NOWCASTING MIXING HEIGHT AND VENTILATION FACTOR FOR RAPID ATMOSPHERIC DISPERSION ESTIMATES ON LAND

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Abstract

On the basis of boundary-layer parameterization schemes published in the open literature, several value-added atmospheric dispersion criteria are developed for rapid estimation of mixing height and ventilation factor. It is shown that when the wind speed measured by the Automated Surface Observing System (ASOS) at airports exceeds 6 m s^{-1} *(12 kt) under neutral conditions during day or night, the dispersion potential is good. During the night when the wind speed is less than 4 m s*$^{-1}$ *(8 kt), the ability of the atmosphere to disperse pollutants is poor. Under unstable conditions during the day when the wind speed is less than 5 m s*$^{-1}$ *(10 kt), the dispersion potential is found to be variable depending on the wind speed. Specific formulas to estimate mixing height and ventilation factor as a function of stability classes required for dispersion model inputs are also summarized for operational use.*

1. Introduction

From the viewpoints of homeland security and emergency preparedness, operational meteorologists will inevitably be called upon to provide "educated" meteorological inputs so that pertinent analytical or numerical models can be run. According to Arya (1999), the mixing height or the planetary boundary layer (PBL) depth (h) is the most important parameter, which not only determines the limit on the vertical diffusion of the plume or puff of materials released, but also determines a host of other parameters and scales related to turbulence and diffusion. According to Turner (1994), the primary inputs to a dispersion model consist of emission information, meteorological data, and receptor information. The meteorological parameters that are required for input to a dispersion model are hourly Pasquill stability class, wind direction, wind speed, temperature, and mixing height.

The purpose of this study is to provide information for rapid estimation of both mixing height and ventilation factor, since other parameters such as wind and temperature are routinely measured by ASOS at airports. Note that the ventilation factor is defined as the product of wind speed and mixing height. This air pollution dispersal index (see Table 1) has been used for forecasting purposes by the State of Colorado Department of Health in Denver (Eagleman 1996).

2. Nowcasting The Mixing Height

For atmospheric dispersion on land, the Pasquill Stability Classification has been the most widely used. The scheme is provided in Table 2, which was originally developed by Pasquill (1961). Note that during overcast conditions or when the wind speed exceeds 6 m s^{-1} (~12 kt), the stability is mainly or near neutral, meaning that the mechanical turbulence is dominant. Unstable conditions prevail when heat convection dominates. Stable conditions exist when mechanical turbulence is dampened by temperature stratification (Panofsky and Dutton 1984).

a. Under near-neutral conditions

As shown in Table 2, Class D prevails when the wind speed exceeds 6 m s^{-1} (12 kt) or the sky is overcast during day or night. Panofsky and Dutton (1984) suggest that

$$h_D = 0.17 \frac{u_*}{f} \qquad (1)$$

where h_D is the mixing height for Class D, u_* is the friction velocity and f is the Coriolis parameter.

In the atmospheric boundary layer, the variation of wind speed with height can be estimated by the following power-law wind profile (Irwin 1979):

$$U_Z = U_{10}\left(\frac{Z}{10}\right)^P \quad \textit{for } Z < 200\ m \qquad (2a)$$

$$U_{200} = U_{10}\left(\frac{200}{10}\right)^P \quad \textit{for } Z \geq 200\ m \qquad (2b)$$

where U_Z is the wind speed at a different height Z other than the typical ASOS anemometer at 10 m, and P is the exponent that varies with the stability (Table 3). Note that for heights greater than 200 m, the value at 200 m should by used as shown in Eq. (2b) (Irwin 1979).

According to Hsu (1988),

$$u_* = \kappa P U_{10} \qquad (3)$$

where κ(=0.4) is the von Karman constant. Note that Eq. (3) varies not only with U_{10} but also stability, which is reflected in P according to Table 3.

Table 1. Pollution Dispersion Forecast Categories Related to Atmospheric Ventilation (product of wind speed and mixing height) (after Eagleman 1996).

Pollution Dispersion	Ventilation ($m^2 s^{-1}$)
Poor	0 - 2000
Fair	2001 - 4000
Good	4001 - 6000
Excellent	6001 or more

Table 2. Meteorological Conditions Defining Pasquill Turbulence Types (after Hanna et al. 1982).

A: Extremely Unstable
B: Moderately Unstable
C. Slightly Unstable
D: Neutral*
E: Slightly Stable
F: Moderately Stable

Surface Wind speed, $m s^{-1}$	Daytime isolation Strong	Moderate	Slight	Nighttime Conditions** Thin overcast or >4/8 low cloud	≤3/8 cloudiness
< 2	A	A - B	B		
2 - 3	A - B	B	C	E	F
3 - 4	B	B - C	C	D	E
4 - 6	C	C - D	D	D	D
> 6	C	D	D	D	D

*Applicable to heavy overcast day or night.
**The degree of cloudiness is defined as that fraction of the sky above the local apparent horizon that is covered by clouds.
Note: "Strong" incoming solar radiation corresponds to a solar altitude greater than 60° with clear skies; "slight" insolation corresponds to a solar altitude from 15° to 35° with clear skies. Table 170, Solar Altitude and Azimuth, in the Smithsonian Meteorological Tables (List 1984), can be used in determining the solar altitude (Hsu 1988).

Table 3. Values of the Parameter P For Estimating the Wind Speed at Various Heights (after Irwin, 1979).

Stability Class	Urban	Rural
A	0.15	0.07
B	0.15	0.07
C	0.20	0.10
D	0.25	0.15
E	0.40	0.35
F	0.60	0.55

Now, substituting κ(=0.4), P (= 0.15) for the rural area where the airport is typically located, and f (~ 10^{-4} for mid-latitude approximation), Eq. (1) becomes

$$h_D = 102\, U_{10} \tag{4}$$

where h_D is in meters and U_{10} in m s^{-1}.

b. Under unstable conditions

Unstable conditions prevail when heat convection is dominant. According to Zannetti (1990),

$$h_{unstable} = \kappa\left(-L\right)\left(\frac{w_*}{u_*}\right)^3 \tag{5}$$

where $h_{unstable}$ stands for the mixing height under unstable conditions, L is the Monin-Obukhov stability length, and w_* is the convective velocity, which is related to the standard deviation of the vertical velocity (σ_w) (Arya 1999) by

$$\frac{\sigma_w}{w_*} = 0.60 \tag{6}$$

Substituting Eq. (6) into (5) we have

$$h_{unstable} = 0.4\left(-L\right)\left(\frac{\sigma_w}{0.6\, u_*}\right)^3 \tag{7}$$

From Zannetti (1990), no single value is provided for (σ_w / U_{10}) under stability B and C conditions, but it ranges from 0.1 to 0.15. If one takes the mean σ_w / U_{10} and L between Classes B and C from Zannetti (1990) and Hanna et al. (1985), they are $\sigma_w / U_{10} = 0.125$ and L = -12.5 m, respectively. Substituting these values into Eq. (7), one obtains

$$h_{B,C} = 0.4\left(12.5\right)\left(\frac{0.125}{0.6}\frac{U_{10}}{u_*}\right)^3 \tag{8}$$

where $h_{B,C}$ stands for the mixing height under stability Classes B and C.

From Eq. (3) and P = 0.085 (from Table 3) for the average value between Classes B and C (Rural), we have

$$\frac{U_{10}}{u_*} = \frac{1}{\kappa P} = \frac{1}{\left(0.4\right) * \left(0.085\right)} = 29 \tag{9}$$

Substituting Eq. (9) into (8) yields

$$h_{B,C} = 1103\ m \tag{10}$$

This value is in reasonable agreement with the one commonly cited that when L = -10 m, $h_{unstable}$ is approximately 1000 m (Panofsky and Dutton 1984).

c. Under stable conditions

In stable nighttime conditions at mid-latitudes, Venkatram (1980) has proposed the following formulas for L and h

$$L_{stable} = 1.1 * 10^3 u_*^2 \tag{11}$$

and

$$h_{stable} = 2.4 * 10^3 u_*^{3/2} \tag{12}$$

where L_{stable} and h_{stable} are the values L and mixing height under stable conditions, respectively.

Now, solving Eq. (11) and (12) simultaneously by eliminating u_*, we have

$$h_{stable} = 2.4 * 10^3 \left(\frac{L_{stable}}{1.1 * 10^3} \right)^{3/4} \tag{13}$$

From Hanna et al. (1985), L = 17.5 m and 7.5 m for stability Classes E and F, respectively. Substituting these values into Eq. (13), we get

$$h_E = 108\ m \tag{14}$$

and

$$h_F = 57\ m \tag{15}$$

3. Nowcasting the Ventilation Factor

As discussed in the Introduction, the ventilation factor (VF) is defined as

$$VF = \bar{u} * h \tag{16}$$

where $\bar{u}$ is the mean wind speed (m s^{-1}) in the mixed layer and h is the mixing height (m).

a. Under neutral conditions

From Table 2, Class D prevails when $U_{10} \geq 6$ m s^{-1}. Substituting this value into Eq. (4), $h_D > 200$ m. Therefore, Eq. (2b) should be employed, and, using P = 0.15 from Table 3,

$$\bar{u}_{200} = U_{10} \left(\frac{200}{10} \right)^{0.15} = 1.57\, U_{10} \tag{17}$$

Substituting Eq. (17) into (16), we have

$$VF_D = \left(1.57\, U_{10}\right)\left(102\, U_{10}\right) = 160\, U_{10}^2 \tag{18}$$

Because Class D prevails when $U_{10} \geq 6$ m s^{-1}, $VF_D > 5755$. From Table 1, this is in the "Good" category.

b. Under unstable conditions

According to Eq. (10), the mixing height is approximately 1 km, which is higher than 200 m. Thus, we use Eq. (2b) for $h_{B,C}$ and again setting P = 0.085 for the mean of Classes B and C, so that

$$\bar{u}_{200\, m} = 1.29\, U_{10} \tag{19}$$

Thus, from Eqs. (19) and (10), we have

$$VF_{B,\,C} = 1.29\, U_{10} * 1103 = 1423\, U_{10} \tag{20}$$

where $VF_{B,C}$ represents the VF under stability Classes B and C.

c. Under stable conditions

Equations (14) and (15) indicate that both mixing heights from Classes E and F are lower than 200 m. From Eq. (2a) and Table 3 for Class E, if we assign Z = 54 m as the mid-point of the mixed layer (h_E / 2) and set P = 0.35 (Table 3),

$$\bar{u}_E = U_{10} \left(\frac{54}{10} \right)^{0.35} = 1.80\, U_{10} \tag{21}$$

Thus

$$VF_E = 1.80\, U_{10} * 108 = 195\, U_{10} \tag{22}$$

Similarly, from Eqs. (15) and (2a) and Table 3, Z = 29 m (h_F / 2), and P = 0.55 gives

$$\bar{u}_F = U_{10} \left(\frac{29}{10} \right)^{0.55} = 1.80\, U_{10} \tag{23}$$

and

$$VF_F = 1.80\, U_{10} * 57 = 102\, U_{10} \tag{24}$$

Because $U_{10} < 4$ m s^{-1} for Classes E and F, Table 1 indicates that the VF are in the "Poor" category.

4. Summary and Conclusions

On the basis of the foregoing analyses, the results are summarized in Table 4. Equipped with this information and Table 1, an operational meteorologist is able to rapidly provide "educated" estimates of both mixing height and ventilation factor for emergency preparedness officers, who can in turn run dispersion models. As indicated in Table 4, the only required input for these estimations is the wind speed measurement from an ASOS site located in the flat open country.

Table 4. A Summary for the Rapid Estimation of Mixing Height and Ventilation Factor as a Function of Stability Class.

Stability Class	Mixing Height (in meters)	Ventilation Factor	Dispersion Potential (see Table 1)
B C	[1103]	[1423 U_{10}]	[varies with U_{10}]
D	102 U_{10}	160 U_{10}^2	Good
E	108	195 U_{10}	Poor
F	57	102 U_{10}	Poor

Notes:
1) U_{10} (in m s^{-1}) is the wind speed measurement from an ASOS site.
2) 1 m s^{-1} = 1.94 kt = 2.24 mph or 1 mph = 0.446 m s^{-1}.

The basic equations used in this study are all based on "open literature", and the purpose of this research is a "value-added" study. It is concluded that during the nights when Classes E and F prevail, the ability for the atmosphere to disperse pollutants is poor. When $U_{10} > 6$ m s^{-1} or under overcast conditions, Class D exists, so the dispersion is good. Under unstable conditions during the day when winds are light, the dispersion power is found to be variable depending on the wind speed. If $U_{10} > 2$ m s^{-1}, the ventilation factor exceeds 2000, and the dispersion potential will be at least fair.

Author

Dr. S. A. Hsu has been a Professor of Meteorology at Louisiana State University since 1969, after he earned his Ph.D. in Meteorology from the University of Texas at Austin. He is the author of *Coastal Meteorology* (Academic Press, 1988) and numerous papers on coastal and marine meteorology and air-sea interaction. Dr. Hsu is also an AMS Certified Consulting Meteorologist. Dr. Hsu can be contacted at the LSU Coastal Studies Institute, 308 Howe-Russell Geoscience Building, Baton Rouge, Louisiana 70803-7527;
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