MODELLING AND ESTIMATION OF MIXING HEIGHT FOR BRISBANE AIRSHED

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Abstract The transport and diffusion of pollutants in the urban airshed is highly depend upon the structure of the planetary boundary layer. The turbulent mixing forms and maintains this layer which is directly influenced by the ground conditions. The variation of this height due to diurnal variation of solar radiation, synoptic conditions and local terrain strongly affects pollutant concentrations. A simple one-dimensional model is developed for the estimation of hourly mixing height values from routinely measured upper air and surface meteorological data. The mixing height is modelled by considering convective and mechanically produced boundary layer conditions. In the scheme, for day time hours the mixing depth is determined as the larger of the convective and mechanical mixing height values. At night time hours, only the mechanically produced mixing height values are considered. A diagnostic technique is used in the model to calculate the convective and mechanically induced mixing height values under different atmospheric, and day and night time conditions. Three hourly mixing height values were estimated using once a day upper air temperature profile data and three hourly synoptic meteorological data. The spatial and temporal variation of mixing height values were estimated in the Brisbane airshed and their relationship with the atmospheric stability and transport wind speed was developed. The mixing height values were found to be highly related with the diurnal variation of solar radiation.

1. INTRODUCTION

The transport and diffusion of pollutants in the lower atmosphere is highly depend upon the structure of the planetary boundary layer. Pollutants are mixed nearly uniform throughout this layer by turbulence which results from strong surface heating during the daytime hours. The vertical structure of planetary boundary layer at any location is highly dependent on the ground conditions and surface roughness. The mixing layer is capped by a temperature inversion which hinder entrainment of air above, thereby limiting the height of the mixing. The top of the mixed layer is called the mixing height. The variation of this height due to diurnal variations of solar radiation, synoptic conditions and local terrain strongly affects pollutant concentrations and its dispersion. Over a typical rural location, there is a pronounced daily cycle in the lapse rate in the lowest few hundred meters. On a clear night, earth emits longwave radiation. Most of this radiation passes out to space and since there is no incoming solar radiation, the earth and the lower layers of the atmosphere cool. After sunrise, the night-time inversion is eroded from below by convective mixing. Usually well before noon, the stable inversion is completely replaced by a well-mixed surface layer which prevails until sunset. The cloud cover and strong winds is responsible for weakening the daily cycle. The cloud re-radiates long wave radiation back to earth, with the result that the night-time cooling is lessened. During the day, on the other hand, the cloud reduces the incoming insolation and there is less warming of the surface layer. Strong winds tend to stir the air and reduce the vertical temperature gradients.

The urban temperature regime is quite different due to the mesoscale features which influence the radiation balance. The night time inversion occurs less frequently in a city than in the surrounding countryside. This is due to the urban heat-island effect. A night-time inversion over the suburbs is enhanced by the subsidence, while the inversion over the city is weakened by the rising air. Shoreline also has an effect on the formation of mixing height. Air passing from the ocean to a land surface has its temperature structure changed in the lowest layers. As the air passes over the relatively warm land, heating creates and unstable surface layer, eroding the inversion from below. The unstable layer, therefore, deepens as the air proceeds inland.

Theoretical investigation of the boundary layer has led to the detailed understanding of two separate mixing-depth regimes. These regimes are day-time convective layer and the nocturnal buoyancy layer. The day-time convective layer have been described by the one-dimensional model developed by Zeman and Tennekes (1977), Carson (1973) and Stull (1976). The day-time models require that the surface heat flux be both positive upward and follow some time-dependent behaviour. The above models do not handle the effects of large-scale advection. The nocturnal models require some knowledge of ground surface or soil characteristics and are not applicable in conditions when boundary layer is not cooling. Models developed by Deardorff (1971), Delage (1974) and Blackader (1976) solved the problems associated with the mechanically mixed nocturnal layer using numerical simulation technique. However, these models are generally too sophisticated and difficult to apply for routine operational use.

The US EPA models use an empirical scheme (EPA, 1977) to estimate hourly values of the mixing depth. The scheme is based on a linear interpolation between morning and afternoon mixing depths that are derived from the methods proposed by Holzworth (1967). Holzworth's mixing height estimation does not include the important effect of temperature advection. In addition to that, the US EPA interpolation scheme does not adequately represent the physical process accompanying the diurnal and hourly changes in the depth of the mixed layer. In order to estimate the temporal and spatial variation of mixing height values, we need to have hourly temperature sounding data at several locations in the airshed, which is not feasible due to economical reasons. A simple scale relationship based on easily obtainable surface meteorological data is a better choice. Yu (1978) provided a review and validation study of such formulations. The correlation coefficients he generated emphasise that the simple parameterisation $H_m = CU_*/f$, where U_* is the friction velocity and f the coriolis parameter, is as successful as sophisticated numerical models. The values of constant C in this simple parameterisation range an order of magnitude from about 0.05, suggested by the numerical modelling results of Delage (1974), to 0.35 mentioned by Arya (1981).

2. THE PROPOSED MODEL

The turbulent mixing can be either convective or mechanically produced. In order to estimate hourly mixing height from routinely available upper air and surface meteorological data, a simple one-dimensional model is developed. The proposed scheme for the determination of mixing height in this model needs the upper air sounding records at least once a day (early morning) and hourly surface meteorological data such as temperature, wind speed, sky cover and ceiling height. In the scheme, at all daytime hours the actual mixing depth is determined as the maximum of the convective and mechanical mixing height values determined from the procedure discussed in the following section. The convective mixing height values is set equal to zero for all night time hours. Both mechanical and convective mixing height production usually occur simultaneously in the daytime layer. The larger of the two estimates (convective and mechanically induced mixing height) is chosen as the best estimate for the mixing height model. This choice is based on the assumption that the large estimate will correctly reflect the dominant turbulence generation mechanism. In general, with clear skies, light winds and little temperature advection, the convective depth will be greater of the two values. However, some warming after sunrise may cause the mixing depth computed by the convective method to exceed the depth computed by the mechanical method. During overcast, windy conditions, the mechanical method will produce greater mixing heights. Mixing height due to mechanically produced turbulence for different stability class were determined using the equations discussed in the following section. During the day time, convectively produced mixing height were estimated from the upper air temperature sounding data.

2.1 Mechanically Produced Mixing Height

The formulation for the day-time and nocturnal boundary layer depth have been suggested by various scientists. Arya (1981) provides a summary of diagnostic and prognostic models to parameterise the height of boundary layer. Earlier Deardorff (1971) and recently Pielke (1984) have suggested that the variation of mixing height (H_m) is strongly influenced by surface heating. The prognostic representation for the planetary boundary layer height (or mixing height) is presented by Pielke (1984) as follows:

$$\frac{\partial H_m}{\partial t} = -\bar{u}_H \frac{\partial H_m}{\partial x} - \bar{v}_H \frac{\partial H_m}{\partial y} + \bar{w}_H + \frac{[1.8(w_*^3 + 1.1u_*^3 - 3.3u_*^2 f H_m)]}{\left(g \frac{H_m^2}{\theta_h} \frac{\partial \bar{\theta}}{\partial z} + 9w_*^2 + 7.2u_*^2\right)} , \tag{1}$$

Where w_* is the convective velocity scale which is represented as follows:

$$w_* = \begin{cases} \left(-\frac{g}{\theta_h} u_* \theta_* H_m\right)^{1/3} , & \theta_* \leq 0 \\ 0 , & \theta_* \geq 0 , \end{cases}$$

where $\bar{\theta}_h$ is the potential temperature at the top of the surface layer. The growth of mixing height (H_m) is directly proportional to the surface heat flux and mesoscale vertical velocity and inversely proportional to the overlying stability. If it is assumed that the boundary layer height is unchanging in time and horizontally homogenous, $\theta_* = 0$, and the net radiation flux divergence is zero. Therefore, when

$$\bar{w}_H = 0 , \quad \frac{\partial \bar{\theta}}{\partial z} = 0 , \quad \text{and} \quad \frac{\partial H_m}{\partial t} = 0 ,$$

equation (1) reduces to $H_m = 0.33\ U_*/f$, which is the expected depth of the planetary boundary layer in a steady-state, horizontally homogenous, neutrally stratified boundary layer (i.e. Pasquill stability Category D).

The above relationship is similar to the parameterisation suggested by Yu (1978), where the constant C = 0.33. Therefore, it appears that the form $H_m = CU_*/f$ is most general and most attractive relationship for mixing height calculation under neutral conditions. Plate (1971), on the basis of matching theory derived C = 0.185 for neutral conditions. Benkley (1979) also recommended to use the same value for his model. He suggested that Plate's value of C = 0.185 is most firmly based on theory and falls near the mean of values reported by the other investigators. Therefore, the diagnostic relationship used in the proposed model for Category D is:

$$H_m = 0.185 \frac{U_*}{f} \qquad (2)$$

In order to ensure a coherence with other stability Categories (i.e. A to C unstable and E to F stable atmospheric conditions) researchers have developed different diagnostic relationships. Stull (1989) suggested a simple diagnostic relationship for unstable atmospheric conditions (i.e. Pasquill Stability Class A, B and C) as follows:

$$H_m = -kL \left\{\frac{w_*}{U_*}\right\}^3 \qquad (3)$$

For stable atmospheric condition (i.e. Pasquill Stability Class E and F), Arya (1981) suggested different relationship, which is:

$$H_m = 113 + 0.34 \left[\frac{LU_*}{f}\right]^{0.5} \qquad (4)$$

where H_m is the mixing height, U_* is the friction velocity, f is the Coriolis factor, k is the Von Karbnan Constant, L is the Monin-Obukhov length, and w_* is the convective velocity scale.

The surface friction velocity (U_*) is determined using the straight forward analytical techniques proposed by Wang and Chen (1980) for unstable conditions and Weil and Brower (1983) for stable conditions. To determine Monin-Obukhov length (L) an iteration procedure similar to that described by Koo et. al. (1984) is employed. The values of convective velocity scale (w_*) were determined by the method outlined by Venkatram (1978). The coriolis factor f is defined by $f = 2\,\omega \sin \phi$, where ω is the rate of rotation of th.e earth and ϕ is the latitude of the location. The coriolis factor f takes into account the effect of the earth's rotation which influence the vertical wind shear and thereby the intensity of turbulence and the height of the boundary layer.

2.2 Convectively Produced Mixing Height

During the day time, when convective turbulence is dominant, the mixing height is estimated as the depth of the neutral layer defined by drawing an adiabatic from the surface temperature to an intersection with the morning sounding. Holzworth (1967) and Miller (1967) developed a method for estimating the mixing height which is based on the morning radiosonde observation of the vertical temperature profile and the afternoon surface temperature. Their concept is based upon the principle that heat transferred to the atmosphere at the earth's surface results in convection, vigorous vertical mixing and establishment of a dry-adiabatic lapse rate. The depth through which such mixing takes place depends upon the initial vertical temperature structure and the heat input at the surface.

Since in Brisbane upper-air sounding are made only once (between 8 to 9 am), which is sunup, the day time mixing depths were estimated using upper-air sounding and hourly surface meteorological data. The day time mixing depth values were determined from temperatures profile and the dry adiabatic lapse rate (10°C/km) through the surface temperature. The height at which the dry adiabatic lapse rate (i.e. the line defined by $\Delta T/\Delta Z = 0.01°C/m$) from the day time surface temperature intersects the morning temperature profile provides convectively produce mixing height during the day time. The technique consists of plotting each morning's observed vertical temperature profile and drawing a dry adiabat upward from the observed day time surface temperature. The height at which the two lines intersect provides the day time mixing height. The estimated height defined the lowest level at which the vertical gradient of temperature exhibits a discontinuity. For example, during well-mixed afternoon periods when an adiabatic layer near the ground is capped by a relatively stable inversion layer, the mixing height corresponds to the level of the base of the inversion layer. During a clear, calm night when there is a ground based inversion, the level of mixing height corresponds to the tope of the strong inversion layer.

3. MODEL RESULTS

Five years (Jan 1982 - Dec 1987) synoptic and upper air meteorological data was collected from six meteorological stations in Brisbane airshed. Three hourly mixing height values were estimated for the five years period at six locations. The meteorological parameters such as radiation, prevailing wind direction, wind speed, atmospheric stability and mixing height was analysed to determine the relationship between different variables. The diurnal variation of these parameters during summer and winter period at the Brisbane Airport is presented in Figure 1. A reasonable coherence between mixing height and other meteorological parameters was observed. The Brisbane meteorological conditions are characterised by low wind speed specially during the night time and poor mixing in the period prior to noon. During winter period, the atmosphere was found to remain more stable for an extended period of time. The clear sky conditions in Brisbane in all season (peak summer radiation is close to 500 W/m^2) allow abundant ultraviolet energy to react with the precursors of photochemical smog. The wind regime of Brisbane is also characterised by a diurnal variation of wind direction. The surface wind pattern comprises valley drainage in the morning with a seaward direction and an afternoon sea breeze. Polluted air masses carried out to sea by the night/morning land breeze may return to the land with the after noon sea breeze. Low wind speed from the land and high atmospheric stability (Pasquill stability class F) prevails during the night and morning hours. Consequently, there is a low nocturnal and early morning mixing height values between 350 and 500 m are found in all seasons. More stable atmosphere in winter is reported mainly due to low wind speed.

Mixing height values (in the band of 200 m) and the corresponding wind speed and atmospheric stability category were also analysed for the Brisbane Airport for five years period. The results are presented in Figures 2 and 3 as

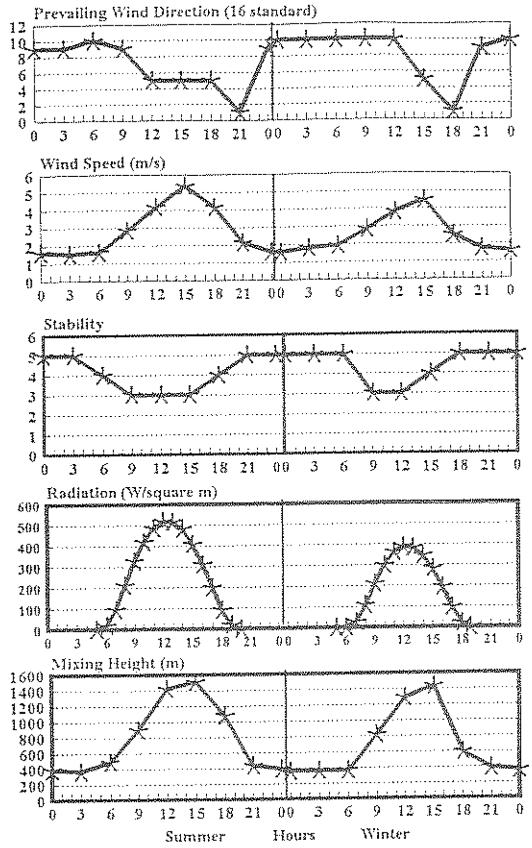

Figure 1. Diurnal variation of wind direction, wind speed, atmospheric stability, radiation and mixing height.

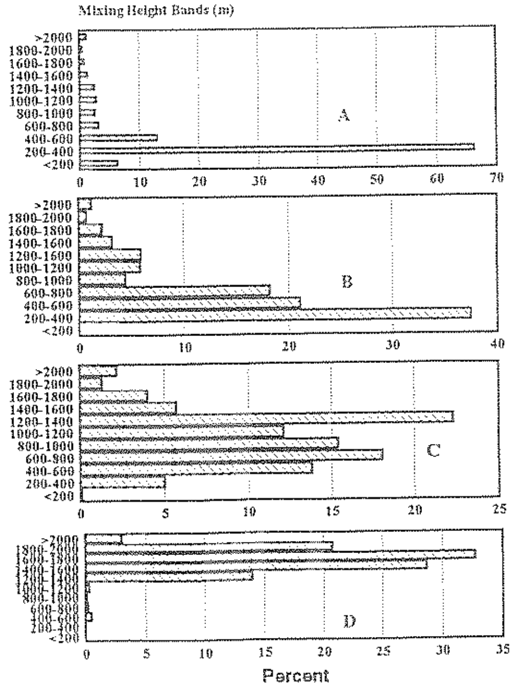

Figure 2. Frequency distribution of mixing height bands by wind speed category.

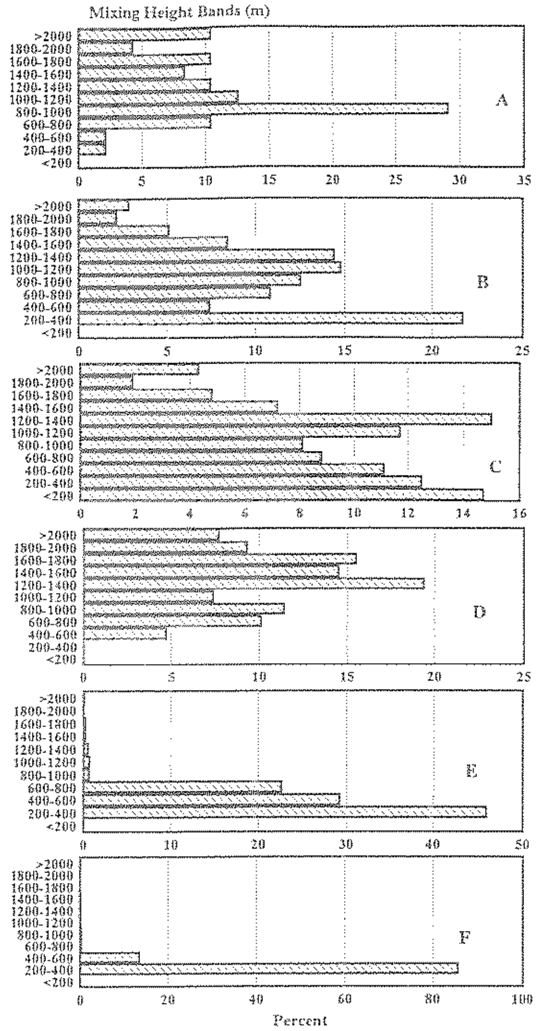

Figure 3. Frequency distribution of mixing height bands by atmospheric stability category.

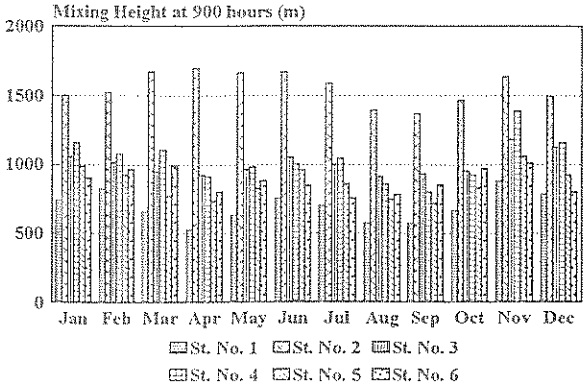

Figure 4. Monthly average mixing height at 9am in all stations.

frequency distribution of mixing height, grouped by wind speed and stability category. The distribution of mixing height for the wind speed category are the most interesting in the context of this work. The wind speed ranges used in this analysis for wind speed category A, B, C, D, and E are: <1.5, 1.5-3, 3-5, 5-8 and >8 m/s respectively. The frequency distribution of mixing height (Figure 2) revealed that when wind speed is less than 1.5 m/s (category A) mixing height most likely (about 67%) is less than 400 m. While in other case when wind speed is in between 5- 8 m/s (category D) mixing height values about 95% of time are in the range of 1200-2000 m. For category E, (not shown in this figure) when wind speed is greater than 8 m/s mixing height is always greater than 2000 m. The reason for getting high mixing height values in wind speed category D and E is due to the significant contribution of mechanically induced mixing height component. The most significant feature of the distributions is the increase in frequency of lower mixing heights with the change from unstable to stable atmospheric conditions (Figure 3). For example, where only 2% of mixing height were below 400 m in stability A, the corresponding value for F stability was 87%. The spatial distribution of mixing height values in the Brisbane airshed was also analysed using 9 am data of six stations for five years period (Figure 4). Monthly average mixing height values were estimated for each station. Lowest mixing height values were observed at the Amberly (Station No. 1) location throughout the year. This station is located inland about 80 Km from the sea shore and has a very low altitude (27 m above MSL). A consistent low wind speed is recorded at this location. This analysis shows that Brisbane has a high potential for air pollution, because of its low wind speed, high atmospheric stability and low mixing height conditions.

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