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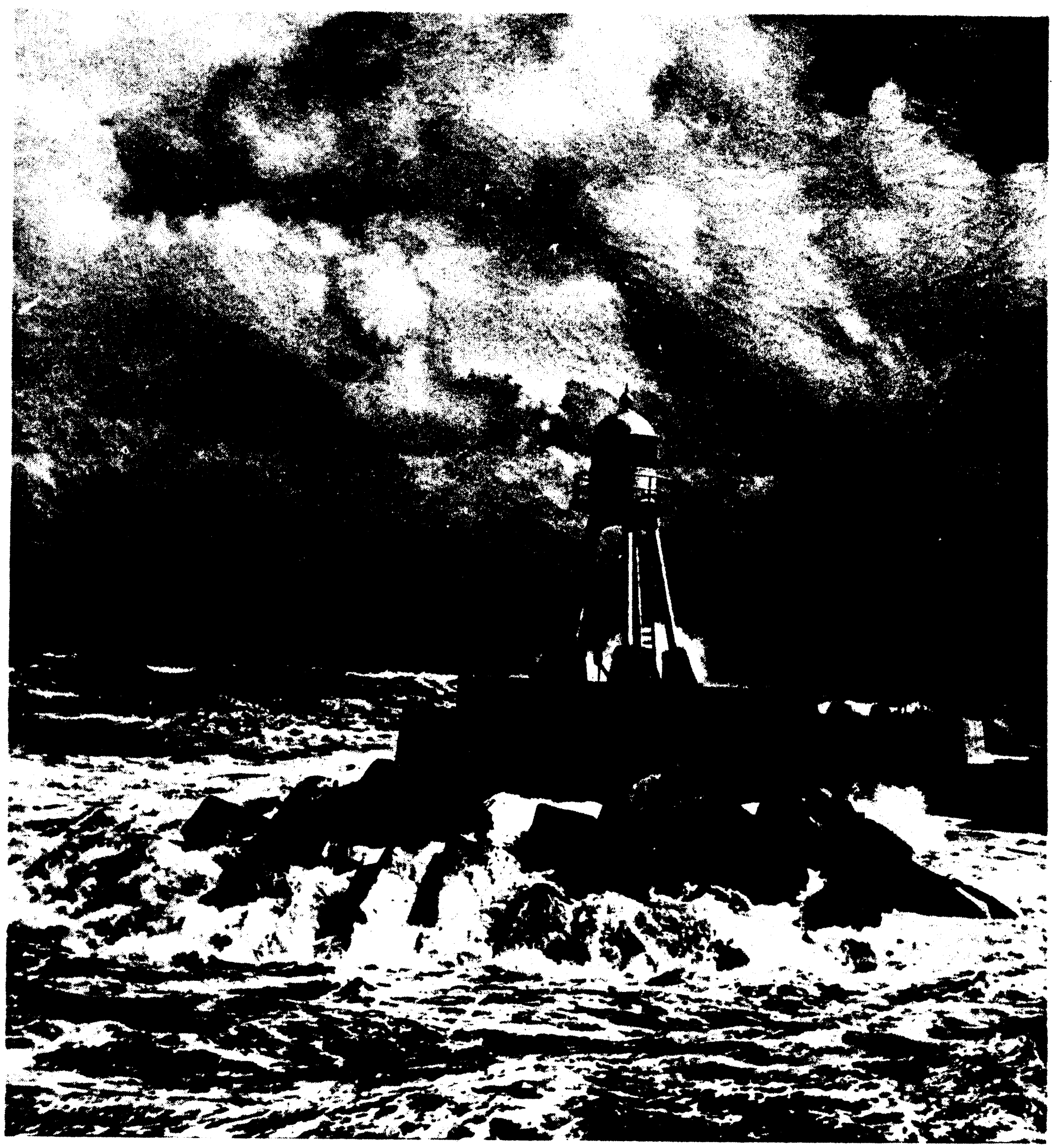

AMERICAN METEOROLOGICAL SOCIETY
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COMPARISON OF STABILITY CLASSIFICATION METHODS FOR PARAMETERIZING COASTAL OVERWATER DISPERSION

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1. INTRODUCTION

During September of 1980 and January of 1981 the Naval Postgraduate School (NPS) and Aerovironment, Inc. (AI) conducted an intensive series of tracer measurements off Ventura, California. SF_6 gas was released from the NPS research ship RV/Acania while the ship was anchored at a point approximately 5 miles from shore. The positior and dimensions of the plume were determined at three downwind distances by analyzers aboard an aircraft and van, and by collecting gas samples at fixed shore locations and from a small boat. Local meteorological conditions were determined both at shore stations and on the ship, including radiosondes. The ship also obtained both short and long term averages of the variance of the horizontal wind direction.

The purpose of the work reported here is to develop schemes for classifying stability for use in modeling dispersion in the overwater regime and to develop relationships between the schemes and the wind direction variance. Comparisons with the tracer measurements will be presented in another paper.

2. LOCAL METEOROLOGY

In order to describe the conditions for which the data were obtained we briefly describe the locality and observed meteorological conditions. The Ventura region is an area where the weather is controlled by the interplay of numerous local influences and the mesoscale features which are typical of the rest of the coast. The area lies within the embayment formed by the Santa Barbara Channel, Santa Monica Bay, and the Gulf of Santa Catalina. A plane approximately 20 miles long, extends from the beach to five to ten miles inland and is surrounded by coastal hills with peaks two to three thousand feet high. The channel islands are approximately 20 miles to sea. Within [illegible] miles inland mountains extend to [illegible] feet. These geographic features cause a complex pattern of eddies and channeled flow, and a very persistent diurnal land-sea breeze cycle.

Because of the complexity of the local influences measurements made in this area are not representative of open coastal regions. Experiments are planned for an area further to the north on the California coast which will yield data for an open coastal area. This experiment was conducted for two approximately two week periods, one in the late summer and one in the winter.

The summer season is dominated by the North Pacific Semipermanent Subtropical High which lies to the west of the area and controls the synoptic scale. Clockwise flow around the high produces northwesterlies along much of the coast. The general onshore flow is aided by the inland thermal trough, which is created by overland heating. Strong subsidence creates the prevalent capping inversion. During the period of the experiment the surface pressure gradients in the area were very weak and the flow was dominated by the land-sea breeze cycle.

The winter period was similar to the summer. The Pacific high was very strong producing a mini-drought for what is normally the beginning of the rainy season for California. Frontal passages were again far to the north. There was no well established onshore flow and as before, the land-sea breeze cycle was dominant. Unfortunately, fairly persistent highs over the inland western US strengthened the offshore flow so that periods of sea breeze were shortened, making tracer experiments difficult.

Although the strong local influences make it difficult to accurately predict the wind in the Ventura area, the seasonal patterns are quite reproducable. This makes a climatology useful for assessing expecting onshore impact.

3. WIND DIRECTION VARIANCE

The wind direction was measured by a vane mounted on the RV/Acania 20m above the water line. The vane responded to both the wind and ship roll; since the ship pointed approximately into the wind during the measurements, pitch had little effect. A pendulum mounted on the roll axis of the ship was used as a roll sensor. The roll induced transverse component of wind at the vane is the roll rate times the radius from the roll axis to the vane.

Wind speed and direction were measured every 1.5 sec. Mean wind direction and speed were determined for one half hour periods. Wind direction was also averaged for 15 sec periods and these averages stored for later processing to determine the variance. For this short term average the wind data is corrected for the ship roll component and ship heading for each 1.5 sec wind determination.

The standard deviation has been calculated for three averaging periods, one minute, ten minute, and one hour. The shorter averages are then averaged for one hour periods so that all results are directly comparable. The one hour averages can be related to the one hour average measured plume concentration. The one minute averages can be related to single transects of the plume by the aircraft.

4. STABILITY CLASSIFICATION

It is common to use some measure of the stability of the atmosphere to determine the expected dispersion of a plume. The relationship between the three dimensional spreading and stability is complex and will not be presented here. Atmospheric stability depends on the heat flux, which is a result of the temperature gradient, and the amount of mechanical turbulence which is generated by the wind. Several schemes for specifying the stability are in current use; all require a measurement or an estimate of the flux and turbulence. We discuss three schemes and their interrelations. One of these, the Pasquill, is in fairly wide use and we will show the method we use to modify it for the overwater regime. Our normal method for specifying stability is to determine the Monin-Obukhov length. In what follows we will compare the wind direction variance to this length, to the modified Pasquill classes, and to temperature gradient to assess the usefulness of the classification schemes.

4.1 Monin-Obukhov Length

The Monin-Obukhov length can be determined from measured gradients of wind, temperature, and water vapor content in the surface layer. Gradients are difficult to measure, especially from a moving platform such as a ship. Under such conditions it is preferable to use the bulk aerodynamic method, the measurements required being sea surface temperature and wind speed, temperature, and water vapor content at a reference height, Z. One assumes that the wind speed is zero and that the relative humidity is 100% at the surface. The air-surface differences in these bulk parameters are used to calculate fluxes and stability. The measurements must be made in the "surface layer", which is a layer approximately 30m thick, where the heat flux and friction velocity can be assumed constant.

The Monin-Obukhov length is calculated from

$$L = (T/kg)(U_*^3/Q), \tag{1}$$

where T is the absolute temperature, k is Von Karman's constant (0.35), g the acceleration due to gravity, and U_* the friction velocity (scaling velocity). The "temperature flux", Q, is related to the virtual heat flux, H, by $H = \rho C_p Q$, where ρ is the air density and C_p is the specific heat at constant pressure. The temperature flux is directly related to the virtual potential temperature scaling parameter, θ_{V*}, by

$$\begin{aligned} Q &= U_* \theta_{V*} \\ &= U_*(\theta_* + 6.1 \times 10^{-4}\ Tq_*), \end{aligned} \tag{2}$$

where T is the absolute temperature and q_* is the water vapor mixing ratio scaling parameter (gm/kg). The potential temperature is $\theta = T + 0.0098Z$. We see that L can be calculated from the surface layer fluxes, or the scaling parameters, since they are directly related. Note that for upward heat flux (unstable air) L is negative and it is positive for downward heat flux (stable air). We will work with 1/L in what follows, which has the value zero for neutral conditions where the heat flux is zero.

The method we use to determine 1/L is to determine the scaling parameters directly from the measured mean values using stability corrected drag coefficients. Briefly, the method is as follows:

The scaling parameters are related to the gradients by

$$\frac{dX}{dZ} = \frac{X_*}{\alpha_X kZ} \phi_X(\xi), \tag{3}$$

where X represents U, T, or q, $\xi = Z/L$, ϕ is the gradient stability function, and α is the turbulent diffusivity ratio. Current evidence suggests that the transport of the scalars heat, and water vapor, obey the same relationship to their gradients. Thus, $\phi_T = \phi_q$ and $\alpha_T = \alpha_q = 1.35$ ($\alpha_U = 1$) (Businger, 1973).

To obtain the stability, the scaling wind speed and virtual potential temperature are needed. They are obtained from bulk measurements using an integrated form of Equation 3. We integrate Equation 3 from the surface to a reference height Z, usually 10m.

$$\begin{aligned} X_Z - X_S &= (X_*/\alpha k) \int_0^Z \phi_X(\xi)/Z\ dZ \\ &= (X_*/\alpha k)[\ln(Z/Z_{oX}) - \psi_X(\xi)], \end{aligned} \tag{4}$$

where X_s is the surface value and ψ is the profile stability function. We have dropped the subscript on α for convenience.

For analysis of data, it is convenient to solve Equation 4 for X_* and rewrite in terms of the drag coefficient. The neutral stability drag coefficient is given by

$$C_{XN}^{1/2} = \alpha k/(\ln z/z_{OX}) \qquad (5)$$

and corrected for stability by

$$C_X^{1/2} = C_{NX}^{1/2}[1 - \psi_X(\xi)C_{NX}^{1/2}/\alpha k]^{-1} \qquad (6)$$

Thus, the scaling parameter is given by

$$X_* = C_X^{1/2}(X_Z - X_s) \qquad (7)$$

X_* is used in Equations 1 and 2 to obtain the stability. An iterative technique must be used since stability corrected drag coefficients are needed and they can only be calculated if stability is known. The procedure is outlined in Schacher, et. al. (1982).

4.2 Pasquill Class

The Pasquill classification is a simplified scheme which requires a determination of wind speed but not temperature. A heat flux category is determined from an estimation of the solar insolation at the surface. The scheme has been developed for overland use and is not appropriate for the overwater regime because of the vastly different thermal properties of water. Stability is divided into five classes, A-F, determined as follows:

U (m/sec)	Daytime Insolation: Strong	Moderate	Small	Nighttime Cloud Cover: >4/8	<3/8
<2	A	A-B	B		
2	A-B	B	C	E	F
4	B	B-C	C	D	E
6	C	C-D	D	D	D
>6	C	D	D	D	D

In this scheme A-C are unstable, D neutral, and E-F stable conditions. This classification scheme is imprecise but due to its simplicity, it is in widespread use.

4.3 EPA Temperature Gradient Classification

The Environmental Protection Agency has guidelines(EPA,1980) for relating the Pasquill classifications to the wind direction standard deviation, σ_θ, and also to the temperature gradient in the surface layer. This scheme considers only the temperature gradient; no determination of the wind is used. Categorization is as follows:

ΔT/ΔZ (°C/100m)	Pasquill Class	σ_θ(deg)
<-1.9	A	≥22.5
-1.9 > -1.7	B	22.5 > 17.5
-1.7 > -1.5	C	17.5 > 12.5
-1.5 > -0.5	D	12.5 > 7.5
-0.5 > 1.5	E	7.5 > 3.8
1.5 > 4.0	F	<3.8
>4.0	G	

It is important to realize that this scheme was also developed by examination of overland data; it is not expected to be valid over water.

5. MODIFICATION OF PASQUILL CLASSIFICATION FOR OVERWATER USE

As has been stated above, the Pasquill classification scheme was derived for overland use. The overwater regime is quite different because of the vastly different response of water to incoming solar radiation and the variation of roughness length with wind speed. Because of the widespread use of this scheme we here modify it for overwater use; this should not be interpreted as a recommendation that this scheme remain in common use.

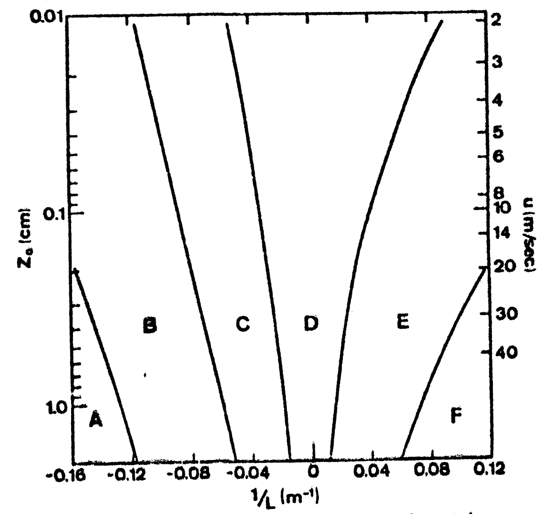

Figure 1. Pasquill classification boundaries as a function of the Monin-Obukhov stability length and the roughness length.

Golder(1972) has related the Pasquill class boundaries to the roughness length and the Monin-Obukhov length. The results are shown in Figure 1. Overwater roughness length is a function of wind speed. We relate them using the parameterization of Kondo(1975), which gives the wind speed scale shown on the right hand side in Figure 1.

The Monin-Obukhov length is calculated by the method described in the previous section, for a height of 20m. Wind speed, temperature, and relative humidity (or dew point) are the meteorological parameters which are commonly measured, not 1/L, so it si of ihnterest to parameterize the overwater classes in terms of these quantities. We have calculated 1/L as a function of wind speed, air-sea temperature difference (T_A-T_S) and relative humidities of 50%, 80%, and 95%. The results are shown in Figure 2 for 80% humidity. Also plotted on this figure are the boundaries of the Pasquill classes, as determined from Figure 1. Note that classes A and F do not appear because these classes are outside the range of parameters that can be expected to occur over water (particularly, very large air-sea temperature difference).

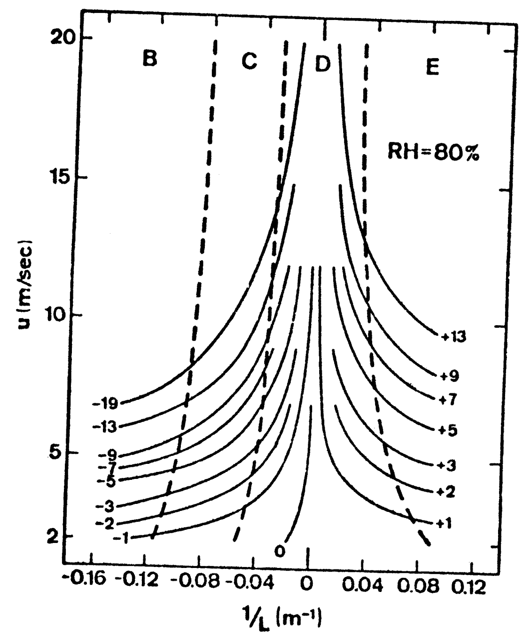

Figure 2. Dependence of 1/L on the wind speed and air-sea temperature difference for a relative humidity of 80%.

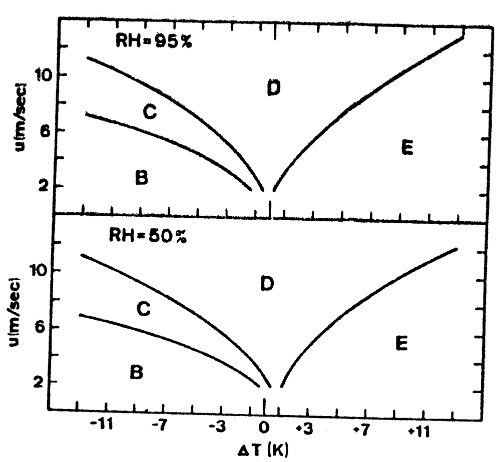

Figure 3. Pasquill classification boundaries as a function of wind speed and air-sea temperature difference.

The desired results are obtained by using Figure 2 to determine the Pasquill class boundaries as functions of wind speed and T_A-T_S. The results are plotted in Figure 3 for 50% and 95% relative humidity. The humidity is not a major factor; it is most important near neutral (small T_A-T_S or high wind speed) where high humidity shifts the curves toward greater instability.

6. COMPARISON OF CLASSIFICATION SCHEMES WITH σ_θ

The ultimate test of a stability classification scheme is how well it can predict the behavior of a plume. It is also useful to test the ability of a classification scheme to predict the variability of the horizontal wind direction, which, of course, is the cause of cross wind spreading of a plume. This is the approach taken here. Short and long term average standard deviations are compared to 10/L. Only one hour averages are compared to air-sea temperature difference, the temperature gradient, and the modified Pasquill classes since these schemes are used to predict one hour average plume behavior. We have examined the air-sea temperature difference and temperature gradient because of the EPA quidelines. We do not expect them to be of much use because stability cannot be determined from temperature information alone.

6.1. Air-Sea Temperature Difference and Temperature Gradient

On the ship the air temperature at 7m and 20m above sea level, and the sea surface temperature, T_S, were measured continuously and averaged every one half hour. The air-sea temperature difference, T_{20}-T_S, and, in place of the gradient, T_{20}-T_7 have been compared to σ_θ. The results are very poor and are not shown here. There is no correlation between σ_θ and these parameters so, as expected it would be very difficult to determine σ_θ from temperature measurements alone. It is interesting to note that (T_{20}-T_S) values range from -2 to +2 °C whereas the range of (T_{20}-T_7) is a factor of ten smaller. This emphasizes the great difficulty in measuring temperature differences in the air over the ocean. The differences are normally too small to yield reliable results. It is much better to use the air-sea temperature difference when stability is being determined.

6.2. 10/L

We have compared hourly averages of the one minute, ten minute, and one hour averages of σ_θ with hourly averages of 10/L. The results are shown in Figure 4. The data points are averages of all data in the bins $-10/L < 0.1$, $0.1 \leq -10/L < 0.2$, $0.2 \leq -10/L < 0.5$, $0.5 \leq -10/L < 1.0$, $1.0 \leq -10/L$. The solid lines are linear regression fits to all of the data for $\sigma_\theta = A + B(-10/L)$. The linear regression results for $\sigma_\theta = C + D \ln(-10/L)$ are

Average	intercept	slope	correlation
1 minute	1.9	0.98	60
10 minute	3.3	2.6	68
1 hour	5.4	2.7	45

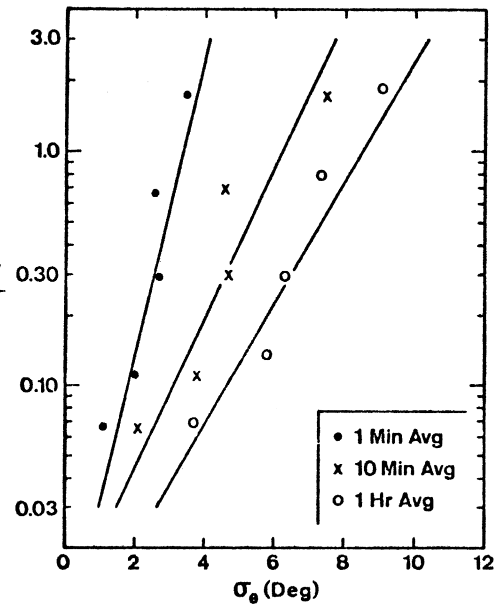

Figure 4. Wind direction variance for one minute, ten minute, and one hour averages versus the ln of the stability parameter. The points are bin averages of the data. The solid lines are the linear regression fits to the data.

The correlations are not good, but they are not surprising when one considers the wide range of conditions encountered and the region in which the measurements were made. We were not dealing with a spatially homgeneous air mass which had a long fetch over the open ocean. As described previously, the area has a complex pattern of eddies and channeling of the wind.

For the one hour averages σ_θ shows a better correlation with ln(-10/L) than with -10/L (0.57 vs 0.45). It would be unreasonable to use a logarithmic dependence on stability, unless the function were truncated, since σ_θ would become negative as neutrality is approached. The relationship

$$\sigma_\theta = 10.2 + 2.4 \ln(-10/L) \quad (10/L < -0.05)$$
$$\sigma_\theta = 3.0 \quad (-0.05 \leq 0/L < 0)$$

does represent the data better than the linear regression fit to -10/L. Which to use for the one hour averages is a matter of choice.

For stable conditions (+10/L) there is too little data to enable preforming a linear regression calculation. For reasons to be discussed below, it is best to use the average measured values, which are

σ_θ (1 min) = 2.3
σ_θ (1 hour) = 12

The most striking aspect of these results is the large values of σ_θ for slightly stable conditions. Previous experiments, both over land and over water, have shown a continuous increase of σ_θ (or σ_y) as atmospheric stability goes from stable to unstable (Hosker, 1974; Raynor, et. al. 1974; Slade, 1962). We believe that the results found in this study are location specific. Stable conditions over California coastal waters are very unusual, and are normally associated with offshore flow or cases where the air has not equilibrated after passing over a variation in sea surface temperature. In the Ventura area local eddies or flow over the channel islands could produce a stable surface layer. In both cases variations in the wind direction could be large due to orographic effects. Such variations would presist over long distances due to the stability of the atmosphere. Thus, the stable results reported here for σ_θ should not be thought to apply to stable onshore flow in open coastal areas. Evidence that the stable results are orographic in nature rather than due to equilibrium turbulence structure as shown in Figure 5. The figure shows the

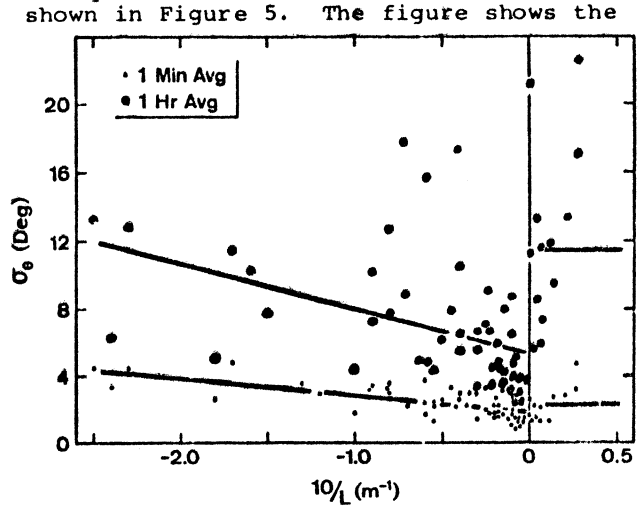

Figure 5. One minute and one hour average standard deviations of wind direction versus the reciprocal of the Monin-Obukhov length.

data and the linear regression fits to -10/L for the one minute and one hour averages. The solid lines for +10/L show the average values of σ_θ. The one hour averages show a large increase for stable conditions, which is not present in the one minute averages. If the equilibrium overwater turbulence structure for stable conditions resulted in a large horizontal wind direction variability it should be present for both long and short term averges. Large eddies due to orographic effects would persist and affect long term averages but the short term fluctuations would be more in equilibrium with the local stability.

We have attempted to reduce the scatter in the results by plotting σ_θ versus wind direction and 10/L to see if the local air mass trajectory had an effect. The results are shown in Figure 6, where different symbols are used for four σ_θ bins. The results are not very helpful; in particular, wind direction does not appear to play an important role. This points out the difficulty in parameterizing transport and dispersion in the coastal regime. The local flow

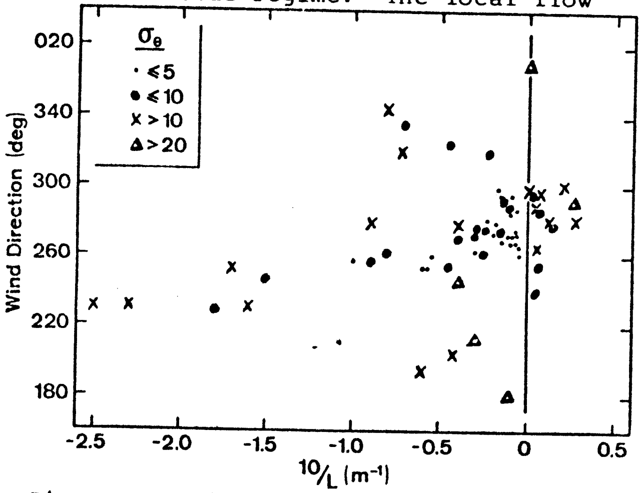

Figure 6. Wind direction variance as a function of wind direction and the stability parameter.

patterns can be very complex and variable. The air mass in which transport is taking place may not be in equilibrium with the locally measured meteorological quantities. Thus, results obtained in a study of the type described here may be location specific.

6.3. Overwater Modified Pasquill

We have determined one hour averaged values of the modified classes from the meteorological measurements made on the RV/Acania, using the method described in Section 5. The measured values of σ_θ and the modified classes for these time periods are shown in Figure 7. Because of the wide range of parameters applicable for each class, particularly D, we have arbitrarily divided ech class into three subclasses, each subclass representing one third of the original class. For example, D+, D, and D- where the +/- refer to the stable/unstable side of the original class. This division is shown in Figure 7. Even though there are 48 hours of data, this is insufficient to yield a good σ_θ versus class relationship because so much of the data is near neutral. We cannot verify that the classes should be divided into subclasses, though it does appear to be valid for class D. The results suggest the following relation to obtain the classes from σ_θ, or vice-versa:

Pasquill Class	σ_θ (deg)
B	10 - 14
C	6 - 10
D(unstable)	2 - 6
D (stable)	7 - 14

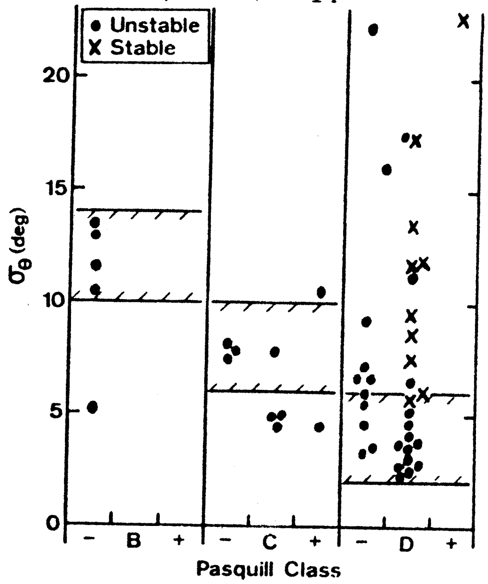

Figure 7. Wind direction variance for the overwater Pasquill classes. The shaded regions show the recommended class-variance groups.

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