Comparison of Upper Air Mixing Height Estimation Methods for Urban Air Pollution Modeling

Afsana Khandokar, Abdullah Mofarrah[1] and Tahir Husain[2]

[1] Graduate student, Faculty of Engineering and Applied Science, Memorial University, St. John's, NL, A1B 3X5 Canada afsana_shapla@yahoo.com (corresponding author)
[2] Professors, Faculty of Engineering and Applied Science, Memorial University, St. John's, NL, A1B 3X5 Canada

Abstract

Mixing height (MH) is one of the most important parameters requested by different atmospheric pollution models as an input data for forecasting the air quality. When pollutants emitted into the atmospheric boundary layer (ABL), they dispersed horizontally and vertically because of the action of convection and mechanical turbulences until it becomes completely mixed. In spite of the fact that there is still no unique definition and no general accepted method for calculating the mixing height. However, the depth of the mixed layer is defined as the mixing height, which determines the volume available for the dispersion of pollutants. The greater depth of the mixed layer makes larger available volume to dilute the atmospheric pollutants. A number of indirect algorithms for the estimate of MH in upper air in stable conditions are reported in the literature. The aim of this paper is to review the different methods for the upper air mixing height estimate and compared them with the MH derived from radiosonde measurement in order to achieve a critical awareness on their application, and to identify the most suitable methods. Four indirect methods based on surface observations and the standard algorithm used in AERMET pre-processor is used in this case. The meteorological data from Jeddah in Saudi Arabia is considered to demonstrate the proposed methodology.

Keywords: Mixing height, upper air, AERMET pre-processor

1. Introduction

The planetary boundary layer (PBL) is in the lowest part of the troposphere where the air is influenced by the earth's surface and responds to surface forcing such as frictional drag, evapo-transpiration, heat transfer, pollutant emission, and topography (Cooper and Eichinger 1994). Above the PBL is the free atmosphere where the effects of friction from the earth's surface are negligible and the motion of air can be treated as an ideal fluid (Glickman 2000). The PBL is the layer where the earth's surface interacts with the large scale atmospheric flow. Since substances emitted into this layer disperse gradually horizontally and vertically through the action of turbulence, and become completely mixed if sufficient time is given and in the absence of sinks or sources, this layer also called the mixing layer (Seibert et al., 1978).

The PBL height or mixing height (MH) is a key parameter in air pollution models determining the volume available for pollutants to dispersion and the structure of turbulence in the boundary layer (Seibert et al., 2000). In spite of its importance there is no direct method available to determine the MH. The most common methods for determining the MH are utilization of radio-soundings, remote sounding systems and parameterization methods. All these methods have advantages and disadvantages and consider different related or assumed properties of the PBL. Thus, it is relevant to identify and evaluate different techniques or methods in order to lower the inherent uncertainty involved in the determination of the MH. In the present paper, different methods for MH estimate have been evaluated, in order to achieve a critical awareness on their application, and to identify the most suitable methods. The target mixing height was determined using radio-soundings observations. Several diagnostic methods based on surface observations and standard algorithms used in the ARMET pre-processor are used in comparison purpose.

A set of meteorological data in the Jeddah in the city of Saudi Arabia during January to July 2006 in stable conditions, has been collected, including wind and temperature profiles from radio-soundings systems. The values of MH derived from temperature profiles were then compared with the diagnostic estimates. The reliability of the different methods was tested by means of significant statistical indexes (bias, normalized mean square error, linear correlation coincident), and the results are critically discussed.

2.1. Mixing height by Radio-soundings

The meteorological data used in this study were taken for the period of January to July 2006 in Jeddah city in Saudi Arabia. This site is located at 21.42 N and 39.11 E with a height of 17 m above the sea level. It is still a representative of an urban environment due to the large extension of the urbanized area of Riyadh city. The available data are profiles of wind speed and direction, and temperature profiles.

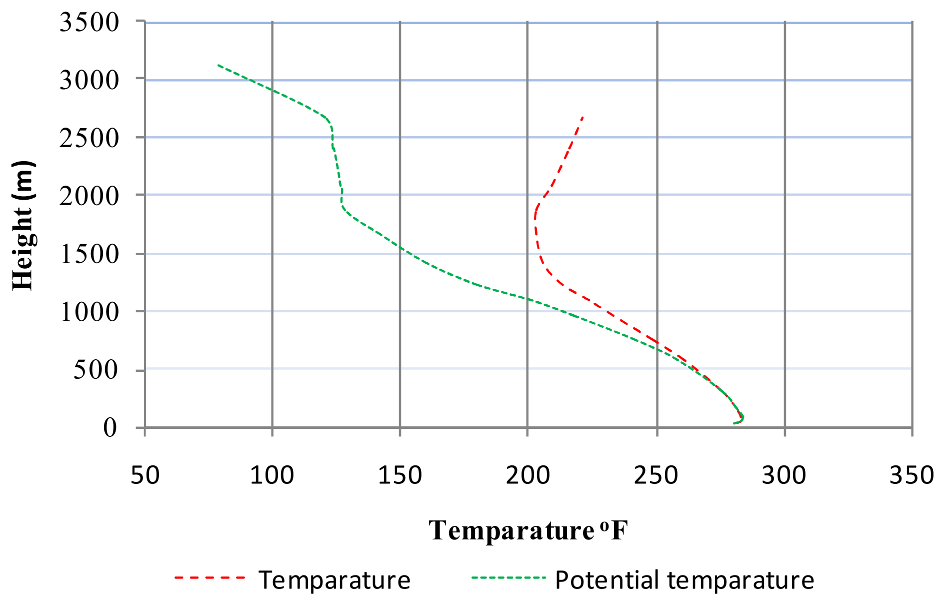

Figure 1 Illustration of the Holzworth-method, temperature profile at Jeddah, 01 January, 6.00 AM, 2006

In convective situations, the MH was estimated from radio-sounding temperature profiles using the Holzworth-method (Holzworth, 1964). The soundings were performed hourly basis during the observation periods. Its principle is to follow the dry adiabatic starting at the surface up to its intersection with the actual temperature profile (Figure. 1). Thus, the method determines the maximum mixing height. This method depends strongly on the surface temperature (Seibert et al., 2000), and a high uncertainty may occur in a situation without a clear inversion at the convective boundary layer top.

2.2. Mixing height diagnostic models

Several diagnostic models in Table 1 were review for the determination of MH. They are based on friction velocity $u*$, and wind speed near the ground, u_{10}. The general expression of these models is as follows:

$$h_1 = \alpha\left(\frac{u^*}{f}\right) + \beta \qquad (1)$$

Where f is the Coriolis parameter was first suggested by Zilitinkevich (1972); later, through the comparison with various sets of observations, different values of the constants α and β have been established (Arya, 1981; Mahrt et al., 1982; Nieuwstadt, 1984). In the present study the computation of mixing heights, according to the above-mentioned models, has been carried out using surface wind speed measurements. The values of friction velocity and Monin-Obukhov length was determined from AERMET pre-processor, under stable conditions. The roughness length z_0 is evaluated considering land use category for urban area, values ranging between 0.5 and 1.5 m have been tested, and since the results are comparable, a value of z_0=1.5 m, used in AERMET MH calculation. The evaluation of MH using diagnostic models is reported in Table 2.

Table 1 Mixing height evaluation diagnostic methods

1.	$h_1 = 0.142\left(\frac{u_*}{f}\right)$	Arya (1981)
2.	$h_2 = 0.089\frac{u_*}{f} + 85.1$	Arya (1981)
3.	$h_3 = 0.06\left(\frac{u_*}{f}\right)$	Mahrt (1982)
4.	$h_4 = 0.4\left(\frac{u_* L}{f}\right)^{0.5}$	Nieuwstadt (1984)

Table 2 Mixing height using diagnostic models

Mixing height	Mean	Standard
h1	752.29	374.64
h2	556.62	234.81
h3	317.87	158.30
h4	1009.96	740.29

3. Results and Discussions:

The available meteorological data such as; wind speed and direction, and temperature profiles were collected from KAAIA stations in Jeddah city. Most values of wind speed, observed during the selected period, are lower than 4 ms-1, with the exception of 30% cases where wind speed ranged from 4.5 to 11 ms-1; the sky was generally clear. The MH values were calculated for the period of January to July with the available data. These include the average values of mixing height at 12:00 and 00:00 (UTC). The 00:00 mixing height values calculated are partially in agreement with those obtained from the dry adiabatic method. Figure 2 and Figure 3 is shown the calculated mixing height (MH) in Jeddah city for January 1st from dry adiabatic process. Figure 3 is shown the calculated morning and afternoon mixing height from

AERMET using surface data of Jeddah city in 2006. As shown in Figure 2 there are no very much difference between the AM and PM mixing height values in summer days. On the other hand, during the winter months (January), the mixing heights are also quite uniform, but show smaller differences. This discrepancy is mainly due to missing data in the data profile. If we analysis Figure 3, MH from surface data, there are big differences in summer days, but winter period has some uniformity. These observations are related to the weather condition, the drastic changes of the surface roughness, and the high level of solar radiation that prevails in Jeddah city. Table 3 is shown the mixing height calculation comparison summary of different diagnostic model, AERMET and upper air observation. From the analysis of diagnostic models for January it shows that equation of *h4* correlates close to AERMET prepossesses and radio- soundings.

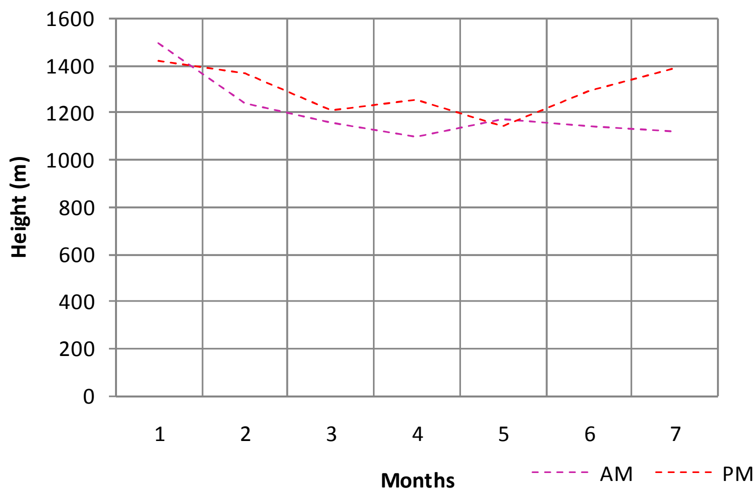

Figure 2 Monthly average mixing heights from radio- soundings

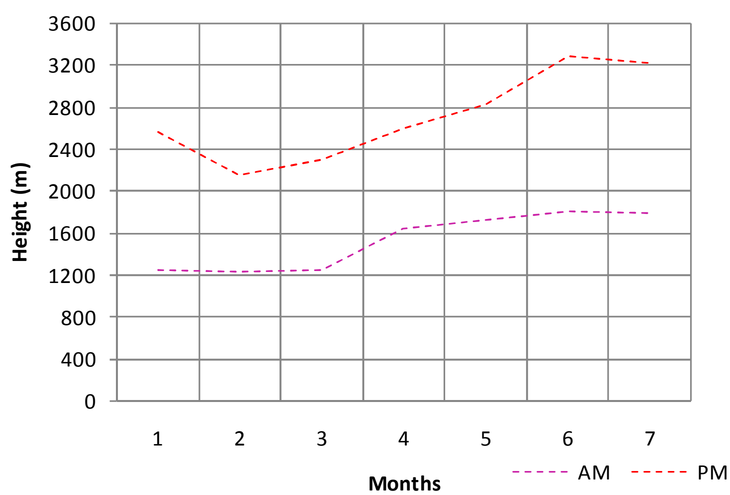

Figure: 3 Monthly average mixing heights from AERMET pre-processor

Table 3 Comparison and correlation of MH evaluated from different methods.

	Radio-soundings	AERMET	h1	h2	h3	h4
Average MH (m)	1247.28	2114.28	752.29	556.62	317.87	1009.96
Standard deviation	118.55	356.25	374.64	234.81	158.3	740.29
Correlation coefficient	0.590	1.000	0.356	0.263	0.150	0.478

4. Conclusion:

The aim of this study was to calculate mixing height in the city of Jeddah for the year 2006. This approach is adopted using the meteorological conditions observed at the surface stations in Jeddah city. There are no any remote sounding methods. The assumption is that these meteorological measurements are representative of the urban area. Estimation of *MH* values based on similarity theory, with respect to surface wind profile data. The test of these diagnostic algorithms indicates that a rash application of them to urban cases could lead to very inaccurate *MH* estimates and, as a consequence, to large errors in the vertical diffusivity and in the ground-level pollutant concentrations. Among the others, the AERMET shows a relatively good performance, but with underestimation or overestimation in low and high wind conditions respectively. For preliminary estimation diagnostic model by Equation 4 may be used. For future studies, mixing height derived here should be compared with different remote sounding systems (i.e., lidars, sodars, RASS, etc) taking into account the impact of terrain irregularities, changes in the surface roughness and surface heat fluxes.

Acknowledge

Financial support provided by the Natural Science and Engineering Research Council of Canada (NSERC) is highly appreciated.

References:

Arya, S. P. S., 1981: Parameterizing the height of the stable atmospheric boundary layer, *J. Appl. Meteorol.* 20, 1192-1202.

Cooper, D.I., and W.E. Eichinger, 1994: Structure of the Atmosphere in an Urban Planetary Boundary Layer from Lidar and Radiosonde Observations, J. Geophys. Res., 99, 22937-22948.

Glickman, T.S., 2000: Glossary of Meteorology. American Meteorological Society, 855 pp.

Holzworth, G.C, 1964: Estimates of Mean Maximum Mixing Depths in the Contiguous United States, Mon. Weather Review, 92, 235-242.

Mahrt, L., Andre«, J.C., Heald, R.C., 1982. On the depth of the Nocturnal Boundary Layer. Journal of Applied Meteorology 21, 90-92.

Nieuwstadt, F.T.M., 1984a: Some aspects of the turbulent stable boundary layer. *Boundary-Layer Meteorology*, 30, 31-55.

Nieuwstadt, F.T.M., 1984b: The turbulent structure of the stable, nocturnal boundary layer. *J. Atmos. Sci*., 41, 2202-2216.

Seibert, P., F. Beyrich and S.E. Gryning (1978): Regional Patterns of Mixing Depth and Stability: Sodar Network Measurements for Input to Air Quality Models, "Bullatine American Meteorological Society" Vol 59, pp 1275-1287.

Seibert, P., F. Beyrich, S.E. Gryning, S. Joffre, A. Rasmussen, and P. Tercier, 2000: Review and Intercomparison of Operational Methods for the Determination of the Mixing Height, Atmos. Environ., 34, 1001-1027.

Zilitinkevich, S.S., 1972: On the determination of the height of the Ekman boundary layer. *Boundary-Layer Meteorol.,* 3, 141-145.