World Academy of Science, Engineering and Technology
International Journal of Environmental and Ecological Engineering
Vol:2, No:8, 2008

A Model to Determine Atmospheric Stability and its Correlation with CO Concentration

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***Abstract*—**Atmospheric stability plays the most important role in the transport and dispersion of air pollutants. Different methods are used for stability determination with varying degrees of complexity. Most of these methods are based on the relative magnitude of convective and mechanical turbulence in atmospheric motions. Richardson number, Monin-Obukhov length, Pasquill-Gifford stability classification and Pasquill–Turner stability classification, are the most common parameters and methods. The Pasquill–Turner Method (PTM), which is employed in this study, makes use of observations of wind speed, insolation and the time of day to classify atmospheric stability with distinguishable indices. In this study, a model is presented to determination of atmospheric stability conditions using PTM. As a case study, meteorological data of Mehrabad station in Tehran from 2000 to 2005 is applied to model. Here, three different categories are considered to deduce the pattern of stability conditions. First, the total pattern of stability classification is obtained and results show that atmosphere is 38.77%, 27.26%, 33.97%, at stable, neutral and unstable condition, respectively. It is also observed that days are mostly unstable (66.50%) while nights are mostly stable (72.55%). Second, monthly and seasonal patterns are derived and results indicate that relative frequency of stable conditions decrease during January to June and increase during June to December, while results for unstable conditions are exactly in opposite manner. Autumn is the most stable season with relative frequency of 50.69% for stable condition, whilst, it is 42.79%, 34.38% and 27.08% for winter, summer and spring, respectively. Hourly stability pattern is the third category that points out that unstable condition is dominant from approximately 03-15 GTM and 04-12 GTM for warm and cold seasons, respectively. Finally, correlation between atmospheric stability and CO concentration is achieved.

***Keywords*—**Atmospheric stability, Pasquill-Turner classification, convective turbulence, mechanical turbulence, Tehran.

I. INTRODUCTION

ATMOSPHERIC stability plays the most important role in the transport and dispersion of air pollutants. It can be defined as the atmospheric tendency to reduce or intensify vertical motion or alternatively, to suppress or augment existing turbulence [1]. It is related to the change of temperature with height (the lapse rate) and also wind speed [2, 3]. The degree of stability of the atmosphere must be known to estimate the ability of atmosphere to disperse pollutants [3]. Different methods are used for stability determination with varying degrees of complexity [4]. Most of these methods are based on the relative importance of convective and mechanical turbulence in atmospheric motions. Difference between such methods is due to use of different indicators for both convective and mechanical turbulence. Generally, when convective turbulence predominates, winds are weak and atmosphere is in unstable condition. When importance of convection decreases and mechanical turbulence increases, atmosphere tends to neutral conditions. Finally in absence of convective turbulence when mechanical turbulence is dampened and there is no vertical mixing, atmosphere is in stable condition [5]. Richardson number, Monin-Obukhov length, Pasquill-Gifford stability classification and Turner stability classification are some of common schemes [4]. The Richardson number is a turbulence indicator and also an index of stability which is defined as [2]:

$$Ri = \frac{g\left(\dfrac{\Delta\Theta}{\Delta z}\right)}{T\left(\dfrac{d\bar{u}}{dz}\right)^2} \tag{1}$$

where, g is the gravity acceleration, $\Delta\Theta/\Delta z$ is the potential temperature gradient, T is the temperature and $d\bar{u}/dz$ is the wind speed gradient. In this equation, $g(\Delta\Theta/\Delta z)/T$ is indicator of convection and $\left(d\,\bar{u}/dz\right)^2$, is pointer of mechanical turbulence due to mechanical shear forces.

The other key stability parameter is the Monin-Obukhov length, L, which treats atmospheric stability proportional to third power of friction velocity, u_*^3, divided by the surface turbulent (or sensible) heat flux from the ground surface, H_s. Monin-Obukhov length is defined as [2]:

$$L = \frac{-\left(u_*^3/k\right)}{\left(gH_s/C_p\rho T\right)} \tag{2}$$

where u_* is friction velocity, g is the gravity acceleration, Cp is the specific heat of air at constant pressure, ρ is the air

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Manuscript received September 19, 2008. This work was supported in part by Graduate Faculty of Environment, University of Tehran.

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density, T is the air temperature, and k is von- Karman constant taken to be 0.40. H_s is positive in daytime and negative at nighttime.

Pasquill-Gifford method for estimating atmospheric stability, incorporating considerations of both mechanical and buoyant turbulence was proposed by Pasquill (1961). It is a simple method because it is easy to use and tends to give satisfactory results [1]. In this classification, it is assumed that stability in the layers near the ground depends on net radiation as an indication of convective turbulence and on wind speed at 10 m height as an indication of mechanical turbulence. Net radiation could be determined based on insolation (incoming solar radiation) and cloud cover at day or night time separately and finally stability is defined as six categories. The primary advantages of this classification are its simplicity and its requirement of only routinely available information from surface meteorological stations, such as the near-surface (10 m) wind speed, solar radiation and cloudiness [6].

The Pasquill–Turner Method (PTM), which is employed in this study, is based upon the work of Pasquill, that has been revised by Turner (1964) by introducing incoming solar radiation in terms of solar elevation angle, cloud amount and cloud height. It classifies atmospheric stability with seven distinguishable categories [7]. The importance of this method lies in the relation of atmospheric dispersion coefficients and classified stability for mechanically and thermally generated boundary-layer turbulence [1]. Also, PTM has been made completely objective so that an electronic computer can be used to compute stability. Table I shows the atmospheric stability classification using mentioned schemes.

In this study, an attempt was made to introduce a model to determination of atmospheric stability conditions using PTM. Also, relation between these conditions and ground-level concentration of pollutants is investigated. First, more details about PTM and relative concepts are illustrated. Then the structure of proposed model and used algorithms are presented. As a case study, meteorological data from Mehrabad stations in Tehran from 2000 to 2005 is applied to model and results are evaluated seasonal, monthly and hourly. Finally, the correlation between atmospheric stability and CO concentration (from Azadi air pollution station) is proposed as a decision support model.

II. METHODOLOGY

A. Pasquill-Turner's Stability Classification

As mentioned in previous section, Pasquill used meteorological data from surface stations for the characterization of atmospheric stability and derived six stability classes from A for extremely unstable to F for extremely stable conditions [8]. Turner improved this scheme by introducing Net Radiation Index (NRI) as indicator of insolation. This produced a new version of Pasquill's algorithm in which radiation is categorized into classes related to solar altitude, cloud cover and cloud height [7]. The method is generally acceptable for studies of atmospheric pollution, even if it overestimates the neutral stability class [1]. A brief comparison between Pasquill method and PTM is presented in Table II.

The NRI in PTM is determined in reference to the following procedure [1, 5]:

(1) 0, when the total cloud cover is 8/8 and the ceiling height of cloud base is less than 7000 ft (low clouds).

(2) -2, during the night if the total cloud cover is ≤3/8, and if it is >3/8, then -1

(3) 4, (high radiation levels) ranging to 1 (low radiation levels) during daytime and depending on the solar altitude (Table III). Corrections of NRI during daytime are as follows:

  (a) If the total cloud cover is ≤4/8, then the indices are used as from Table III.
  (b) If the cloud cover is >4/8 two cases are distinguished:
    (b-1) ceiling <7000 ft, then 2 is subtracted and
    (b-2) ceiling ≥7000 ft and <16000 ft then 1 in subtracted.
  (c) If the total cloud cover is 8/8 and the ceiling height is ≥7000 ft, then 1 is subtracted.
  (d) If the corrected value is less than 1, then it is considered equal to 1.

When the solar altitude is higher than 60 degrees, i.e. in the afternoon summertime, then the atmosphere is unstable.

Moderate instability occurs during a summer day with few clouds. Weak atmospheric instability happens usually in the afternoons of autumn or summer days with few low clouds. The neutral category governs during cloudy days and nights.

Finally, the creation of inversions during nights with clear sky indicates stable atmosphere [5].

Stability class in PTM is determined according to the corrected NRI and the wind speed, as it is shown in Table IV.

TABLE I
INTERPRETATION OF FOUR DIFFERENT ATMOSPHERIC STABILITY SCHEMES [5, 9]

Stability condition	Richardson	Monin-Obukhov	Pasquil-Gifford	PTM
Extremely unstable	$Ri < -0.04$	$-100 < L < 0$	A	1
Unstable		$-10^5 \le L \le -100$	B	2
Slightly unstable	$-0.03 < Ri < 0$		C	3
Neutral	$Ri=0$	$\lvert L \rvert > 10^5$	D	4
Slightly stable	$0 < Ri < 0.25$	$10 \le L \le 10^5$	E	5
Stable	$Ri > 0.25$		F	6
Extremely stable		$0 < L < 10$		7

TABLE II
COMPARISON BETWEEN PASQUILL METHOD AND PTM

Scheme	Parameter involved	Remarks
Pasquill-Gifford	Insolation/ cloud cover and wind speed	Valid for idealized conditions; does not consider surface roughness, stratification effects; stability defined broadly and in a discrete manner; can be used as a general guideline or reference scheme
PTM	Net radiation and wind speed	Considers cloud effects but not roughness effects; based on a more directly related parameter; classes are defined in a more refined way

TABLE III
INSOLATION AS A FUNCTION OF SOLAR ALTITUDE

Solar Altitude $h(^{o})$	Insolation	Insolation Class Number
$60<h$	Strong	4
$35<h<60$	Moderate	3
$15<h<35$	Slight	2
$h<15$	Weak	1

TABLE IV
STABILITY CLASS AS A FUNCTION OF NRI AND WIND SPEED

Wind Speed	Net Radiation Index (NRI)						
(knots)	4	3	2	1	0	-1	-2
0-1	1	1	2	3	4	6	7
2-3	1	2	2	3	4	6	7
4-5	1	2	3	4	4	5	6
6	2	2	3	4	4	5	6
7	2	2	3	4	4	4	5
8-9	2	3	3	4	4	4	5
10	3	3	4	4	4	4	5
11	3	3	4	4	4	4	4
≥12	3	4	4	4	4	4	4

In urban areas, during the day, surfaces are more reflective and become hotter and thus, producing more convective eddies. As a result, convective turbulence in an urban area is more significant than it is in the rural areas and urban areas are rarely as stable. Therefore, while using PTM for urban areas, like this study, it is possible to combine stability categories 6 and 7 into one category [5].

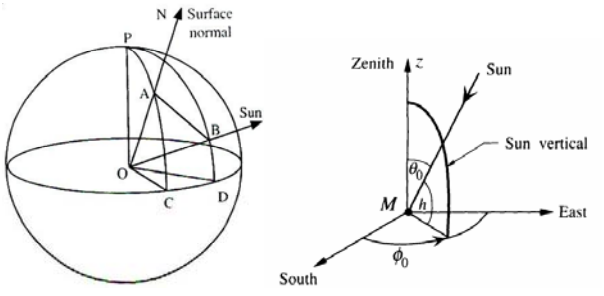
B. Model Description

FORTRAN90 has been used as programming language for model developing. Inputs of model are designed to be in separated files include meteorological data and information about time and location that made it useable for any time and location. Model, consists of two main parts; first part to calculate solar altitude and second part to determine stability class.

First Part: Solar Altitude Calculation: Solar altitude is calculated by means of following equation [10]:

$$\sin(h)=\sin(\varphi)\sin(\delta)+\cos(\varphi)\cos(\delta)\cos(\gamma) \tag{3}$$

where h is solar altitude, γ is solar hourly angle, φ is geographical latitude, δ is solar declination angle (Fig. 1). The most important quantity in this part is day number (N_{JD}) that is the number of days from the beginning of Julian year 2000 and could be calculated as follows [10]:



(a) (b)

Fig. 1 (a) Geometry for solar altitude calculations on a sphere. The ray OAN is the surface normal or zenith above the point of interest. Angle BOD is the solar declination (δ), angle AOC is the geographical latitude (φ) and angles COD=CPD=APB are hour angles (γ) [10]. (b) Horizontal coordinates of sun: θ_0= zenith angle; h=altitude angle and φ_0=azimuth angle [9]

$$N_{JD}=364.5+(Y-2001)\times 365+D_L-D_J$$

$$D_L=\begin{cases} INT(Y-2001)/4 & \text{Y}\geq 2001 \\ \\ INT(Y-2000)\ /4-1 & \text{Y}<2001 \end{cases} \tag{4}$$

where Y is the current year, D_L is the number of leap days since or before the year 2000, D_J is the Julian day of the year. The model algorithm is based on equations (3) and (4). Orbital elements such as mean distance from sun, eccentricity, etc. are calculated using N_{JD} [11] and parameter of equation (3) are determined by means of these elements that results in measurement of solar altitude in time and location of interest.

Second Part: Stability Class Determination: This part uses solar altitude obtained from first part and meteorological data include wind speed, cloud cover and cloud height, to determine turner's stability class for specific time and location according to PTM algorithm described in previous section.

III. CASE STUDY

Tehran is the capital and the largest city of Iran which is located in 35^{o} 45' N and 51^{o} 30' E. As a case study, model is applied to Merhabad meteorological station in west of Tehran at 35^{o} 41' N and 51^{o} 19' E with height of 1190.8 m above sea level. To analyze correlation between stability conditions and air pollution, CO concentration data of Azady station in vicinity of Mehrabad are used (Fig. 2). Air pollution and also meteorological data include wind velocity; cloud cover and cloud height during 2000-2005 are used.

IV. RESULTS AND DISCUSSION

Four different time categories for stability pattern are obtained from the results of model include: total, seasonal, monthly and hourly patterns.

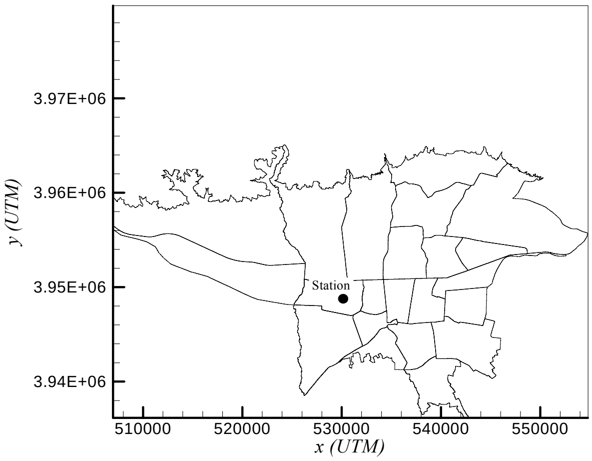


Fig. 2 City of Tehran with Mehrabad meteorological and Azadi air pollution stations

A. Total Stability Pattern

Implementation of developed model on the meteorological data of study area, shows that atmosphere is mostly stable with relative frequency (here after RF) of 38.77% for stable condition (Fig. 3-a). From more comprehensive aspect (Fig. 3-b), RF of extremely unstable category 1 is 5.38% that is considerably less than RF of extremely stable category 6 with quantity of 33.55%. As a consequence, air pollution accumulation, could occurs most of times.

During days, where solar radiation is present, it is expected that atmosphere be chiefly unstable. Dividing total stability pattern into two parts and investigate daytime and nighttime stability separately, approved this expectance. Fig. 4 shows results of this investigation where dominance of instability during days is obvious with 66.50% RF (Fig. 4-a). Stability at nights with 72.55% RF is dominant due to creation of inversions during nights with clear sky that indicates stable atmosphere (Fig. 4-b) and it is never at unstable condition. This phenomenon could be explained by physical realities that there is no solar radiation and refer to Table III, NRI is between -2 to 0 that spans classes 4 to 7.

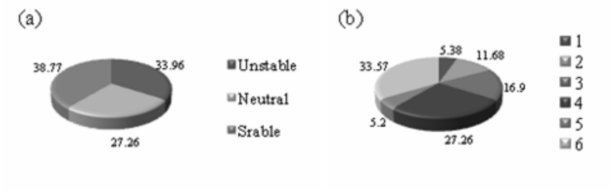


Fig. 3 (a) Total pattern of atmospheric stability (b) Total pattern of atmospheric stability based on Turner's classification

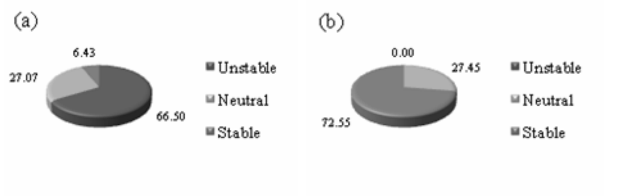


Fig. 4 (a) Daytime stability pattern (b) Nighttime stability pattern

TABLE V
SEASONAL COMPARISON OF ATMOSPHERIC STABILITY CONDITION

Season	Unstable (%)	Neutral (%)	Stable (%)
Spring	41.85	31.07	27.08
Summer	42.64	23.17	34.38
Autumn	25.27	24.05	50.69
Winter	26.16	31.05	42.79

B. Seasonal and Monthly Stability Pattern

As shown in Table V, comparison between stability patterns of different seasons reveals that atmosphere is more stable during cold seasons than warm ones. It is also observable that the autumn is the most stable season with 50.69%, 24.05%, 25.27% RF for stable, neutral and unstable conditions, respectively. Consequently, air pollution accumulation during this season is more probable than other ones.

Monthly stability variations are presented in Fig. 5 where a relative decrease in instability and an increase in stability are obvious during warm months to cold ones. From April to August, instability is dominant while from September to March, stability is relevant. This matter could be elucidated regarding the fact that during warm months, insolation is high and there are no strong winds, so convective eddies play main role in atmospheric motions and atmosphere is more unstable than cold seasons where there is less insolation and stronger winds. As a result, there is relatively more chance for pollution accumulation during cold months due to more stable condition.

It should be noted that, the most stable month is the November with 54.9% RF for stable condition while the June is the most unstable month with 44.7% RF for unstable condition.

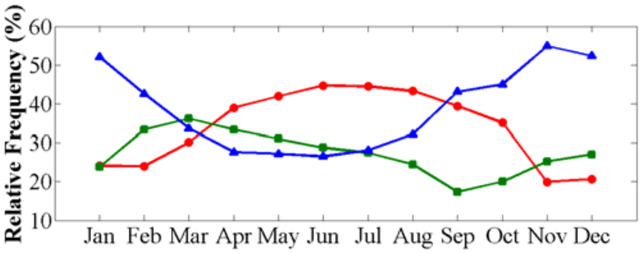
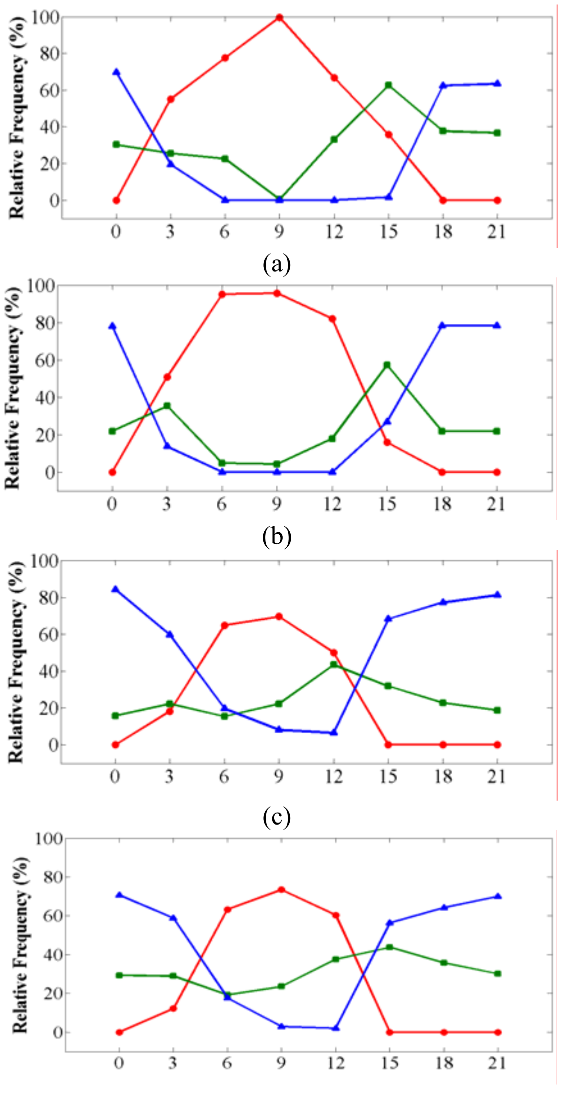


Fig. 5 Variations in atmospheric stability pattern during different months (Unstable: ●, Neutral: ■, Stable: ▲)

C. Hourly Stability Pattern

Fig. 6 shows that stability at nighttime and instability at daytime are dominant during all seasons. From sunrise to local noon (3-8:30 GTM), instability increases and from noon to sunset (8:30-15 GTM), it decreases while variations in stability are vice versa. In the spring and the summer (Figs. 4-a, b), rise of instability starts sooner than cold seasons and for approximately 12 hours (3-15 GTM), atmosphere is mostly unstable. In the autumn and the winter (Figs. 4-c, d), dominance of instability during days, is approximately 8 hours (4-12 GTM) with relatively less intensity.



(a)

(b)

(c)

(d)

Fig. 6 Hourly variations of atmospheric stability during different seasons; (a)Spring; (b)Summer; (c)Autumn; (d)Winter; (Unstable: ●, Neutral: ■, Stable: ▲; vertical axis: Relative frequency, horizontal axis: hours of day (GTM))

V. AIR POLLUTION VERSUS STABILITY

Basic assumption here is that the short-term evolution of air pollution in urban area is mainly dependant on atmospheric stability. To reveal the relationship between atmospheric stability and ground-level concentration, monthly average of CO from 2000-2005 is depicted in Fig. 7 where absolute frequency of stable conditions in this period is also demonstrated. It should be noted that carbon monoxide is used as a tracer because: (a) it remains at high values within cities; (b) it is practically inert over urban scales [12].The relatively appropriate correlation between two mentioned parameters is obvious and both graphs have similar trends. For instance, from April to August, where stability is decreased, CO concentration is at lowest levels while from September to November, dominance of stability leads to occurrence of maximum CO concentrations.

Linear regression between absolute frequency of stability and CO concentration in different seasons, is shown in Fig. 8. Strong relationship between air quality and atmospheric stability in summer and rather weak in winter is revealed in Figs. 8-b and 8-d, respectively while in spring and autumn, correlation is fairly weak (Figs. 8-a, 8-c).

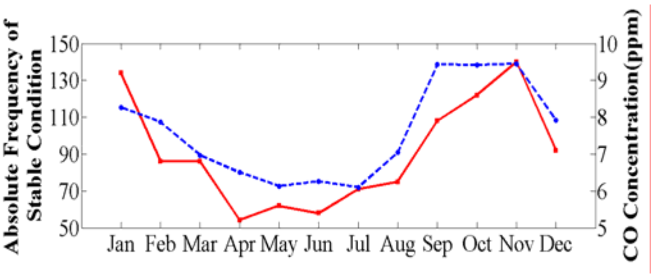


Fig. 7 Time series of absolute frequency of stable conditions and CO concentration for 2000-2005 (Solid line: Stability; Dashed line: CO average concentration)

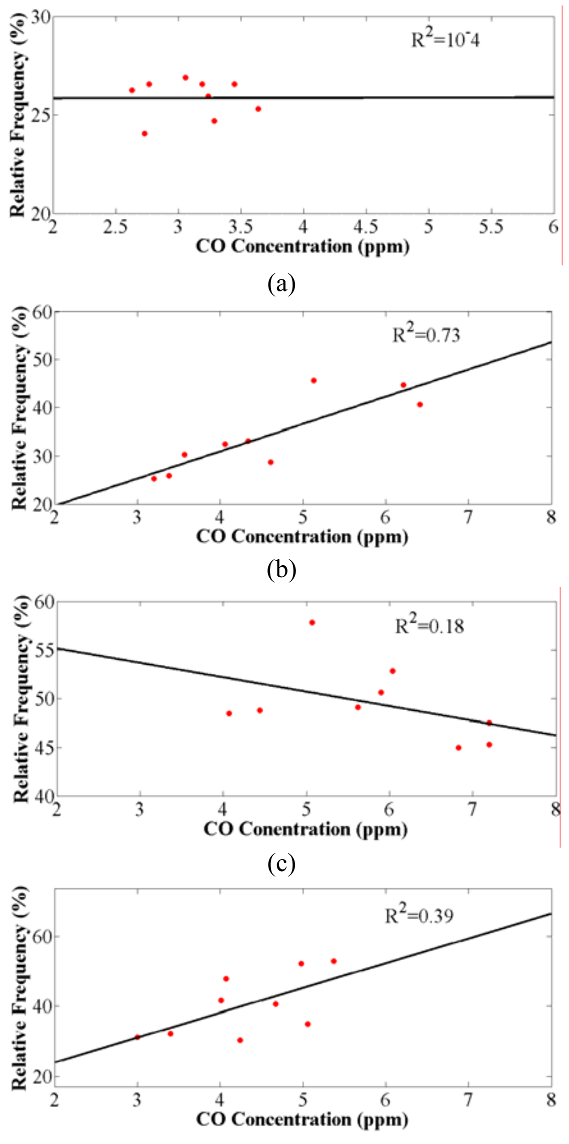
In fact, strong winds in spring and autumn dominate nonlinear character of atmosphere and lead to disappearance of linear dependence between stability and pollution. Inaccuracy of Pasquil-Turner in presence of strong wind could be another reason for weak correlation in these two seasons [1].

The obtained relationship between stability condition and air pollution can be used as a decision support model to modify traffic management schemes in different seasons and months. It must be emphasized that, by this modeling approach, it is intended to forecast the monthly and seasonal trend of pollutant. Thus, it might be possible, in the context of an environmental warning system, to reschedule urban activities in case of critical estimations above air quality standards.

VI. CONCLUSION

This study was an effort to represent a model to determine stability condition of atmosphere using PTM. In comparison with other stability indexes, PTM seems to be a suitable method without complexities of others. This method classifies the atmospheric conditions in seven categories based on wind velocity and net radiation index. Recent parameter is determined as a number between -2 to 4, using a set of routine meteorological data include solar altitude, cloud cover and cloud height. Model is developed by means of FORTRAN90, based on mentioned parameters and is applied on data of Mehrabad meteorological station from 2000 to 2005. Results show the relevance of instability in days and stability at nights with relative frequency of 66.5% and 72.5%, respectively. Instability is decreased from spring to winter in such way that during the autumn most relative frequency (50.69%) for stability is occurred. As a result, based on hourly stability pattern, nights of the autumn have the most risk for pollution accumulation. Hourly evaluation of results reveals that from sunrise to local noon, instability increases and from noon to sunset, it decreases while variation in stability is vice versa.

Evaluation of correlation between stability pattern and CO concentration reveals that a decision support model could be proposed for summer and winter, using linear regression. But for spring and autumn that nonlinear nature of atmosphere is dominant due to presence of strong winds, linear correlation leads to relatively inappropriate results.



(a) (b) (c) (d)

Fig. 8 Correlation between relative frequency of stability and CO concentration in different seasons for 2000-2005; (a) Spring; (b) Summer; (c) Autumn; (d) Winter

ACKNOWLEDGMENT

We gratefully acknowledge University of Tehran and I. R. Iran Meteorological Organization specially Mr. Askari for their cooperation in this research. We also appreciate the useful comments of Professor Benoit Cushman-Roisin that helped us improve the paper.

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