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RESEARCH ARTICLE

Estimation of Seasonal Atmospheric Stability and Mixing Height by Using Different Schemes

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Abstract

Different atmospheric stability schemes were used to characterize the plume growth (dispersion coefficients σ) in the lateral and vertical directions to determine the concentration distribution of pollutants through the Planetary Boundary Layer (PBL). The PBL is the region in which surface friction has a large effect on the mixing of pollutants. It is also suffer large fluctuation in temperature and wind and its depth (mixing depth) changes over a diurnal cycle. In this study, 2773 hours of data have been utilized from four months of surface meteorological parameters (represent different seasons) to determine seasonal stability classification in Inshas area, Egypt. Five different stability schemes were estimated based on temperature gradient, standard deviation of the horizontal wind direction fluctuation, gradient and Bulk Richardson numbers and Monin-Obukhov length. The hourly classification of atmospheric stability from the above mentioned schemes were compared with the Pasquill scheme. In general, all schemes show a wide variation of stabilities in comparison to Pasquill scheme. Due to this variation some statistical performance were used to establish the relative importance of one scheme over the others compared with Pasquill scheme in a statistical sense. However, schemes based on Monin- Obukhov length give reasonable comparison than the rest of schemes except for spring season where bulk Richardson number scheme had the first ranking followed by Richardson number scheme. Friction velocity (u^*) for each stability scheme was estimated for characterizing the hourly mixing height for each stability class.

Introduction

Intensity of turbulence and dispersion of pollutants released into the lower atmosphere are strongly dependent upon the local winds as well as the resistance of the atmosphere to vertical mixing, which called atmospheric stability *(IA-80)*. It is the most important parameter in models used to determine the diffusion processes. Pasquill (1961) introduced the concept of expressing atmospheric stability in terms of stability categories ranging from A, most unstable, to F, most stable. Later a more stable category, G, was added to respect low wind nighttime stable conditions ($\sigma_y^G = 0.6\ \sigma_y^F$ and $\sigma_z^G = 0.6\ \sigma_z^F$) *(Ri-93and Ak-96)*. Stability Category can be determined according to observed wind speed, cloud cover, insolation conditions, and the variations of temperature and specific humidity with height. Radioactive materials from sources such as nuclear power plants, medical facilities, and research reactors are typically released to the atmosphere into a region of the atmosphere called the Planetary Boundary Layer (PBL). The height of the PBL generally ranges from 200 to about 2000 m *(Jo-83)*. Another important parameter, which not only determines the limit on the vertical diffusion of plumes in the PBL but also determines a host of other parameters (e.g. Z/h and h/l) and scales (e.g. W_*, h/W_*, L_x, L_y, etc.) related to turbulence and diffusion, is the mixing height (H_m) or the PBL depth *(Pa-99)*. It is defined as that layer of the lower atmosphere through which relatively vigorous mixing occurs. Therefore, the mixing height is assumed to occur with unstable and neutral conditions and to be undefined when the surface layer is stable *(Br-94)*. The vertical and to a lesser extent, horizontal dispersion properties of the PBL are mainly characterized by the PBL stability conditions, the PBL's height Z_i , the mixing depth, terrain and mesoscale phenomena. While atmospheric stability can be characterized by empirical methods (Pasquill scheme and Turner method), vertical temperature gradient ($\partial T/\partial Z$), the horizontal fluctuation of the wind direction (σ_θ), the Richardson number (R), and the Monin-Obukhov length (L) *(Za-90)*.

THEORETICAL ASPECTS

1- Atmospheric Stability Classification:

The stability of the atmosphere within the PBL largely determines the intensity of turbulence and subsequently, the diffusion processes which affect effluents released into this layer. In this study, depending on the availability of surface meteorological data obtained from Inshas meteorological tower, different stability schemes were computed for four seasons at a smooth flat site (Inshas area, Egypt). Surface meteorological data at two levels (10m and 60m) for Four months were used to represent the four seasons. Atmospheric stability were estimated by using five different stabilities classification schemes based on vertical temperature gradient ($\partial T/\partial Z$), the horizontal fluctuation of the wind direction (σ_θ), the Richardson number (Ri), the Bulk Richardson number (R_{iB}) and the Monin-Obukhov length (L)

a. Temperature gradient method ($\partial T/\partial Z$):

The temperature lapse rate method uses the bulk vertical temperature gradient ($\partial T/\partial Z$) between two levels (10m and 60m) in the atmosphere to characterize both the horizontal and vertical turbulence. This method is generally applicable in smooth and even terrain (table 1) *(Se-80)*.

Table (1): A correspondence between ($\partial T/\partial Z$), σ_θ, and the Pasquill stability classes.

Pasquill classes	($\partial T/\partial Z$)($C^oK/100m$)	σ_θ
A	($\partial T/\partial Z$)<-1.9	$\sigma_\theta > 22.5^o$
B	$-1.9 \leq (\partial T/\partial Z) < -1.7$	$17.5^o < \sigma_\theta \leq 22.5^o$
C	$-1.7 \leq (\partial T/\partial Z) < -1.5$	$12.5^o < \sigma_\theta \leq 17.5^o$
D	$-1.5 \leq (\partial T/\partial Z) < -0.5$	$7.5^o < \sigma_\theta \leq 12.5^o$
E	$-0.5 \leq (\partial T/\partial Z) < 1.5$	$3.75^o < \sigma_\theta \leq 7.5^o$
F	$1.5 \leq (\partial T/\partial Z) < 4$	$2.0^o < \sigma_\theta \leq 3.75^o$
G	$(\partial T/\partial Z) \geq 4$	$\sigma_\theta \leq 2^o$

b. Standard deviation of the wind direction fluctuation method (σ_θ):

Fluctuation of wind direction is the indicator which directly reflects the degree of atmospheric stability. The standard deviation of wind direction fluctuation is obtained by means of electronic devices. The evaluation of σ_θ should be done at the plume height level, in this study it was evaluated at two levels 10m and 60m. A relation between intervals of σ_θ values and the Pasquill stability classes were obtained as shown in table (1) *(IA-80)*.

c. Richardson number R_i method:

The atmospheric turbulence may be of mechanical as well as thermal origin. The ratio of the two processes is called the Richardson number (R_i) which reflects the imbalance between thermal, or convective, turbulence and mechanical turbulence *(Ha-80)*. It is a function of height, and is a dimensionless parameter defined by:

$$R_i = \frac{g/T\,[(\partial T/\partial Z)+\Gamma]}{\left(\partial U/\partial Z\right)^2} \qquad (1)$$

Where: g is the acceleration due to gravity (m/s^2)
T is the temperature (^oC)
Γ is the adiabatic lapse rate ($^oC/m$)
U is the mean wind speed (m/s)
Z is the height above ground (m) and $[(\partial T/\partial Z) + \Gamma]$ is called the potential temperature.

d. Bulk Richardson number R_{iB} method:

R_{iB} is also an appropriate dynamic stability parameter and it can be measured more easily than R_i since it does not involve wind speed gradients *(Mc-69)*.This is defined by:

$$R_{iB} = \frac{g/T\,[(\partial T/\partial Z) + \Gamma]Z^2}{U_z^2} \qquad (2)$$

Where U_z is the wind speed at the geometric mean of the heights at which temperature is measured to obtain the temperature profile and Z is usually taken to be the geometric mean height $[(Z_1Z_2)^{1/2}=24]$. Here Z_1 is 10 m, Z_2 is 50 m. The R_i and R_{iB} limits associated with each of the Pasquill stability class were represented in table (2), *(Ma-98)*.

Table (2): A correspondence between R_i, R_{iB} and the Pasquill stability classes.

Pasquill classes	R_i	R_{iB}
A	R_i <-2.038	R_{iB} <-0.023
B	-2.038≤ R_i < –0.75	-0.023≤ R_{iB} <-0.011
C	-0.75 ≤ R_i < –0.18	-0.011≤ R_{iB} <-0.0036
D	-0.18≤ R_i < 0.083	-0.0036≤ R_{iB} <0.0072
E	0.083 ≤ R_i <0.16	0.0072≤ R_{iB} <0.042
F	0.16 ≤ R_i <0.18	0.042≤ R_{iB} <0.084
G	R_i ≥ 0.18	R_{iB} ≥0.084

e. Monin-Obukhov Length (L) method:

Because both mechanical and convective forces determine turbulence, Monin and Obukhov (1954) proposed a similarity theory that introduced two scaling parameters, the friction velocity u_*, and the length L. Monin-Obukhov length is a measure of the depth of the near-surface layer in which shear effects are likely to be significant under any stability condition *(Pa-99)*. According to Monin-Obukhov similarity theory, the turbulence is determined and controlled solely by the parameters Q_o, g/T, u_*, and depth z. Where $Q_o = H/\rho C_p$, and is termed the surface kinematics turbulent heat flux and has the dimensions of (m ^{o}C/s). These governing surface-layer parameters result in the more familiar Monin-Obukhov length *(Ka-00)*:

$$L = -\rho C_p T u_*^3 / kgH \qquad (3)$$

Similarity theory also states that z/L is a function of the Richardson number and the Pandolfo- Businger hypothesis is a good approximation to the relation between R_i and Z/L in *unstable* air as follow:

$$1/L = R_i / Z \qquad (4)$$

In *stable* air, an empirical relation found by McVehil (1964) has been confirmed by others *(Do-72)*:

$$1/L = R_i / Z\,(1-\beta R_i) \qquad (5)$$

L is positive for stable conditions (usually at night), negative for unstable conditions (usually daytime), and approaches infinity for neutral conditions (dawn and dusk transition periods and cloudy, windy conditions). The absolute value of L can be thought of as the depth of the mechanically mixed layer near the surface.

The Monin – Obukhov length (L) limits associated with each of the Pasquill stability class are calculated as shown in table (3) where Z_o =0.5, β=7 and Z=10.

Table (3): A correspondence between R_i, R_{iB} and the Pasquill stability classes.

Pasquill classes	1/L
A	1/L <-0.056
B	-0.056≤1/L < –0.016
C	–0.016≤ 1/L < –0.004
D	–0.004≤ 1/L < 0.002
E	0.002≤ 1/L <0.006
F	0.006≤ 1/L <0.022
G	1/L ≥ 0.022

The hourly classification of atmospheric stability from the above mentioned schemes has been compared with the Pasquill scheme as this is among the first known classifications and still widely used. Pasquill method requires a measurement of wind speed at 10 m and a measurement of solar insolation during daytime and an assessment of cloud cover during nighttime. The stability class can then be known from table 4 which is the modified Pasquill stability analysis scheme *(Ma-98)*.

Table (4): Modified Pasquill stability classes.

Wind Speed (m/s)	Day time strong $>600\ W/m^2$	incoming moderate 300-600	solar slight <300	radiation Overcast	1 h before sunset or after sunrise[a]	Nighttime 0-3	oud 4-7	amount 8 okta
≤ 2	A	A-B	B	C	D	F or G[b]	F	D
2-3	A-B	B	C	C	D	F	E	D
3-5	B	B-C	C	C	D	E	D	D
5-6	C	C-D	D	D	D	D	D	D
>6	C	D	D	D	D	D	D	D

[a] Night was originally defined to include periods of 1 h before sunset and after sunrise. These 2 h are always categorised as D.

[b] Pasquill said that in light wind and clear nights the vertical spread may be less than for category F but excluded such cases because the surface plume is unlikely to have any definable travel. However, they are important from the point of view of the buildup of pollution and category G (nighttime, 0 or 1 okta of cloud, wind speed 0 or 0.5 m/s) has been added.

2- Hourly mixing height determination:

The atmospheric planetary boundary layer (PBL) is the region in which surface friction has a large effect on the flow, typically the lowest kilometer or so. This layer can also suffer large fluctuations in temperature and wind and its depth changes over a diurnal cycle *(Mc-97)*. The thickness of the PBL is characterized by the thickness of the turbulent region next to the ground and is called the mixing depth *(Ka-00)*. An accurate estimate of the depth of the mixing layer is essential for calculating dispersion of air pollutants in the PBL. From simple theoretical (similarity) considerations, the depth of *a neutral PBL* in middle and high-latitude region is given by:

$$\mathbf{h = 0.3\ (u_* / f)} \qquad \mathbf{(6)}$$

Where $f = 10^{-4}$ and $\mathbf{u_* = 0.4\ (u / \ln [Z/Zo])}$

The applicability of Eq. (6) is restricted, however, to steady-state near neutral conditions with h/L <1 and absence of low-level elevated inversions. Whenever an inversion is present at a height less than that given by (6), the height of inversion base z_i would determine the mixing height.

In stable conditions with stratified nocturnal boundary layer with moderate and strong winds. The mixing height is also given by a simple diagnostic formula:

$$\mathbf{h = 0.4\ (u_* [L/f])^{1/2} \quad for\ Z/L > 0} \qquad \mathbf{(7)}$$

Where $\mathbf{u_* = 0.4\ (u / \ln [Z/Zo + 5\ Z/L])}$

which is strictly valid for the steady-state, equilibrium conditions. Comparisons with direct observations of h indicate that equation (7) provides a fair estimate of the mixing height even during the more typical, slowly evolving, non-stationary conditions prevailing in the nocturnal boundary layer *(Pa-99)*.

For *unstable and convective conditions*, the mixing height is given by:

$$\mathbf{h = [12-(\sigma_\theta\ u / u_*)^3\ L]\ / 0.5 \quad for\ Z/L < 0} \qquad \mathbf{(8)}$$

Where $\mathbf{u_* = 0.4\ (Z / 1\text{-}15[Z/L]^{-1/4})\ \Delta u/\Delta z}$

RESULTS AND DISCUSSION

2773 hours of meteorological data (were obtained from Inshas meteorological tower) have been utilized from four different months, viz., February, May, August and October which represent winter, spring, summer and autumn respectively. The hourly and daily classification of atmospheric stability has been compared for the five schemes mentioned above. The percentage variations of each stability scheme in different seasons were shown in tables (6-9). $(\partial T/\partial Z)$ represents vertical temperature gradient, (σ_θ) represents the horizontal fluctuation of the wind direction, (R_i) represents the Richardson number, (R_{iB}) represents the Bulk Richardson number and (1/L) represents the Monin-Obukhov length. From these tables we can conclude that all schemes show a wide variation of stabilities. So, the hourly classification of atmospheric stability from the above mentioned schemes has been compared with the Pasquill scheme as this is among the first known classifications and still widely used. The distribution of total number of observations in each Pasquill stability classes, A, B, C, D, E, F, and G for different seasons was shown in table (5). In general, all schemes show a wide variation of stabilities in comparison to Pasquill scheme. Due to this variation some statistical performance were used to establish the relative importance of one scheme over the others compared with Pasquill scheme in a statistical sense.

Table (5):The distribution of total number of observations in each Pasquill stability classes for different seasons.

Stability class	February	May	August	October
A	26	8	29	19
B	153	26	101	114
C	185	108	173	228
D	83	416	22	36
E	38	126	14	60
F	102	19	137	156
G	108	6	173	108

Table (6):The percentage variation of each stability scheme in spring season.

Stability class	$\partial T/\partial Z$ %	σ_θ %	R_i %	R_{iB}%	1/L%	Pasquill%
A	43.2	55.6	18.8	27.6	43.3	1.1
B	1.13	10.4	23.6	12.4	10.2	3.7
C	2.4	12.7	10.9	20.6	15	15.2
D	13.3	12.6	38.8	28.9	15.4	58.7
E	37.2	4.94	3.95	8.04	5.92	17.8
F	2.82	2.82	0.71	1.69	6.63	2.7
G	0	0.99	3.39	0.71	3.67	0.8

Table (7):The percentage ratio for each stability classification for summer season.

Stability class	$\partial T/\partial Z$ %	σ_θ %	R_i %	R_{iB}%	1/L%	Pasquill%
A	83.02	26.39	19.75	31.33	25.31	4.4
B	4.63	0.62	7.87	12.35	8.18	15.6
C	3.55	0.62	15.12	9.72	10.03	26.7
D	3.09	5.25	26.39	12.35	30.09	3.3
E	2.47	45.52	2.16	2.31	8.80	2.2
F	1.08	6.17	0.31	4.17	4.17	21.1
G	2.16	15.43	28.40	27.78	13.43	26.7

Table (8):The percentage ratio for each stability classification for autumn season.

Stability class	$\partial T/\partial Z$ %	σ_θ %	R_i %	R_{iB}%	1/L%	Pasquill%
A	32.32	65.60	29.96	33.98	39.81	2.6
B	0.97	7.49	8.60	4.72	14.42	15.8
C	1.53	5.69	5.41	3.74	4.85	31.6
D	6.24	3.88	15.81	23.30	6.10	5.0
E	53.26	7.91	3.47	21.78	3.61	8.3
F	5.69	5.55	1.25	6.93	3.88	21.6
G	0.00	3.88	35.51	5.55	27.32	15.0

Table (9):The percentage ratio for each stability classification for winter season.

Stability class	∂T/∂Z %	σ_θ %	R_i %	Ri_B%	1/L%	Pasquill%
A	7.48	66.47	6.19	7.05	10.50	3.7
B	0.29	5.32	2.59	2.45	12.52	22.0
C	0.58	5.18	4.89	5.32	5.18	26.6
D	5.61	9.78	18.85	33.09	5.76	11.9
E	59.86	6.62	8.20	28.92	4.32	5.5
F	25.76	3.88	2.30	8.78	15.40	14.7
G	0.43	2.73	56.98	14.39	46.33	15.5

The statistical performance measures used to quantify the differences between Pasquill scheme and other schemes are:

1. Normalized mean square error (NMSE)

$$NMSE = \frac{(C_o - C_p)^2}{C_o C_p}$$ It is given by

Where C_o is the mean value of the stability frequency calculated by Pasquill method,
C_p is the mean value the stability frequency calculated by other schemes.
Its value should be as small as possible for a good scheme.

2. Correlation coefficient (R):

It describes the degree of association or agreement between the variables and is defined as:

$$\frac{(C_{oi} - C_o)(C_{pi} - C_p)}{\sigma_o \sigma_p}$$

Where C_{oi} is the ith stability frequency calculated by Pasquill method,
C_{pi} is the ith, stability frequency calculated by other schemes and
n is the total number of paired for each scheme.
Its value lies between 0 and 1 inclusive, R may assume any value between -1 and +1, if R=1 there is a perfect direct linear correlation between the observed and calculated concentrations, While R= -1 indicates perfect inverse linear correlation. If R=0 the two variables are not correlated.

3. Fraction within a factor of two (FAC2):

It is defined as **FAC2** = fraction of data for which $\mathbf{0.5 \le C_p / C_o \le 2}$ *(Wa-87).*

Fraction Bias statistic measure was calculated but it does not appear to be a robust measure due to that all values for all schemes were within the possible values (-2 and +2) and in most values it was close to zero, so it was excluded. Table (10) shows the computed statistics for the complete stability distribution using modified Pasquill method compared to other schemes. Amongst the three statistics, in all comparisons, the M-O length scheme shows the best comparison among three seasons, winter, summer and autumn. While for spring season the $\mathbf{R_{iB}}$ scheme had the first rank and $\mathbf{R_i}$ had the next ranking. In Winter season the $\mathbf{R_{iB}}$ scheme had the second rank, while in Summer season $\mathbf{R_i}$ had the second rank and in Autumn season ∂T/∂Z scheme follow the M-O length scheme. We can conclude that, the scheme based on M-O length, $\mathbf{R_{iB}}$**,** and $\mathbf{R_i}$ **show** better performance which may be attributed to the fact that these schemes represent ratio of mechanical to convective turbulence while σ_θ is more directly associated with mechanically generated turbulence only and ∂T/∂Z associated more with thermally generated turbulence. Also, σ_θ classification may vary from place to place and be influenced by local topographical and climatic features. This, together with the fact that single-level and unidirectional representation of turbulence in the form of σ_θ may not incorporate the dynamics of the whole mixing layer, could explain the poor comparison of this scheme with the Pasquill scheme *(Ma-98).*

Table (10): Computed Statistical Measures for different schemes, in different seasons N=7 for each scheme.

February				**May**		
scheme	NMSE	R	FAC2	NMSE	R	FAC2
$\partial T/\partial Z$	3.16	-0.55	2.18	3.07	0.05	6.01
σ_θ	3.47	-0.59	2.95	3.72	-0.13	7.95
R_i	1.95	-0.03	1.27	**1.05**	**0.65**	**3.59**
R_{ib}	**1.32**	**0.5**	**1.68**	**0.66**	**0.8**	**2.62**
1/L	**1.11**	**0.09**	**1.27**	2.65	-0.07	7.33
August				**October**		
scheme	NMSE	R	FAC2	NMSE	R	FAC2
$\partial T/\partial Z$	2.53	-0.58	4.21	**0.48**	**0.4**	**0.6**
σ_θ	5.47	-0.4	3.02	2.02	0.04	0.48
R_i	**0.97**	**0.06**	**2.19**	1.52	-0.63	1.85
R_{ib}	1.39	-0.56	2.88	1.57	-0.8	1.39
1/L	**0.97**	**0.05**	**2.01**	**1.09**	**0.65**	**1.14**

The rate of change of total turbulent kinetic energy in the PBL is quite slow and a quasi-balance exists between the production and destruction of turbulence. When production is large, such as on a sunny summer day, the PBL is both chaotic and very deep. When the production rate is small, the PBL is shallow and less turbulent (Ca-79). Figures (1-3) show an example for the calculated friction velocity u_* and the mixing height H for different stability classes for the daily average for spring season.

Figure (1): Daily average correspondence between friction velocity and mixing height in $\partial T/\partial Z$ (left) and σ_θ (right) stability classes for spring season.

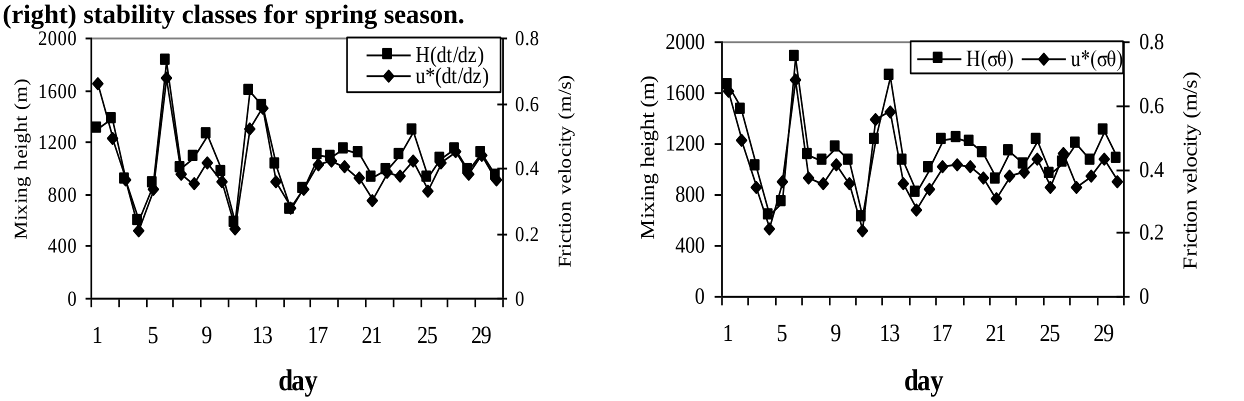


Figure (2): Daily average correspondence between friction velocity and mixing height in R_i (left) and R_{ib} (right) stability classes for Spring season.

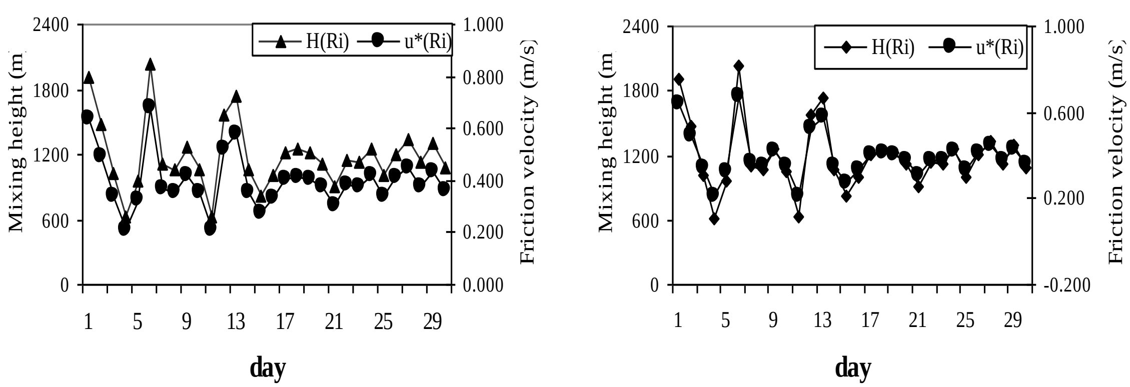
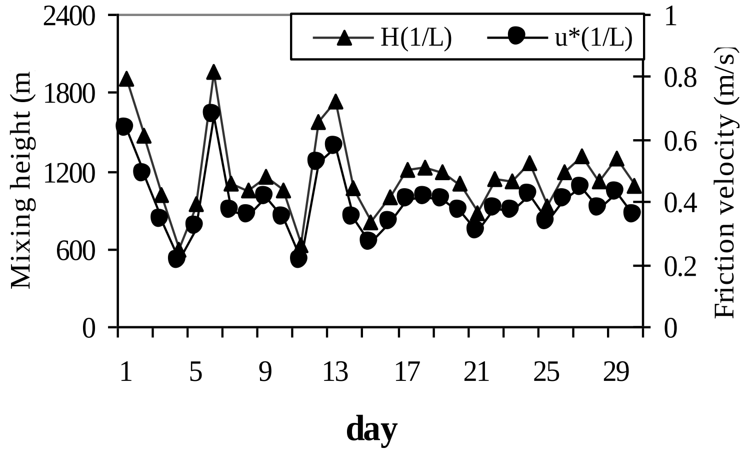


Figure (3): Daily average correspondence between friction velocity and mixing height in Monin-Obokhov length stability class for spring season.



Figures (4-6) show an example for the calculated friction velocity u_* and the mixing height H for different stability classes for the hourly average.

Figure (4): Hourly average correspondence between friction velocity and mixing height in ∂T/∂Z (left) and σ_θ (right) stability classes for winter season.

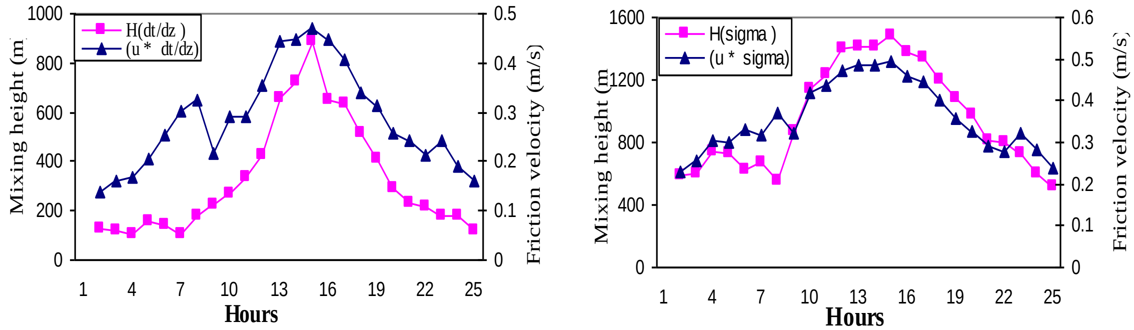


Figure (5): Hourly average correspondence between friction velocity and mixing height in R_i (left) and R_{ib} (right) stability classes for Winter season.

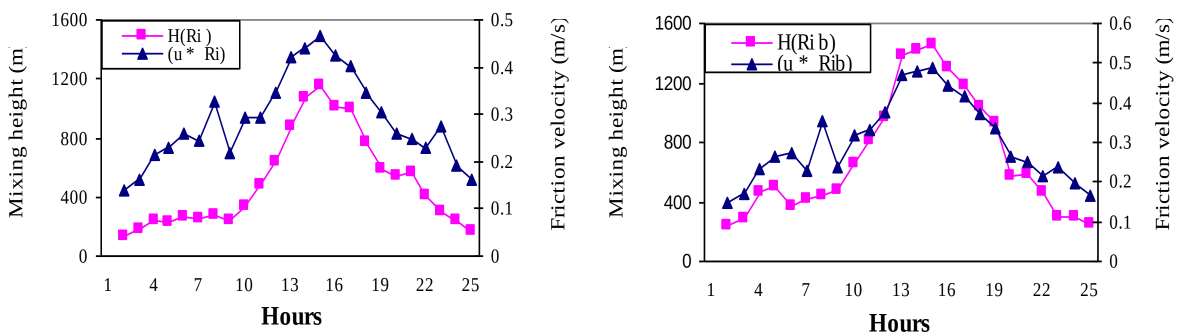
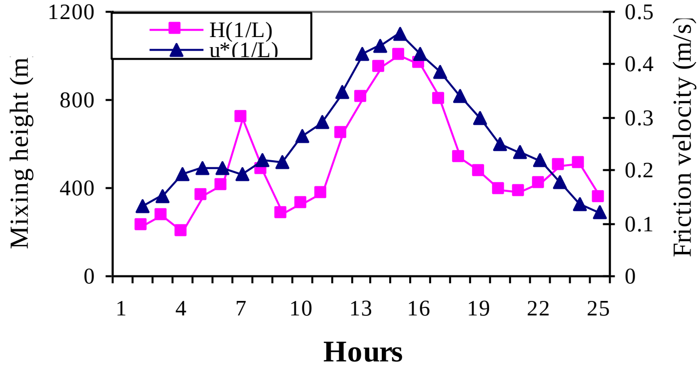


Figure (6): Hourly average correspondence between friction velocity and mixing height in Monin-Obokhov length stability class for winter season.



CONCLUSION

The hourly classification of atmospheric stability from the above mentioned schemes were compared with the Pasquill scheme. In general, all schemes show a wide variation of stabilities in comparison to Pasquill scheme. Due to this variation some statistical performance were used to establish the relative importance of one scheme over the others compared with Pasquill scheme in a statistical sense. However, schemes based on Monin- Obukhov length give reasonable comparison than the rest of schemes except for spring season where bulk Richardson number scheme had the first ranking followed by Richardson number scheme. In Winter season the R_{iB} scheme had the second rank, while in Summer season R_i had the second rank and in Autumn season $\partial T/\partial Z$ scheme follow the M-O length scheme. We can conclude that the schemes which are represented by either the mechanical turbulence, viz σ_θ or the thermal turbulence, viz, $\partial T/\partial Z$ would perform poorly in comparison to the other schemes which are represented by both thermal as well as mechanical turbulence viz. L, R_i, and R_{iB}. Also, σ_θ scheme does not give a good comparison as some of the other schemes mentioned above due to that this classification may vary from site to another and the involvement of only a site level measurement, which may not necessarily represent the characteristics of the entire surface boundary layer. Also, we can conclude that σ_θ could be correlated well empirically with the lateral dispersion parameters, but, this may not be true to the same extent with the atmospheric stability.

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