Mausam, (1996), 47, 1, 31-40

551.501

Estimation of surface parameters from a 30 metre micro-meteorological tower over a deep moist convective region

R. PRADHAN and U. K. DE
Deptt. of Physics, Jadavpur University, Calcutta
and
P. K. SEN
Deptt. of Mathematics, Jadavpur University, Calcutta
(*Received 19 November 1993, Modified 30 May 1995*)

सार — माइक्रो मेट टॉवर के आंकड़ों की सहायता से सतही परत में u_*, θ_*, q_* तथा ओबुकोव-लम्बाई के आकलन का कार्य करना अभी तक एक महत्वपूर्ण चुनौती बना हुआ है। इस अध्ययन में प्राचलिक आकलन हेतु एक प्रक्रिया विकसित की गई है जो सादृश तथा प्रोफाइल दोनों तरह के संबंधों के लिए समान रूप से लागू होती है। इस अध्ययन में तीव्र तथा मंद प्रतिक्रिया दोनों तरह के टॉवर-आंकड़ों का उपयोग किया गया है। चूंकि सादृश्य संबंध एक विशेष तल Z में निहित है। अत: परत से आरम्भ करने के स्थान पर प्राचलों का संबंध एक तल विशेष से ही होना चाहिए। यह सुझाव दिया गया है कि एक सुविधाजनक तल स्तर की ज्यामितीय माध्य ऊँचाई है।

स्थिर एवं अस्थिर दोनों ही स्थितियों में भंवर विसरण शीलता (के० एच०/के० एम०) के अनुपात का आकलन किया गया और इस अनुपात को एक अभिव्यक्ति द्वारा प्रस्तुत किया गया है जो संयोगवश निहित स्थिरांक के एक नए मान को दर्शाता है।

ABSTRACT. The estimation of u_*, θ_*, q_* and Obukov-length in the surface layer from micro-meteorological tower data still poses an important challange. In the present study a procedure for the parametric estimation has been developed which is consistent both with the similarity relation and the profile relation. The study has been done using both fast response and slow response tower data. Since similarity relations involve a particular level z so inspite of starting from a layer, the parameters should be attributed to a particular level only. It has been suggested that the convenient level is geometric mean height of the layer.

The ratio of eddy diffusivities (K_h/K_m) has been estimated both for stable and unstable situation and this ratio is presented by a single expression which incidentally yields a new value of a constant involved.

Key words — Surface parameter, Richardson number, Stability parameter.

1. Introduction

In the present study a set of data collected during Monsoon Trough Boundary Layer Experiment, 1990 (MONTBLEX '90) are being analysed to develop a methodology for the evaluation of the surface layer parameters. The present data set are procured during the monsoon time of 1990 from a 30 m micro-meteorological tower located at Kharagpur (22.30°N, 87.20°E), West Bengal. It is well-known that a monsoon trough exists over northern India for four long months (June-September) and over this trough the present site is considered as a deep moist convective zone. In the present study both slow as well as fast response sensor data are analysed for 15 days starting from 27 May to 17 June 1990. However fast response files are available only from 7 June 1990.

To evaluate the surface layer parameters like u_*, θ_*, q_*, θ_r, and q_r the entire 30 m of surface layer can be divided into a number of sub-layers (Deardorff 1972, Kramm 1989), taking suitable flux-profile relationships for u and θ, which on the other hand depend on the similarity relations for ϕ_m and ϕ_h. To answer which similarity relations are valid for the present data set, a simple statistical procedure has been undertaken in absence of directly measured fluxes.

Following Kramm (1989), convergent u_*, θ_* and q_* in an unstable condition are derived for each sub-layer and these values are attributed to the geometric mean height (Deardorff 1972, Paulson 1970) of the sub-layer. However, it is expected that these parameters should satisfy the related similarity expressions. But this did not happen, possibly because of finite width of the layer considered and an average value was taken. So, the initially derived values were just equated with their similarity expressions (Panofsky 1963, Businger *et al.* 1971) at the geometric mean height and hence another iterative process is undertaken to find consistent and convergent values for the parameters.

For stable situation, however, an established analytical procedure is being utilised (Businger 1973, Kramm 1989) and a very consistent result is obtained if the parameters for a sub-layer are attributed again to the geometric mean height of that sub-layer. In section 2, we have discussed the instrumentation and experimental site. Assessment of data and their analysis come under section 3. Method of evaluation of the parameters and the results are presented in sections 4 and 5.

2. Method and analysis

2.1. *Instrumentation and experimental procedures*

During MONTBLEX '90, a 30 m micrometeorological tower with 6 levels (1, 2, 4, 8, 15 and 30 m) was set at Kharagpur in the campus of the Indian Institute of Technology (IIT). The terrain was flat with short grass, for which zero-plane displacement may be taken as zero (Monteith and Unsworth 1990, Garratt 1992). This point is further strengthened by the estimation of consistent roughness length over Kharagpur terrain alongwith the above assumption (Pradhan *et al.* 1994).

The slow response data were recorded on a Campbell data logger and the fast response data were put on a PC based telemetry system. The slow response sensors had a response rate of 1 Hz, on the other hand, though the fast response sensors were capable of recording at the rate of 30 per second, it were made at 8/9 Hz. After proper validation process, slow response data were presented to the users by MONTBLEX National Data Centre as 3 minute average values. Fast response data were initially stored on binary format and these were presented in real terms after usual standardisation methods. The details about the instrumentations and validation processes are available in various literatures (Prabhu *et al.* 1990, Rudrakumar *et al.* 1990).

2.2. *Assessment of data and data analysis*

In the present study both slow as well as fast response data are analysed. In case of slow response data, a detailed study of most suitable time averaging is undertaken and 30 minute average is found to be most suitable as the pattern of variations, then, remains almost intact though smoothing out too many fluctuations.

The fast sensor data are available for 10 minute duration only. Here the data set for analysis are developed taking mean of every 500 samples existing in the original data files.

The vertical profile of temperature always shows a zig-zag pattern for both types of files. To tackle this situation only three levels are considered instead of six. The bottom level at 1 m and the top one at 30 m are retained, but for the third level, the geometric mean height of these levels at 5.477 m is introduced. The mean values of the data obtained at 2 and 15 m levels are rendered as the data for that level: This approach gives some consistency with the actual profile between 1 and 30 m. Incidentally, the temperature variation is always very sharp between 4 and 8 m levels though the sharpness somewhat decreases in fast data set.

In the present approach the two layers, one of which is between 1 and 5.477 m and other one is between 5.477 and 30 m, are considered as sub-layers.

The relative humidity sensors are kept at three levels (1, 4 and 30 m) during the period but except the data at 1 m level, those of other two levels are neither continuous nor very reliable. Since the contribution of specific humidity is meagre in the estimation of Monin-Obukov length, there is not much error if one accepts that the relative humidity is same at all levels and that is same as at 1 m level.

2.3. *Method of parameter evaluation*

The non-dimensional wind shear and temperature stratification are expressed as,

$$\phi_m = \frac{kz}{u_*}\frac{\partial u}{\partial z} \tag{1}$$

$$\phi_h = \frac{kz}{\theta_*}\frac{\partial \theta}{\partial z} \tag{2}$$

If the similarity expressions for ϕ_m and ϕ_h are known for both the stability conditions, then one can write down the expressions for wind and temperature profiles by integration.

For the present study, the following similarity expressions are being considered and the justifications in favour are given afterwards.

$$\frac{kz}{u_*}\frac{\partial u}{\partial z} = (1-16\zeta)^{-1/4} \quad (3)$$

$$\frac{kz}{\theta_*}\frac{\partial \theta}{\partial z} = (1-16\zeta)^{-1/2} \quad (4)$$

(Kramm and Herbert 1984)

The necessary profile relations, then, become identical with Kramm's (1989) work, with zero-plane displacement as zero. In this regard one may utilise the Eqns. (12) to (20) of that work for the unstable condition.

Following Kramm's method, one can find the converged magnitudes of the parameters like u_*, θ_*, q_* and L_j. These may be taken as constant for the jth layer. But this assumption leads to a finite error if the thickness of the layer is finite. In the present method, however, these converged quantities are assigned to the geometric mean height of that layer. Then, it may be checked whether these calculated parameters really satisfy the respective similarity expressions given by Eqns. (3) & (4). However, in actual analysis there always exist some discrepancies between Eqns. (1) & (3) and also Eqns. (2) & (4). This is not at all unexpected, as during the iterative process some errors have crept in the value of the parameters. To diminish these discrepancies, hereby a second iterative process is being proposed. For this the L value derived from the previous method, which might be called the erroneous L, is put in the expression for ϕ_m and ϕ_h in Eqns. (3) & (4). Besides z is taken at the geometric mean height of the layer, suffixed by l. Then using Eqns. (1), (2), (3) & (4), the new magnitude of the parameters can be estimated,

$$u_{*l}^{(k+1)} = k\,[1-16\zeta_l^{(k)}]^{1/4}\,\frac{u_{M,\,i+1}-u_{M,\,i}}{\ln\frac{z_{i+1}}{z_i}} \quad (5)$$

and

$$\theta_{*l}^{(k+1)} = k\,[1-16\zeta_l^{(k)}]^{1/2}\,\frac{\theta_{M,\,i+1}-\theta_{M,\,i}}{\ln\frac{z_{i+1}}{z_i}} \quad (6)$$

u_{*l} and θ_{*l} of Eqns. (5) & (6) are now utilised in Eqn. (20) of Kramm's work (1989) by substituting subscript $j\,l$ to derive a new value of L. This process continues until the converged values of parameters are arrived at.

Parameters evaluated for stable situation was through an analytical procedure (Businger 1973, Kramm 1989) which is already mentioned in section 1.

3. Results

As mentioned previously, the entire 30 m layer has been considered as composed of two sub-layers. The first layer is from 1 to 5.477 m and the other layer is from 5.477 to 30 m. When similarity relations are considered for the first layer, the parameters derived are taken as the value located at 2.34 m which is the geometric mean height of the first layer. Similarly, in case of second layer, the parameters derived are taken as the value located at level 12.82 m which is again the geometric mean height of this layer.

3.1. *A statistical approach to establish the best fit surface similarity for the data set*

(a) *Unstable situation* — In this section an attempt is being made to find an answer to the question — which similarity expressions for ϕ_m and ϕ_h are most suitable for the present data set? It should be again stressed that the convincing conclusion would have come out from intercomparison of calculated surface parameters with the directly measured parameters. In the absence of directly measured values, an indirect statistical procedure is being proposed.

For consideration of various similarity relations only those existing in the literature (Sorbjan 1989) are being considered. It should be noted that all surface similarity relations in the literature for unstable situations are in power form. Not only that, ϕ_h has always 1/2 power, whereas, the power of ϕ_m may vary, *i.e.*, 1/3 or 1/4. However, the value of the free constant γ has wide variations.

In the present case γ is taken as 16 for ϕ_m and ϕ_h and the range of ζ is given by $0<-\zeta<10$. The answer is being sought from the expression,

$$R_{i_l} = \frac{(\phi_h)_l}{(\phi_m)_l^2}\,\zeta_l \quad (7)$$

In Eqn. (7), the left hand side depends entirely on the data, so it is independent of the chosen similarity expressions. In fact, after two iterative

TABLE 1

S. No.	Items	Model $0 > \zeta_l > -10$	
		$\phi_m(\zeta_l) = (1-16\zeta_l)^{-1/3}$ $\phi_h(\zeta_l) = (1-16\zeta_l)^{-1/2}$	$\phi_m(\zeta_l) = (1-16\zeta_l)^{-1/4}$ $\phi_h(\zeta_l) = (1-16\zeta_l)^{-1/2}$
1.	Maximum number of iteration steps	(*i*) 18 (*ii*) 20	(*i*) 15 (*ii*) 15
2.	† Convergence limit of L	(*i*) 0.003-.001 m (*ii*) 0.001 m	(*i*) 0.001 m (*ii*) 0.001 m
3.	Root mean square of $R_{i_l} - \frac{(\phi_h)_l}{(\phi_m)^2_l}\zeta_l$ with the limit of (a) $0 > \zeta > -0.2$ and (b) $-0.2 > \zeta > -10$	(a) (*i*) 0.000331 (*ii*) 0.001157 (b) (*i*) 0.003354 (*ii*) 0.003732	(a) (*i*) 0.000250 (*ii*) 0.000967 (b) (*i*) 0.001933 (*ii*) 0.001854

† Here only those cases, where both models satisfy the limit of 0.001, are taken into account.
(*i*) For slow data
(*ii*) For fast data

operations the two sides of Eqn. (7) approach towards equality except for the statistical fluctuation of the individual data points. Since the data have an inherent similarity structure, even the statistical fluctuation is expected to be minimum for the best fitted similarity expressions.

In Table 1,

$$1/N \left[\sum \left(R_{i_l} - \frac{(\phi_h)_l}{(\phi)^2_{m,l}} \zeta_l \right)^2 \right]^{1/2} \quad (8)$$

values are presented for the two similarity sets, considering the entire data set. Besides, in Table 1, ζ range has been split up into two, *i.e.*, $0<-\zeta<0.2$ and $0.2<-\zeta<10$. In the first range, all similarities are expected to give close values for Eqn. (8). But for the later range, the values are expected to play more decisive role. From Table 1, the effectiveness of 1/4 similarity over 1/3 similarity for ϕ_m is evident. In the range (a), the discrepancy in expression (8) for the proposed model is reduced by 24.47% in case of slow data and by 16.42% in case of fast data when compared with respect to the other model. In the other range (b) the corresponding reduced magnitudes are 42.37 and 50.32% respectively.

Once the power law for ϕ_m is decided, one can vary the values of free parameters to minimise the magnitude of expression (8). The effect of γ variation is not presented in the table as the values are very close. However, it is found that the values of free parameters may be taken as 16.

(b) *Stable case* — In the stable case, the similarity relations for ϕ_m and ϕ_h are found to be identical and

$$\phi_m(\zeta_l) = \phi_h(\zeta_l) = 1 + 4.72\,\zeta_l \quad (9)$$

Obviously, the limiting value is 1 in the present case. In Businger *et al.* (1971) model, ϕ_m converges to 1.15 and ϕ_h converges to 0.74 at neutral situation. Hicks (1976) proposed a model which converges to the presently obtained value in the neutral case, though the free constant in stable condition is different.

Figs. 1. (a & b). The dependence of the ratio of eddy diffusivities on stability parameter

3.2. *Ratio of eddy diffusivities* (K_h/K_m)

With the present consideration the ratio of eddy diffusivities should be,

$$(K_h/K_m)_l = \alpha_l = \frac{-H_l\,(\partial u/\partial z)_l}{u_*^2 \rho c_p \{(\partial\theta/\partial z)_l + 0.608(\theta q/\partial z)_l\}} \quad (10)$$

where H_l, the total sensible turbulent heat flux, is calculated considering the influence of water vapour on turbulent heat flux (Brook 1978).

Therefore,

$$\alpha_l = \frac{\phi_m(\zeta_l)}{\phi_h(\zeta_l)} \quad (11)$$

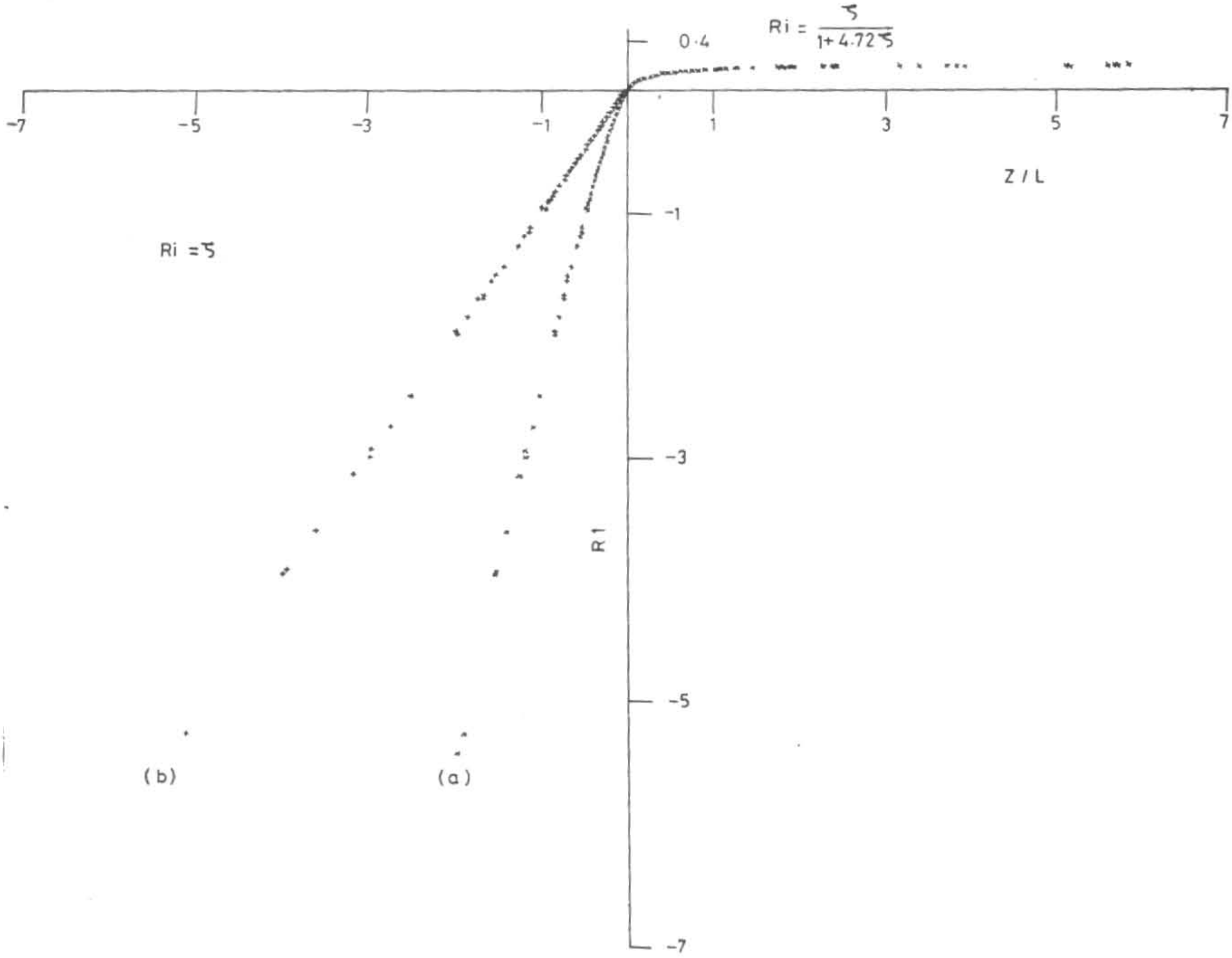
Using Eqn. (10), α_l is plotted against ζ_l both for stable and unstable situations [Figs. 1 (a & b)]. In the unstable condition α_l increases as the instability increases. In the neutral condition, however, the ratio reduces to 1.06 and it remains constant in entire stable condition. This statement remains valid both for fast as well as slow data. From the result it is obvious that

$$\alpha_l = 1.06\,(1 - 16\zeta_l)^{1/4} \quad (12)$$

in unstable situation.

In stable situation, including neutral condition, the expression becomes,

$$\alpha_l = 1.06 \quad (13)$$



Figs. 2 (a & b). Comparison of dependence of Richardson number (R_i) on stability parameter for slow data after (a) first iterative process and (b) two sucessive iterative processes

So, the general form of α covering all situations may be given as,

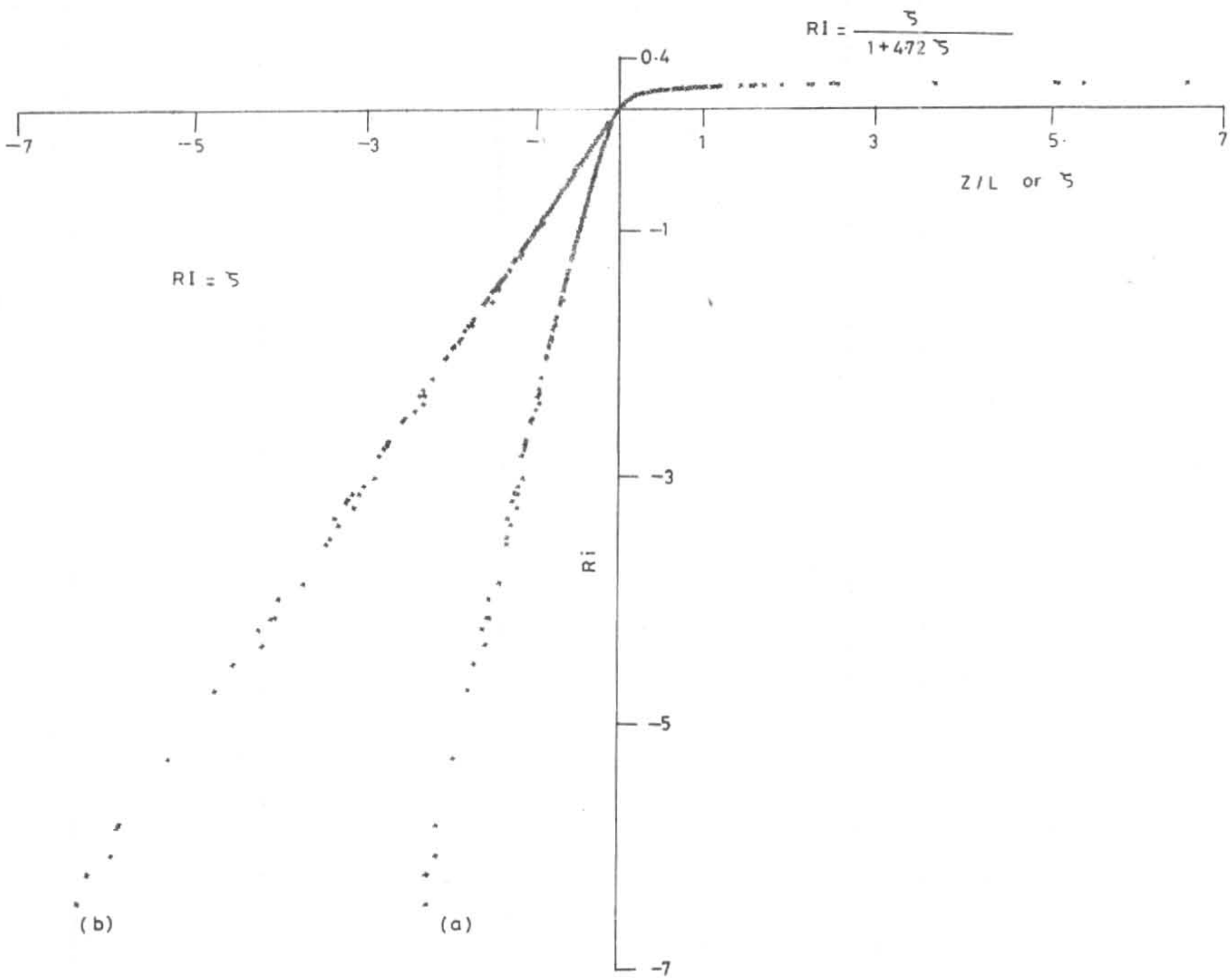
$$\alpha = \frac{K_h}{K_m} = c\frac{\phi_m}{\phi_h} \quad (14)$$

where, c is a proportionality constant and may be termed as eddy diffusivity constant with value 1.06.

3.3. *Similarity relation for R_i*

Comparing Eqns. (7) & (13), one can express the relation between R_i and ζ as,

$$\alpha\, R_i\, \phi_m = c\zeta \quad (15)$$



Figs. 3 (a & b). Comparison of dependence of Richardson number (R_i) on stability parameter for fast data after (a) first iterative process and (b) two sucessive iterative processes

Hence, in unstable case,

$$R_i = \zeta \quad (16)$$

But in stable, including neutral case, the expression is found to be

$$R_i = \frac{\zeta}{1 + 4.72\zeta} \quad (17)$$

As suggested by previous authors the upper limit for R_i in the stable case is 0.2. From Figs. 2 and 3 it is obvious that at the limiting value of R_i (0.2), ζ goes to infinity ($+\infty$). It transpires that the choice of limiting value of R_i is quite consistent.

As theoretically R_{i_l} is equal to ζ_l, in the unstable situation R_i may be compared with respective value of ζ_l from the first iterative process and also with the same parameter, ζ_l, obtained after both the iterative processes.

When value of L_l is considered after both the iterative processes, the curve comes much closer to Eqn. (16) both for fast as well as slow data which is evident from Figs. 2 & 3.

TABLE 2

S. No.		$1/N \left\{ \sum_{C=1}^{N} (R_i - \zeta)^2 \right\}^{1/2}$ where O indicates number of observations	
		$0 > R_i \geqslant -0.2$	$-0.2 > R_i \geqslant -10$
1.	After 1st iteration	(*i*) 0.00154	(*i*) 0.088693
		(*ii*) 0.00636	(*ii*) 0.060585
2.	After 2nd iteration	(*i*) 0.00025	(*i*) 0.001933
		(*ii*) 0.00097	(*ii*) 0.001854
3.	Remarks	Relative error diminished after both iterations with respect to 1st iteration is	
		(*i*) 83.75%	(*i*) 97.78%
		(*ii*) 84.48%	(*ii*) 96.93%

(*i*) For slow data
(*ii*) For fast data

The standard deviation of R_i from ζ has been calculated using two different values of L (L_j and L_l) and the results for unstable situation are presented in Table 2.

It is obvious that after two successive iterative procedures, the surface parameters attain values closer to the theoretical relations.

4. Conclusion

Using two successive iterative processes the parameters like u_* and θ_*, which can satisfy both the profile and the similarity relations, may be obtained. However, to have this success, a new concept has been introduced to consider the layer value as a level value for similarity comparison. The present methodology has been established considering both fast as well as slow response data of MONTBLEX '90. As the two data sets are independent, this stresses the strength of the methodology.

The closeness of R_i, value with its actual similarity expression in the present methodology, adds credence to the proposed model.

However, in the present model, α is no longer a constant in the unstable case as found by some other authors as well. The expression for α turns out as a simple one and the relation for all stability condition may be expressed as,

$$\alpha = c \frac{\phi_m}{\phi_h}$$

where c is a constant and the magnitude here comes out as 1.06.

It seems that this methodology is appropriate for layers with any finite thickness.

Acknowledgement

The authors are thankful to the Deptt. of Science and Technology (DST), Govt. of India for sanctioning a research project and present work is a part of this project.

APPENDIX

List of Symbols

d	zero-plane displacement
g	acceleration due to gravity
$k+0.4$	Von Karman constant
L	Monin-Obukov length
H	total sensible turbulent heat flux
q	specific humidity
q_*	water vapour flux concentration
u	wind velocity
u_*	frictional velocity
z	vertical co-ordinate
z_0	roughness length
ζ	dimensionless height
θ	potential temperature
θ_m	mean potential temperature
θ_*	scaling temperature
$\phi_m = \frac{kz}{u_*}\frac{\partial u}{\partial z}$	dimensionless wind shear
$\phi_h = \frac{kz}{\theta_*}\frac{\partial \theta}{\partial z}$	dimensionless temperature gradient
ψ_m	dimensionless stability function for momentum
ψ_h	dimensionless stability function for heat
$R_i = \frac{g\{\partial\theta/\partial z+0.608\theta_m(\partial q/\partial z)\}}{\theta_m(\partial u/\partial z)^2}$	gradient Richardson number
$K_h = \frac{-H}{\rho c_p(\partial\theta/\partial z+0.608\theta_m \partial q/\partial z)}$	eddy diffusivity coefficient for heat
$K_m = \frac{u_*^2}{\partial u/\partial z}$	eddy diffusivity coefficient for momentum
i	(subscript) level
M	(subscript) measured value
j	(subscript) layer
l	(subscript) geometric mean height of the layer
r	(subscript) characteristic level, *i.e.*, $z_r = z_0 + d$
(k)	(superscript) iteration step

References

Brook, R. R., 1978, "The influence of water vapour fluctuation on turbulent fluxes", *Bound. Layer Met.*, **15**, 481-488.

Businger, J. A., 1973, "Turbulent transfer in the atmospheric surface layer", in D.A. Haugen (Ed.), Workshop on Micrometeorology, Amer. Met. Soc., Boston, **67**, 100.

Businger, J. A., Wyngaard, J. C., Izumi, Y. and Brodley, E. F., 1971, "Flux-profile relationship in the atmospheric surface layer", *J. Atmos. Sci.*, **28**, 2, 181-189.

Deardorff, J. W., 1972, "Parameterization of the planetary boundary layer for use in General Circulation Models", *Mon. Weath. Rev.*, **100**, 2, 93-106.

Garrat, J. R., 1992, "The atmospheric Boundary Layer", Eds. John T. Houghton Michael J. Rycrot and Alexander J. Dessler. Cambridge, Press Syndicate of the University of Cambridge, 86.

Hicks, B. B., 1976, "Wind profile relationship from the wangara Experiment", *Quart. J. R. Met. Soc.*, **102**, 535-551.

Kramm, G. 1989, "The Estimation of the surface layer parameters from wind velocity, temperature and humidity profiles by least squares method", *Bound. Layer Met.*, **48**, 315-327.

Kramm, G. and Herbert, F., 1984, "Ein numerisches Modell zur Deposition von schadstoffen in der bodennahen Luftchicht" in H. Reuter (Ed.), Probleme der Umwell — und Medizinmeteorologie im Gebrige, Symposium Rauris/Austria, 23-25 Sept., 1983, zentralanstalt f. Meteorologie u. Geodynamic, Wien, Nr. 288.

Monteith, J. L. and Usworth, M. H., 1990, "Principles of environmental physics", Edward Arnold, 113-114.

Panofsky, H. A., 1963, "Determination of stress from wind and temperature measurements", *Quart. J. R. Met. Soc.*, **89**, 85-94.

Paulson, C. A., 1970, "The mathematical representation of wind speed and temperature profiles in the unstable atmospheric surface layer", *J. Appl. Met.*, **9**, 6, 857-861.

Prabhu, A., Ameenulla, S., Rudrakumar, S., Srinivasan, H.P. and Vasudev, S., 1990, "Tower instrumentation for surface layer observation", MONTBLEX Report. No. 90. MD 3.

Pradhan, R., De, U.K. and Sen, P. K., 1994, "Estimation of roughness length at Kharagpur micro-meteorological tower site during monsoon onset of 1990", *Mausam*, **45**, 2, pp 184-185.

Rudrakumar, S., Ameenulla, S., Rudrakumar, S., Srinivasan, H.P. and Prabhu, A., 1990, "PCM Telemetry System", MONTBLEX Report No. 90 Md 5. IISc, Bangalore.

Sorbjan, J., 1989, "Structure of the atmospheric boundary layer", Prentice Hall, Englewood Cliffs, New Jersey 07632.