A GUST-FACTOR CRITERION FOR RAPID DETERMINATION OF ATMOSPHERIC STABILITY AND MIXING HEIGHT FOR OVERWATER DISPERSION ESTIMATES

S. A. Hsu

Coastal Studies Institute
Louisiana State University
Baton Rouge, Louisiana

Abstract

In order to estimate atmospheric pollution concentration downwind from its source, meteorological models (numerical, analytical, or graphical) are usually employed. Included in the model inputs are atmospheric stability and mixing height, which are not routinely measured in the marine environment. On the basis of relationships amongst gust factor, turbulence intensity, and stability parameter, methods are developed for rapid estimation of these two inputs. It is found that, based on the stability classification of the Offshore and Coastal Dispersion Model, when the gust factor (G, which is the ratio of peak gust to the sustained wind speed) is between 1.15 and 1.45, the stability is near-neutral. When G is less than 1.15, it is stable, and for G greater than 1.45, unstable. Using routine buoy measurements as a composite characteristic, equations for the mixing height under various stability classes are also formulated.

1. Introduction

Numerous waterways, marinas, ports, and coastal and offshore facilities (such as oil platforms) are vulnerable if an incidental release of hazardous material occurs. There is a definite need in the component of our homeland security to have a quick response plan to better estimate the concentration downwind from the point of release. In this regard, meteorologists will be inevitably called upon to assist.

The dispersion of atmospheric pollutants, whether chemical, biological, or nuclear, depends principally on the information of emission and meteorology. Estimates of air pollutant concentrations at receptors can be made using dispersion models. The purpose of a dispersion model is to simulate atmospheric chemistry and physics. 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 stability class and mixing height using routine meteorological measurements from buoys. Specifically, in order to estimate the stability class, the routinely measured gust factor is used.

2. Estimating Overwater Stability Categories

Atmospheric stability in the surface boundary layer is broadly classified into three categories. When the sea-surface temperature, T_{sea}, is higher than the air temperature, T_{air}, (i.e., $T_{sea} > T_{air}$), we say it is under unstable conditions. When $T_{air} \sim T_{sea}$, near-neutral condition prevails. When $T_{air} > T_{sea}$, stable conditions exist. On the basis of an offshore and coastal dispersion model (Hanna et al. 1985), Hsu (1992) provided a criterion which is further simplified for this study as follows:

$$\frac{z}{L} \le -0.4 \qquad \textit{Unstable} \qquad (1)$$

$$-0.4 < \frac{z}{L} < 0.4 \qquad \textit{Near Neutral} \qquad (2)$$

$$0.4 \le \frac{z}{L} \qquad \textit{Stable} \qquad (3)$$

where z is the height above the sea surface and is conventionally set to 10 m. Parameter L is called the Monin-Obukhov Stability length (Panofsky and Dutton 1984). The value of L is as follows (Hanna et al. 1985): for unstable, -25 m $\le$ L; neutral, $|L| > 25$ m; and stable, $L \le 25$ m.

In the marine environment, Smith (1980) found that

$$\frac{\sigma_U}{U} = 0.101 - 0.12\frac{z}{L} \qquad (4)$$

where σ_U is the standard deviation of the sustained horizontal wind speed (downwind direction) U and σ_U / U is termed the horizontal turbulence intensity. On the other hand, Hsu (2001) proposed that σ_U / U and the gust factor (G) are related such that

$$G = \frac{U_{gust}}{U} = 1 + 3\frac{\sigma_U}{U} \qquad (5)$$

where U_{gust} is the peak gust. Substituting Eq. (4) into (5),

Table 1. Overwater measurements of sustained wind and peak gust during hurricanes for a 5-year period from 1996 through 2000. The gust factor, G, is the ratio of peak gust to sustained wind. (Data sources: Pasch and Avila (1999), Rappaport (1999), Pasch et al. (2001), Lawrence et al. (2001), and Franklin et al. (2001))

Year	Hurricane	Buoy	Peak Gust (kt)	Sustained Wind (kt)	G	SST* °C
1996	Fran	41004	64	49	1.31	26.8
1997	Danny	42007	46	35	1.31	26.8
		42040	42	33	1.27	28.4
		44004	42	32	1.31	23.7
		44008	37	30	1.23	17.2
		44014	54	42	1.29	25.3
1998	Bonnie	41002	57	42	1.36	27.4
		41004	49	38	1.29	27.4
		44004	46	36	1.28	24.2
		44014	47	37	1.27	24.6
		Georges Bank	45	35	1.29	NA
	Earl	42040	55	41	1.34	29.7
		42039	63	45	1.40	26.9
		42036	47	35	1.34	27.6
		42002	34	26	1.31	30.2
		42001	52	37	1.41	NA
		42007	37	30	1.23	29.2
	Georges	42003	66	51	1.29	28.5
		42039	56	43	1.30	28.2
		42036	48	34	1.41	27.6
		42040	68	54	1.26	26.8
		42007	54	44	1.23	26.9
	Mitch	42003	44	37	1.19	26.7
		41010	45	37	1.22	26.8
1999	Bret	42020	73	58	1.26	NA
	Dennis	41001	63	48	1.31	26.9
		41002	59	43	1.37	27.6
		41004	72	54	1.33	26.1
		41008	43	31	1.39	28.9
		41009	37	29	1.28	27.9
		41010	72	57	1.26	28.2
		44014	53	43	1.23	NA
	Floyd	41004	72	54	1.33	NA
		41009	70	52	1.35	28.9
		41008	31	24	1.29	26.8
		41010	91	72	1.26	NA
		44009	52	39	1.33	22.6
		44014	66	50	1.32	NA
		44025	43	33	1.30	21.2
	Irene	41009	60	45	1.33	27.6
2000	Gordon	42003	57	43	1.33	29.4
		42036	41	31	1.11	29.0
	T.S. Helene	42003	39	32	1.22	28.9
		42039	41	31	1.32	28.9
				Grand Mean	1.30	26.9
				Standard Deviation	0.059	2.5
				Coefficient of Variation (or Dispersion)	4.5%	9.3%
				Number of Measurements	44	37

*SST stands for Sea-Surface Temperature and NA is Not Available. These SST data were obtained from the Web site of the NOAA/National Data Buoy Center (seaboard.ndbc.noaa.gov) we have

$$G = 1.30 - 0.36 \frac{z}{L} \quad (6)$$

Verification of this concept was accomplished using a 5-year hurricane data set (see Table 1) of buoy measurements of peak gusts and sustained winds, which included one tropical storm and 11 hurricanes. This data set was used to be certain strong winds prevailed (Pasch and Avila 1999; Rappaport 1999; Pasch et al. 2001; Lawrence et al. 2001; and Franklin et al. 2001).

The statistical analysis of this data set yielded a coefficient of variation of less than 5% and a grand mean of 1.3. This agrees with the analysis of a 10-year hurricane data set where the grand mean was also 1.3 (Hsu 2002). Therefore, Eq. (6) is verified when z / L = 0. Now, substituting Eq. (2) into (6), G = 1.16 for z / L = 0.4 and G = 1.44 for z / L = -0.4. Hence, the following stability criteria are proposed based on overwater gust factor measurements:

$$G \geq 1.45 \quad \textit{Unstable} \quad (7)$$

$$1.16 < G < 1.44 \quad \textit{Near Neutral} \quad (8)$$

$$G \leq 1.15 \quad \textit{Stable} \quad (9)$$

3. Estimating Mixing Height

a. Under near neutral conditions (Eq. (8))

According to Geer (1996), the mixing height (or depth) is the vertical distance between the earth's surface and the altitude to which convective currents can uniformly disperse pollutants. This upper limit is usually a temperature inversion. Due to potential evaporation, the air over the water is usually moister than that over land, and the top of the marine layer is oftentimes capped by clouds. According to Garratt (1992), the cloud-topped boundary layer can be broadly identified with a turbulent region in which patterns and ensembles of stratus, stratocumulus and cumulus clouds reside beneath a capping inversion. It is a dominant feature of the weather of the lower atmosphere and the climate conditions of many areas of the globe, particularly over the sea. On the basis of analysis of vertical soundings taken by research aircraft, rawinsondes, radar wind profilers and Radio Acoustic Sounding Systems, it has been shown by Garratt (1992) that the mixing height (h) equals the lifting condensation level (LCL) under cumulus cloud conditions (where LCL = cloud base). The height of the LCL (H_{LCL}) may be estimated by (Hsu 1998)

$$H_{LCL} = 125\left(T_{air} - T_{dew}\right) \quad (10)$$

where H_{LCL} is in meters and the dewpoint depression (difference between air and dewpoint temperatures) at the sea surface is in degrees Celsius.

Eq. (10) is recommended for estimating the mixing height under near neutral conditions. Note that in this mixing layer, the vertical distribution of potential temperature is nearly constant (Garratt 1992), meaning the atmosphere is nearly neutral. For example, under hurricane conditions the dewpoint depression is generally within 4°C (see NOAA/National Data Buoy Center Web site: seaboard.ndbc.noaa.gov during Hurricane Lili from 1-3 October 2002, at buoy 42001), hence the mixing height is approximately 500 m. This same value is used as the height of the habitation layer by Simpson and Riehl (1981) and as the boundary layer depth during a hurricane by Anthes (1982). According to Turner (1994), the neutral category should also be used when the wind speed at the standard 10 m height is higher than 6 m s^{-1} or 12 kt.

If T_{dew} for Eq. (10) is not available, it may be estimated by (Hsu 1988)

$$T_{dew} = \frac{237.3 \log_{10}\left(\frac{e_{air}}{6.1078}\right)}{7.5 - \log_{10}\left(\frac{e_{air}}{6.1078}\right)} \quad (11)$$

and

$$e_{air} = \frac{1}{0.62} P\, q_{air} \quad (12)$$

where e_{air} is the vapor pressure (mb), P is air pressure (mb), and q_{air} the specific humidity (g kg^{-1}), respectively. For operational applications (Hsu 1998, Fig. 3 with a correlation coefficient = 0.96)

$$\left(q_{sea} - q_{air}\right) = 5.68 + 0.37\left(T_{sea} - T_{air}\right) \quad (13)$$

and

$$q_{sea} = 0.62 \frac{e_{sea}}{P} \quad (14)$$

where

$$e_{sea} = 6.1078\ X\ 10^{\left[7.5\, T_{sea}/\left(237.3\, +\, T_{sea}\right)\right]} \quad (15)$$

b. Under stable conditions (Eq. (9))

According to Venkatram (1980) for mid-latitude applications and the WAMDI Group (1988),

$$H_{stable} = 2.4 * 10^3\, u_*^{3/2} \quad (16)$$

$$u_* = \sqrt{C_d}\, U \quad (17)$$

$$C_d = 1.2875 * 10^{-3}, \ \textit{when } U < 7.5\ m/s \quad (18)$$

where u_* is the friction velocity and C_d is the drag coefficient.

From Eqs. (16) through (18), we have

$$H_{stable} = 16.3\,U^{3/2} \tag{19}$$

where H_{stable} is in meters and U in m s^{-1}.

c. Under unstable conditions (Eq. (7))

According to Hsu (1997),

$$H_{unstable} = 369 + 6004\,C_T U\left(T_{sea} - T_{air}\right)\left(1 + \frac{0.07}{B}\right) \tag{20}$$

From Smith (1980),

$$C_T = 1.10 * 10^{-3} \tag{21}$$

and from Hsu (1999),

$$B = 0.146\left(T_{sea} - T_{air}\right)^{0.49} \tag{22}$$

C_T is the coefficient for sensible heat flux, and B is the Bowen ratio. Substituting Eq. (21) into (20), we have

$$H_{unstable} = 369 + 6.6\,U\left(T_{sea} - T_{air}\right)\left(1 + \frac{0.07}{B}\right) \tag{23}$$

For example, if (T_{sea} - T_{air}) = 10°C and U = 3 m s^{-1}, $H_{unstable}$ = 598 m or 1962 ft.

4. Concluding Remarks

In order to facilitate rapid determination of atmospheric dispersion characteristics, the concept of gust factor is employed. Although all equations used in this study are based on those already available in the "open literature", further refinement may be needed by providing some cases which address systems over the Atlantic and Pacific in higher latitudes, or even for strong systems over the Great Lakes.

Acknowledgments

This study was partially supported by the Minerals Management Service, U.S. Department of the Interior, through the Coastal Marine Institute of Louisiana State University under a Cooperative Agreement with Louisiana State University. The contents of this paper do not necessarily reflect the views or policies of the MMS. The author also gratefully acknowledges the support of Chevron-Texaco in the form of an Endowed Professorship at LSU. Comments to improve this paper from Cynthia Ann Nelson and Michael J. Bodner are also appreciated.

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;
e-mail: sahsu@antares.esl.lsu.edu.

References

Anthes, R. A., 1982: *Tropical Cyclones - Their Evolution, Structure and Effects.* American Meteorological Society, Boston, MA, 208 pp.

Franklin, J. L., L. A. Avila, J. L. Beven, M. B. Lawrence, R. J. Pasch, and S. R. Stewart, 2001: Atlantic hurricane season of 2000. *Mon. Wea. Rev.*, 129, 3037- 3056.

Garratt, J. R., 1992: *The Atmospheric Boundary Layer.* Cambridge University Press, 316 pp.

Geer, I. W. (Editor), 1996: *Glossary of Weather and Climate.* American Meteorological Society, Boston, MA, 149 pp.

Hanna, S. R., L. L. Schulman, R. J. Paine, J. E. Pleim, and M. Baer, 1985: Development and evaluation of the offshore and coastal dispersion model. *J. Air Poll. Contr. Assoc.*, 35, 1039-1047.

Hsu, S. A., 1992: An overwater stability criterion for the offshore and coastal dispersion model. *Boundary-Layer Meteorol.*, 60, 397-402.

_________, 1997: Estimating overwater convective boundary layer height from routine meteorological measurements for diffusion applications at sea. *J. Appl. Meteor.*, 36, 1245-1248.

_________, 1998: A relationship between the Bowen ratio and sea-air temperature difference under unstable conditions at sea. *J. Phys. Oceanogr.*, 28, 2222- 2226.

_________, 1999: On the estimation of overwater Bowen ratio from sea-air temperature difference. *J. Phys. Oceanogr.,* 29, 1372-1373.

_________, 2001: Spatial variations in gust factor across the coastal zone during Hurricane Opal in 1995. *Natl. Wea. Dig.,* 25:1-2, 21-23.

_________, 2002: The gust factor during hurricanes as measured by NDBC buoys. *Mariners Wea. Log*, 46:2, 12-13.

Lawrence, M. B., L. A. Avila, J. L. Beven, J. L. Franklin, J. L. Guiney, and R. J. Pasch, 2001: Atlantic hurricane season of 1999. *Mon. Wea. Rev.*, 129, 3057-3084.

Panofsky, H. A., and J. A. Dutton, 1984: *Atmospheric Turbulence.* John Wiley & Sons, 397 pp.

Pasch, R. J., and L. A. Avila, 1999: Atlantic hurricane season of 1996. *Mon. Wea. Rev.*, 127, 581-610.

________, ________, and J. L. Guiney, 2001: Atlantic hurricane season of 1998. *Mon. Wea. Rev.*, 129, 3085-3123.

Rappaport, E. N., 1999: Atlantic hurricane season of 1997. *Mon. Wea. Rev.,* 127, 2012-2026.

Simpson, R. H., and H. Riehl, 1981: *The Hurricane and Its Impact*. Louisiana State University Press, Baton Rouge, LA, 398 pp.

Smith, S. D., 1980: Wind stress and heat flux over the ocean in gale force winds. *J. Phys. Oceanogr.*, 10, 709-726.

The WAMDI Group, 1988: The WAM model - a third generation ocean wave prediction model. *J. Phys. Oceanogr.,* 18, 1775-1810.

Turner, D. B., 1994: *Workbook of Atmospheric Dispersion Estimates* (Second Edition). Lewis Publishers, 166 pp.

Venkatram, A., 1980: Estimating the Monin-Obukhov length in the stable boundary layer for dispersion calculations. *Boundary-Layer Meteorol.*, 19, 481- 485.