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Monthly Dispersion Characteristics over the South China Sea for Air Quality Modeling

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Abstract—Monthly dispersion characteristics for air quality modeling over the South China Sea offshore the west coast of Borneo are studied using long-term ship measurements. It is found from monthly averages that the stability condition is nearly neutral throughout the year with the exception of April, May, and November which are slightly unstable. The lifting condensation level ranged from 338 to 450 m. The lowest value of the ventilation factor occurred in April and the highest in January. The friction velocity for each month is also provided to determine the vertical eddy diffusivity and horizontal and vertical dispersion coefficients.

Key words: Dispersion characteristics, South China Sea, mixing height, ventilation factor, friction velocity.

1. Introduction

In order to study the air quality in the offshore region, atmospheric dispersion models may be used. However, nearly all models require the following basic input parameters: Atmospheric stability classification; the dispersion coefficients in the horizontal (crosswind) and vertical directions; the vertical eddy diffusivity (which requires friction velocity formulation) in some diffusion models; and the atmospheric mixing height.

Over the South China Sea off the west coast of Borneo there are long-term records of monthly climatological data including air temperature, sea temperature, relative humidity, and wind speeds (see Table 1). The data source is based on the publication by U.S. Naval Weather Service Command (1975). The purpose of this paper is to employ these data to determine those basic input parameters for air quality modeling over the South China Sea. Some discussion of dispersion characteristics onshore along the west coast of Borneo are provided in Hsu (2003).

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Table 1

Measured and Computed Parameters for Monthly Overwater Dispersion Estimates off the West Coast of Borneo in the South China Sea

Month	T_{air} (°C)	T_{sea} (°C)	RH%	U_Z (m s^{-1})	B	Z/L	Stability Class	LCL (m)	VF (m^2 s^{-1})	u_* (m s^{-1})
Jan	26.8	27.2	84	5.3	0.093	−0.078	D	363	2571	0.18
Feb	26.7	26.9	84	5.0	0.066	−0.051	D	363	2425	0.18
Mar	27.2	27.6	85	3.9	0.093	−0.143	D	338	1749	0.16
Apr	28.2	28.7	82	2.5	0.104	−0.414	C	413	1398	0.14
May	28.4	29.3	81	2.4	0.139	−0.727	C	450	1474	0.15
Jun	28.2	28.9	82	3.0	0.123	−0.378	D	413	1677	0.15
Jul	28.2	28.7	81	3.1	0.104	−0.270	D	450	1905	0.15
Aug	28.0	28.8	82	3.4	0.131	−0.329	D	425	1962	0.16
Sep	27.9	28.7	81	3.1	0.131	−0.396	D	450	1905	0.15
Oct	27.7	28.7	83	3.7	0.146	−0.335	D	400	1997	0.16
Nov	27.3	28.4	84	3.3	0.153	−0.457	C	363	1601	0.16
Dec	26.9	27.8	85	4.8	0.139	−0.183	D	350	2223	0.18

T_{air} = Air temperature; Z/L = Monin-Obukhov stability parameter; T_{sea} = Sea temperature; LCL = Lifting condensation level; RH = Relative humidity; VF = Ventilation factor; U_Z = Wind speed measured by ships; u_* = Friction velocity; B = Bowen ratio

2. *Determining the Stability Classification*

The atmospheric stability for dispersion estimates can be classified by the parameter Z/L, where Z is the height above the ground and L is the Monin-Obukhov length, which is defined as (PANOFSKY and DUTTON, 1984, p. 132)

$$L = -\frac{u_*^3 \rho C_p T_{air}}{g\kappa H\left(1 + \frac{0.07}{B}\right)} \tag{1}$$

where u_* is the friction velocity, g is the gravitational acceleration, κ is the von Karman constant, ρ is the air density, C_p is the specific heat of air at constant pressure, T_{air} is the air temperature, H is the surface layer sensible heat flux, and B is the Bowen ratio (the ratio of sensible to latent heat flux). Note that T_{air} should be T_v, the virtual temperature. However, since $T_v = T_{air}(1 + 0.68\, q)$ and q is at most 5% (see, e.g., KOMEN *et al.*, 1994, p. 59), we use $T_v \cong T_{air}$.

From Eq. (1) and SMITH (1980, Eqs. 3 and 4)

$$\frac{H}{\rho C_p} = C_T U_{10}(T_{sea} - T_{air}) \tag{2}$$

and

$$C_d = \left(\frac{u_*}{U_{10}}\right)^2 \tag{3}$$

or $u_*^3 = U_{10}^3 \, C_d^{3/2}$. Since, from monthly averages $T_{\mathrm{sea}} > T_{\mathrm{air}}$, i.e., unstable conditions prevail,

$$L = -\frac{T_{\mathrm{air}} \, C_d^{3/2} \, U_{10}^2}{g\kappa \, C_T (T_{\mathrm{sea}} - T_{\mathrm{air}}) \left(1 + \frac{0.07}{B}\right)} \tag{4}$$

where C_T is the heat flux coefficient ($= 1.1 \times 10^{-3}$ for unstable conditions (SMITH, 1980 and 1988)), C_d is the drag coefficient, U_{10} is the wind speed at 10 m above the sea surface, and T_{sea} is the sea-surface temperature.

On the basis of thermodynamic conditions, a relationship between B and $(T_{\mathrm{sea}} - T_{\mathrm{air}})$ under unstable conditions (i.e., $T_{\mathrm{sea}} > T_{\mathrm{air}}$) has been proposed by HSU (1998) that

$$B = a \, (T_{\mathrm{sea}} - T_{\mathrm{air}})^b \tag{5a}$$

where a and b are to be determined by field experiments. Based on the availability of additional data sets from tropical oceans and coastal seas, HSU (1999) found

$$B = 0.146 \, (T_{\mathrm{sea}} - T_{\mathrm{air}})^{0.49} \tag{5b}$$

with a high correlation coefficient of 0.94 between B and $(T_{\mathrm{sea}} - T_{\mathrm{air}})$. We can now estimate Z/L from Eq. (4) by employing this B parameterization along with a proven C_d formulation used successfully in the third generation wave model (see WAMDI, 1988, p. 1784) that

$$C_d = \begin{bmatrix} 1.2875 \times 10^{-3}, & U_{10} < 7.5 \text{ m s}^{-1} \\ (0.8 + 0.065 \, U_{10}) \times 10^{-3}, & U_{10} \geq 7.5 \text{ m s}^{-1} \end{bmatrix} . \tag{6}$$

Since the location of anemometers on each ship may vary from approximately 10 m to 20 m depending on the vessel size, we can estimate the difference in wind speed between these two heights. According to HSU (1988) and HSU *et al.* (1994), the power-law wind profile may be applied for offshore applications. That is

$$\frac{U_{20\text{ m}}}{U_{10\text{ m}}} = \left(\frac{20 \text{ m}}{10 \text{ m}}\right)^{0.1} = 1.07 \ . \tag{7}$$

Therefore the difference is within 10%. On the other hand, according to the NATIONAL DATA BUOY CENTER (1990), the total system accuracy of wind speed measurement on buoys can be 10%. Since the wind speed difference between 10 and 20 m height is within 10%, we set $Z = 10$ m here as routinely done for air-sea interaction studies.

Now, values of Z/L can be computed from Eq. (4). Since $T_{\mathrm{sea}} > T_{\mathrm{air}}$ throughout the year, Z/L is negative. The results are listed in Table 1. According to the stability criterion for "L" from the "Offshore and Coastal Dispersion (OCD) Model" set by HANNA *et al.* (1985), and converted to "Z/L" categories by HSU (1992), the letter designation of stability class is also provided in the table. It can be seen that with the exception of April, May, and November which are in the slightly unstable (C) category, the rest of the year exhibits near-neutral (D) stability conditions. Note that for Class D, $|Z/L| < 0.4$ and for Class C, $-1.0 \leq Z/L \leq -0.4$ (for more detail, see Hsu (1992)).

3. *Determining the Mixing Height*

Due to actual evaporation, the air over the water is usually moister than that over land, and the top of the marine boundary layer is often times capped by clouds. On the basis of analysis of vertical soundings by research aircraft, rawinsondings, and radar wind profilers and Radio Acoustic Sounding Systems (RASS), it has been shown by Garratt (1992) that the mixing height can be approximated by the lifting condensation level (LCL) under cumulus cloud conditions (where LCL = cloud base). Note that the LCL is defined as the level in the atmosphere at which an unsaturated air parcel lifted dry adiabatically (i.e., at the rate $\approx -1\,^{\circ}\mathrm{C}/100$ m) would become saturated, i.e., for formation of clouds. According to Hsu (1998) under near-neutral conditions, the height of the LCL may be estimated by

$$H_{\mathrm{sea}} = 125(T_{\mathrm{air}} - T_{\mathrm{dew}}) \qquad (8)$$

where H_{sea} (in meters) is the mixing height over the water surface, and T_{air} and T_{dew} (in °C) are the air and dewpoint temperatures, respectively. However, if the clouds are stratiform (as is often the case over the U.S. West Coast), the height of the cloud top rather than the base is the mixing height.

From the monthly averages of air temperature and relative humidity as provided in Table 1, T_{dew} can be computed using the Smithsonian Meteorological Tables (List, 1984). Using these monthly T_{air} and T_{dew} values, the mixing height is obtained via Eq. (8) and listed in Table 1. It can be seen that the LCL ranges from 338 m to 450 m with lowest values occurring in March and highest in May, July, and September, respectively.

4. *Determining the Ventilation Factor*

The ventilation factor, VF, is defined as the product of the wind speed and mixing height; that is

$$\text{Ventilation Factor} = \mathrm{LCL} \times U_{\text{mixed layer}} \qquad (9)$$

where $U_{\text{mixed layer}}$ is the mean wind speed in the mixed layer, i.e., in the mid-level of LCL, or 0.5 LCL,

$$\frac{U_{\text{mixed layer}}}{U_{10\ \mathrm{m}}} = \left[\frac{(1/2\mathrm{LCL})}{10\ \mathrm{m}}\right]^{0.1} = \left(\frac{\mathrm{LCL}}{20}\right)^{0.1} . \qquad (10)$$

From data provided in Table 1 for $U_Z = U_{10\,\mathrm{m}}$ and LCL, values of VF are determined from Eq. (9) via Eq. (10) and compiled in Table 1. From the viewpoint of monthly averages, Table 1 shows that the lowest VF occurred in April and the highest in January.

5. Determining the Friction Velocity

In some *K*-diffusion models (see, e.g., ZANNETTI, 1990), the vertical eddy diffusivity, K_z, is required,

$$K_z = \kappa\, u_*\, Z\left(1.1 - \frac{Z}{H_{\mathrm{sea}}}\right) \quad , \tag{11}$$

where κ is the von Karman constant, u_* is the friction velocity and H_{sea} is the mixing height. For example, the Urban Airshed Model (UAM), one of the preferred models of the U.S. EPA for ozone studies, has a meteorological preprocessing subroutine which employs the gradient transport (*K*) modeling. In order to estimate the standard deviations of lateral and vertical winds, i.e. σ_v and σ_w, u_* is also needed along with Z/L and the mixing height (see, e.g., PANOFSKY and DUTTON, 1984). They are, when $Z/L < 0$,

$$\frac{\sigma_v}{u_*} = \left(12 - 0.5\frac{Z_i}{L}\right)^{1/3} \tag{12}$$

and

$$\frac{\sigma_w}{u_*} = 1.25\left(1 - 3\frac{Z}{L}\right)^{1/3} \tag{13}$$

where Z_i is the mixing height.

In the atmospheric surface boundary layer, u_* can be estimated by (see, e.g., GARRATT, 1992)

$$u_* = \kappa\, U_Z\left[\frac{\kappa}{\sqrt{C_{DN}}} - \psi_m\left(\frac{Z}{L}\right)\right]^{-1} \quad . \tag{14}$$

According to HSU *et al.* (1999), for overwater applications under unstable conditions when $Z/L < 0$,

$$\psi_m\left(\frac{Z}{L}\right) = 1.05\left(-\frac{Z}{L}\right)^{0.46} \tag{15}$$

and from Table 1 and YELLAND and TAYLOR (1996), when $U_Z \leq 6$ m s^{-1},

$$10^3\, C_{DN} = 0.29 + \frac{3.1}{U_{10}} + \frac{7.7}{U_{10}^2} \quad . \tag{16}$$

Monthly averaged values of u_* as computed from above formulas are provided in Table 1. They range from 0.14 to 0.18 m s^{-1}. These u_* values along with the mixing height and Z/L estimates as provided in Table 1 can be used to compute σ_v and σ_w via Eqs. (12) and (13), respectively. Furthermore, these σ_v and σ_w can be input into dispersion equations to calculate σ_y and σ_z, the horizontal (lateral) and vertical dispersion coefficients used in Gaussian distribution modeling.

6. Conclusions

In order to improve air quality modeling over the South China Sea offshore from the west coast of Borneo, long-term meteorological measurements (on the time scale of monthly averages) from ships are employed. Those monthly averages used here include air temperature, sea temperature, wind speed, and relative humidity. For climatological estimation, monthly data are analyzed. Determination of the stability parameter shows that, in our study area, Z/L ranges from -0.05 to -0.7. Application of the U.S. EPA approved "Offshore and Coastal Dispersion (OCD) Model" stability classification indicates that "D" class for near-neutral conditions generally prevails except for April, May, and November at which time "C" class for slightly unstable is observed.

Using these near-neutral stability conditions, the mixing height can then be estimated based on the lifting condensation level (LCL), determined from the surface dewpoint depression. The range of LCL heights are found to be between 338 and 450 m. For pollution dispersion estimation, the ventilation factor, VF, for each month is also determined. The VF is the product of the wind speed in the middle of the mixing height (calculated from the power-law wind profile) and the LCL height. It is found that the pollution dispersal ability in our study area is lowest in April and highest in January.

In order to provide the modeller with recent advances in air-sea interaction for the drag coefficient formulation, the monthly averaged friction velocity, u_*, is also estimated. It can be used along with the LCL and Z/L for each month to estimate the vertical diffusion eddy diffusivity, K_z, and the standard deviation of crosswind and vertical dispersion coefficients, σ_y and σ_z.

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