49	-.06	-.16	-3.44	-12.06	-.28	-.35
	18	-26.65	-.80	-3.42	-2.75	-6.71		-1.24
	21	-42.57	-2.62	-9.29	-4.06	-9.97	-.82	-1.10
	24	-61.66	-1.75	-55.5	-6.86	-18.65	-1.53	-1.42
4	3	-41.88	-2.42	-42.1	-3.67	-10.29	-.94	-1.24
	6	-39.48	-1.97	-39.7	-3.26	-9.82	-2.33	-1.77
6	18	-1.39	0	-.03	-.92	-3.99		-.52
	21	-4.12	-.02	-.13	-3.57	-14.29	-.58	-.25
7	3	-2.95	-.71	-1.63	-2.45	-20.29	-.35	-.21
	6	-3.91	-.25	-.73	-3.87	-19.99	-.45	-.27
	18	-1.12	-.09	-.31	-.93	-3.59		-.59
	21	-.69	-.38	-.36	0	-16.17	-.35	-2.52
	24	-3.01	-.28	-.78	-2.61	-18.60	-.69	-1.36
10	24	-.62	0	-.02	-.23	-.66		0
[illegible]	24	-60.19	-.16	-1.94	-6.27	-16.64	-1.31	-1.05
[illegible]	6	-4.28	-.14	-2.79	-3.35	-13.73	-1.36	-1.18
	9	-26.39	-.53	-1.47	-3.57	-6.59		-.14
	21	-1.64	-.46	-1.38	-2.34	-18.41	-.85	-1.04
	24	-10.68	-.82	-2.29	-5.43	-18.23	-.77	-.76
13	3	-53.69	-.37	-84.80	-6.18	-13.55	-1.08	-.23
	6	-105.80	-.17	-2.13	-8.72	-28.58	-.74	-.90
	18	-30.96	-.61	-2.53	-2.85	-8.44		-.31
	21	-64.05	-1.03	-2.47	-6.71	-16.05	-.64	-.03
	24	-86.96	-.41	-5.54	-7.73	-2.11	-.56	-.61
14	3	-79.30	-.14	-2.70	-8.34	-17.74	-1.19	-.66
	6	-67.10	-.05	-1.23	-5.61	-16.44	-1.56	-1.49
	21	-6.05	-.73	-.77	-2.59	-8.82	-.35	-.43
	24	-9.19	-.80	-1.92	-4.94	-22.55		-.97
16	24	-1.19	-.39	-.14	-1.30	-7.69		-1.18
18	24	-38.07	-.29	-3.47	-3.93	-8.17	-1.71	-1.25
19	3	-8.41	-.23	-.78	-3.29	-9.96	-1.04	-.92
	6	-3.43	-.13	-.33	-2.31	-8.94	-.91	-.68
25	21	-3.41	-.04	-.31	-2.00	-7.71		-.16
26	6	-.65	-.08	-.12	-.57	-3.97	-.23	-.13
	21	-4.81	-2.17	-2.35	-1.65	-6.43	-.47	-.39
30	21	-39.0	-1.80	-42.0	-4.36	-9.20	-1.42	-1.26
	24	-53.11	-2.42	-53.27	-5.19	-13.11	-1.71	-1.65
31	3	-55.30	-1.32	-6.79	-5.54	-14.89	-1.15	-.92
	6	-66.10	-.70	-10.86	-5.86	-16.54	-.99	-1.00
	21	-5.20	-.45	-.87	-2.67	-10.79	-.36	-.96

APPENDIX III: Cont'd

Day	Hour	Generalized Similarity	Rossby h=1000	Rossby h=500	Deardorff (1972)	Cressman (1960)	Yamada (1976)	Melgarejo Deardorff (1976)
	24	-58.34	-.69	-2.01	-5.96	-13.77	-.48	-.83
32	3	-.88	-.15	-.55	-.87	-17.12	-.22	-.40
	6	-.81	-.04	-.45	-.36	-18.47	-.27	-.28
	24	-4.88	-.04	-.33	-2.84	-13.74	-.36	-.33
33	3	-.11	0	-.02	0	-11.38	-.59	-.50
	18	-.99	-.08	-.26	-.73	-4.89		-.91
	21	-7.62	-.34	-1.07	-4.71	-17.47	-.52	-.34
	24	-2.94	-.56	-1.90	-3.31	-28.29	-.57	-.30
34	3	-2.95	-.34	-1.75	-4.47	-30.99	-.68	-.57
	6	-.32	-.27	-.48	-.06	-22.46	-1.19	-.74
	18	-27.52	-2.06	-22.35	-3.20	-7.85		-1.15
	21	-72.90	-1.19	-3.55	-6.37	-2.12	-.83	-1.00
35	6	-74.45	-1.51	-67.14	-6.47	-15.99	-2.60	-2.15
39	3	-35.01	-.14	-7.41	-3.24	-8.22	-1.00	-.98
	24	0	0	0	0	-2.14		-.06
40	3	0	0	0	0	-1.13		-.47
	21	-1.45	-.06	-.18	-1.73	-7.37	-.51	-1.73
	24	-7.06	-.25	-.34	-3.89	-13.27	-.48	-1.61
43	3	-64.83	-.67	-4.32	-6.92	-16.44	-1.87	-1.88
44	3	-19.19	-35.44	-25.16	-1.86	-3.83	-2.53	-2.42
	6	-18.93	-28.41	-16.93	-.58	-1.28	-2.85	-2.73
				UNSTABLE PERIOD				
1	15	12.53	10.38	21.93	2.03	4.63		3.39
6	15	24.37	23.65	25.80	1.11	2.21		4.43
7	12	19.95	10.47	16.08	2.85	5.43	7.60	7.04
	15	15.65	14.12	16.67	1.99	4.32	3.91	4.58
12	12	12.03	9.38	17.09	2.37	5.25	8.63	7.97
13	12	17.77	8.24	18.87	2.77	6.01	10.34	11.75
	15	22.10	19.45	25.40	3.36	7.45	9.21	10.80
14	15	27.35	22.28	25.56	2.47	5.21	6.11	7.30
25	15	28.96	33.50	35.36	4.69	10.68		11.79
26	12	8.66	-.85	10.26	1.41	2.84	3.63	3.73
	15	7.36	7.03	7.77	1.21	2.69	1.95	3.55
33	9	16.64	-1.40	1.05	2.22	3.42		8.86
	12	76.71	76.71	74.45	3.68	7.92	18.61	15.86
	15	55.37	55.86	49.68	3.23	7.15	9.44	13.59
34	12	48.27	42.36	48.85	6.43	13.26	13.44	19.48
	15	53.80	52.93	50.41	6.33	13.52	10.97	17.91
35	12	27.64	22.02	32.59	5.12	11.30	14.56	16.93

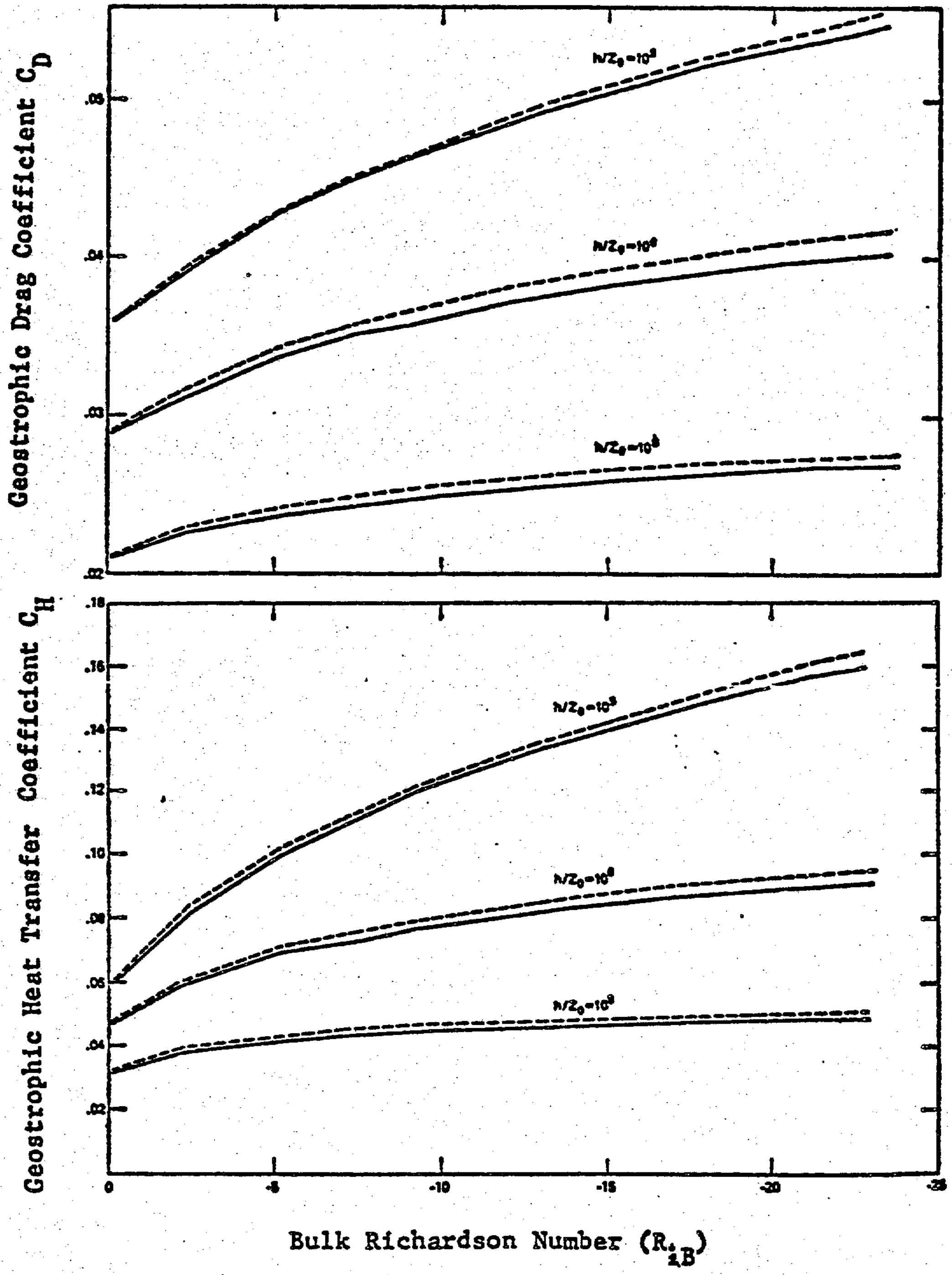

Fig. 1 — Geostrophic drag coefficient C_D (top) and geostrophic heat transfer coefficient C_H (bottom) calculated by given h/L values (solid lines) and by the Bulk Richardson number approach (dashed lines)

TABLE 1: Surface Friction velocity u_* (cm/sec) calculated by various methods for the Wangara Data

	Generalized Similarity Theory	Rossby Number Similarity h=1000 m	Rossby Number Similarity h=500 m	Deardorff (1972) Approach	Cressman (1960) Method	Yamada (1976)	Melgarejo and Deardorff (1975) (MD)
				UNSTABLE CONDITIONS (Totally N=17 runs)			
Mean	24.1	23.3	23.5	17.4	29.1	24.6	25.2
Standard Error	1.65	1.92	1.94	1.63	2.80	2.19	2.28
RMSE	4.1	6.3	4.5	8.6	5.7	—	—
				STABLE CONDITIONS (Totally N=61 runs)			
Mean	24.0	5.8	13.6	19.3	40.4	10.6	10.2
Standard Error	2.42	1.43	2.24	1.38	1.91	0.88	0.73
RMSE	21.1	9.8	14.6	12.2	32.7	—	—

TABLE 2: Kinematic Heat Flux $H_o/\rho C_p$ (cm/sec^{-1}·°K) calculated by various methods for the Wangara Data

	Generalized Similarity Theory	Rossby Number Similarity h=1000 m	Rossby Number Similarity h=500 m	Deardorff (1972) Approach	Cressman (1960) Method	Yamada (1976)	Melgarejo and Deardorff (1975) (MD)
				UNSTABLE CONDITIONS (Totally N=17 runs)			
Mean	27.95	23.89	28.11	3.13	6.66	9.11	9.9
Standard Error	4.70	5.28	4.55	0.40	0.87	2.52	1.30
RMSE	23.55	22.64	23.37	7.76	4.11	——	——
				STABLE CONDITIONS (Totally N=61 runs)			
Mean	-24.98	-1.64	-8.9	-3.43	-12.27	-.96	-.89
Standard Error	3.64	0.73	2.32	0.29	0.89	0.09	0.08
RMSE	36.96	5.41	19.52	3.43	13.35	——	——