NOTES AND CORRESPONDENCE

Enhancement of Crosswind Pollutant Dispersion by Steadily Veering Winds in Sea Breezes

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ABSTRACT

An estimate is given of the relative importance of wind veering and turbulent diffusion in the mean horizontal spread of pollutant plumes in the atmosphere. Documented veering rates in sea breezes are used to illustrate the effect, and it is concluded that for typical sea breeze induced veering, the effect will be significant over much of the range of applicability of the Gaussian plume model.

1. Introduction

The hourly averaged lateral dispersion of pollutant plumes in the lower atmosphere is conventionally treated in Gaussian plume models as if it were caused solely by microscale turbulence, while the longer time scale meandering of diffusing plumes is presumed to be driven by fluctuations in the mesoscale or synoptic scale flow. Implicit in this approach is the assumption that a clear scale break separates the microscale from the larger scales of atmospheric variability. Hanna (1983) has provided a method for explicitly treating the microscale and larger scale fluctuations as separate sources of lateral turbulent intensity and hence mechanisms of turbulent diffusion under stable conditions.

Many conditions exist under which the neglect of the large scale fluctuations will lead to underestimates of lateral diffusion. In cases of extreme nonstationarity (over times of 1 hour, which are typical averaging times for plume diffusion estimates), such as the passage of synoptic or mesoscale fronts, diffusion estimates based on the widely used steady-state Gaussian scheme will yield nearly meaningless results. These cases are excluded from consideration here, but we direct our attention to the case of steadily veering wind direction. This case is intermediate between the discontinuous case in which conventional Gaussian schemes break down, and the stationary conditions under which they work best. This note provides an illustrative evaluation of this case by considering the well-documented veering of sea breezes. This case has apparently not been considered before, although it may be important in the evaluation of air quality in many coastal locations.

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2. Crosswind dispersion in steadily veering mean winds

The following analysis is intended to provide a simple means of estimating the effect on horizontal plume spread of steadily veering mean wind direction, and uses the crosswind plume extent as estimated by the Gaussian plume model as a scaling parameter. The intention is not to provide a modification to the Gaussian plume model, but rather to indicate when a basic assumption of that model may fail due to veering mean wind direction.

Consider a wind speed $\bar{u}$ that veers steadily at a rate $d\alpha/dt$. If a plume of pollutant emitted by a point source is spreading (by turbulent diffusion) into this veering wind, it will travel a source to receptor distance $x = \bar{u}\cdot t$ in a time t. During this time the wind will have veered through an angle θ. The arc s defined by the veering at a radius x is

$$s = x\theta = x\left(\frac{d\alpha}{dt}t\right) = \frac{d\alpha}{dt}\left(\frac{x}{\bar{u}}\right)^2. \qquad (1)$$

From Briggs (1973) the crosswind plume standard deviation σ_y in open country for travel distances of 0.1 to 10.0 km is

$$\sigma_y = cx(1.0 + 10^{-4}x)^{-1/2} \qquad (2)$$

where c is a stability dependent coefficient that takes on the values 0.04, 0.06, 0.08, 0.11, 0.16 and 0.22, for the Pasquill–Gifford stability classes A to F, respectively. The ratio s/σ_y is

$$s/\sigma_y = \frac{d\alpha}{dt}\frac{x}{c\bar{u}}(1.0 + 10^{-4}x)^{1/2}. \quad (3)$$

Using a scaling approach, it is suggested that when $s/\sigma_y \ll 1$, the veering has no significant effect in crosswind spread, and its effects can be ignored. If $s/\sigma_y \gg 1$, the veering effects dominate and the simple Gaussian plume model will not give a meaningful estimate of time averaged pollutant concentrations. In this case the veering-induced spread will result in much lower concentrations than would be estimated by the Gaussian plume model. If $s/\sigma_y \approx 1$, then a simple extension of the Gaussian plume model may be used to estimate pollutant concentrations. Since the veering-induced plume spread is of comparable magnitude to that caused by turbulent diffusion, a better estimate of the pollutant concentration would be obtained by doubling the value of σ_y from the Gaussian plume model.

The foregoing analysis is independent of the cause of veering, which may be a result of any of a number of meteorological phenomena. In order to illustrate the analysis and provide an overview of an important application, section 3 will document sea-breeze veering rates from both theoretical and observational studies.

3. The maximum veering rate in sea breeze flows

One particularly common phenomenon that causes steady veering of the wind is the land/sea-breeze circulation that occurs in coastal regions under conditions of light synoptic wind and strong insolation. Sea breezes in many parts of the world have been the subject of both theoretical and observational studies which have provided a comprehensive picture of the causes and magnitude of the wind veering that is part of their evolution (e.g., Atkinson 1981).

a. Theoretical studies

Haurwitz (1947) in his *dynamic theory of the sea-breeze* shows that the Coriolis force has a significant effect on the evolution of the sea breeze circulation, and shows how its influence is a veering (hodograph rotation) of the wind. Burk and Staley (1979) examine the relative importance of Coriolis and pressure-gradient forces on the veering of sea breezes, and present a time series (their Fig. 1) of the angle of the surface wind to the geostrophic wind from which a veering rate can be derived. Together with Neumann (1977) they discuss the order of magnitude of the three major influences on sea-breeze veering, (pressure gradient, friction and Coriolis forces). Neumann (1977) shows that the mesoscale pressure gradient force is of the same order as the Coriolis force, and Burk and Staley (1979) argue that the frictional force produces an effect that is comparable to the Coriolis-induced rotation. Combining these arguments results in a maximum veering rate on the order of three times the Coriolis parameter. Kusuda and Alpert (1983) present and solve a set of model equations for the rate of wind rotation in a sea breeze under the influence of a bell shaped mountain near the coastline. They tabulate (their Table 1) the veering rates and plot a hodograph (their Fig. 4) from which a maximum veering rate may be extracted. These theoretically determined veering rates are summarized in Table 1, and plotted on Fig. 1, together with the line labeled $3f$ (where f is the Coriolis parameter).

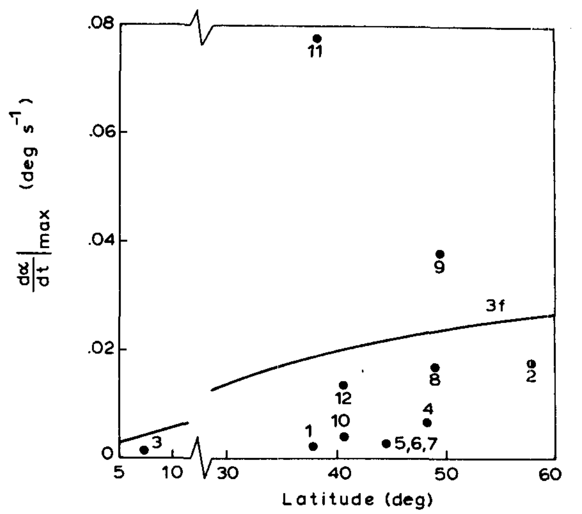

FIG. 1. Maximum observed and theoretical veering rate of sea breezes at various latitudes. The numbers refer to entries in Table 2, and the solid line is the theoretical maximum veering rate of $3f$ where f is the Coriolis parameter. Note the scale break in the latitude axis.

TABLE 1. Theoretical and modeled values for the veering rate of sea breezes; f is the Coriolis parameter, and a dash indicates that no values are given.

Veering rate (s^{-1})	Latitude (deg)	Wind speed ($m\ s^{-1}$)	Source
$(2.29–2.69)f$	All	—	Kusuda and Alpert (1983)
2.45×10^{-4}	—	—	Kusuda and Alpert (1983)
1.39×10^{-3}	—	—	Burk and Staley (1979)
$3f$	All	—	Burk and Staley (1979), Neumann (1977)

b. Observational studies

The literature on observations of sea breezes abounds with hodographs or similar graphical devices from which maximum veering rates may be extracted. The observational studies generally deal with sea breezes in the mid to high (38° to 58°) latitudes of the Northern Hemisphere, and range from low to moderate (0.2 to 6.6 m s^{-1}) wind speeds. The studies are located in places that generally have complex coastlines and often

TABLE 2. Maximum observed veering rates in coastal locations, where * and # indicate summertime and wintertime climatological values, respectively. The row numbers refer to plotted points in Fig. 1.

Row	Veering rate (s^{-1})	Latitude (deg)	Wind speed ($m\ s^{-1}$)	Source
1	2.02×10^{-3}	38 N	6.6	Fosberg and Schroeder (1966)
2	1.30×10^{-2}	58 N	4.0	Gill (1968)
3	5.07×10^{-3}	7 S	1.5	Hann and Suring (1940)
4	6.25×10^{-3}	48 N	2.5	Haurwitz (1947)
5	6.49×10^{-3}	47 N	2.2	Staley (1957)
6	8.89×10^{-3}	47 N	2.2	Staley (1957)
7	9.11×10^{-3}	47 N	1.8	Staley (1957)
8	1.67×10^{-2} *	49 N	1.0	Steyn and Faulkner (1986)
9	3.88×10^{-2} *	49 N	0.2	Steyn and Faulkner (1986)
10	4.12×10^{-3}	42 N	1.2	Weber (1978)
11	7.90×10^{-2} *	38 N	2.0	Zambakas (1973)
12	1.37×10^{-2} #	38 N	0.8	Zambakas (1973)

significant topographic influence. It is to be expected that both coastline and topographic complexity will result in veering rates that differ significantly from the theoretical values. The maximum veering rates from observational studies are summarized in Table 2, and plotted against latitude on Fig. 1. From Fig. 1, it is evident that, apart from two notable outliers, the line $3f$ is a reasonable upper bound for $d\alpha/dt$.

4. Dispersion enhancement by sea-breeze veering

The foregoing discussion provides an upper bound of $3 \cdot f$ for the veering rate in sea breeze flows. If this is substituted into Eq. (3), the ratio s/σ_y becomes

$$s/\sigma_y = \frac{\pi x}{7200} \frac{\sin\phi}{c\bar{u}} (1.0 + 10^{-4}x)^{1/2} \qquad (4)$$

where ϕ is the latitude and c is the coefficient defined in Eq. (2). In order to investigate the behavior of s/σ_y, we apply Eq. (4) with values of c and $\bar{u}$ appropriate to sea breeze conditions. Three cases representing different combinations of c and $\bar{u}$ are illustrated in Fig. 2. (a) Neutral: $c = 0.08$ with $\bar{u} = 5$ m s^{-1}, (b) slightly unstable: $c = 0.11$ with $\bar{u} = 4$ m s^{-1} and (c) moderately unstable; with $c = 0.16$ with $\bar{u} = 3$ m s^{-1}. The ratio s/σ_y is plotted as a function of downwind distance x and for veering rates of $3f$ (left-hand axis) and f (right-hand axis) for latitudes 10° to 55°. The veering rate of $3f$ should treated as a plausible maximum, while the rate of f can be considered a more typical one. As there are only minor differences between the three sets of wind and stability conditions, only Fig. 2b (as summarized in Table 3) will be discussed.

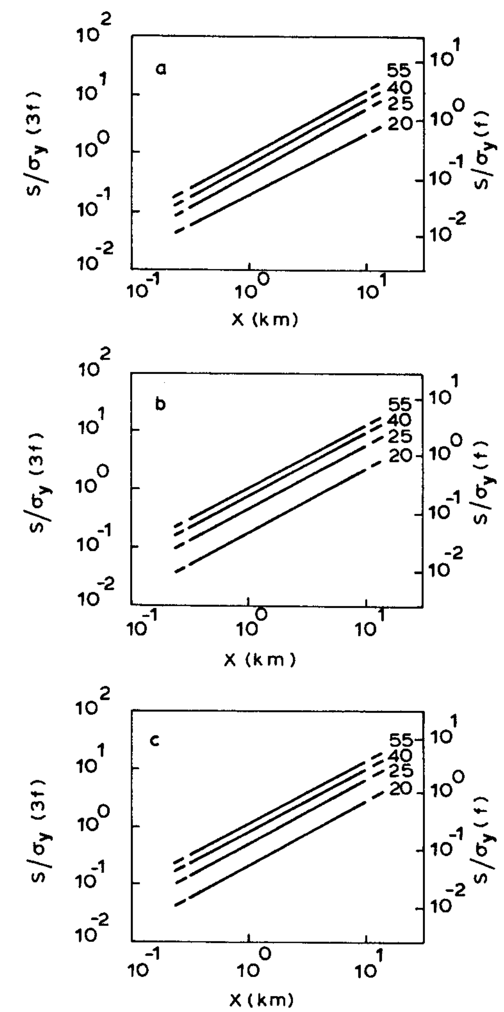

FIG. 2. The ratio of veer-induced plume spread to diffusion-induced plume spread (s/σ_y) as a function of downwind distance for latitudes 20°, 25°, 40° and 55°, and for veering rates of f and $3f$. (a) For Pasquill–Gifford stability class B (unstable) at a wind speed of 3 m s^{-1}, (b) for Pasquill–Gifford stability class C (slightly unstable) at a wind speed of 4 m s^{-1}, (c) for Pasquill–Gifford stability class D (neutral) at a wind speed of 5 m s^{-1}. The left-hand axis is for a veering rate of $3f$ while the right-hand one is for a rate of f where f is the Coriolis parameter.

5. Discussion

Table 3 indicates that the ratio s/σ_y exceeds 1.0 at distances from 0.93 to 4.79 km downwind of the point of emission for the maximum plausible veering rate in sea breezes, while the corresponding downwind distances for a typical veering rate are 2.82 to 14.45 km. In both cases, it is seen that the effects of the veering

TABLE 3. Downwind distance (in km) at which the ratio s/σ_y equals 1.0 for various latitudes and sea breeze veering rates of $3f$ and f (s^{-1}) as extracted from Fig. 2b.

	Latitude			
	10°	25°	40°	55°
$3f$	4.79	1.86	1.07	0.93
f	14.45	5.25	3.63	2.82

are significant (since s/σ_y exceeds 1.0) for wide ranges of downwind distances at which the σ_y formulations (and the associated Gaussian plume model) are valid. This indicates the range of conditions (stabilities, wind speeds and downwind distances) under which the Gaussian plume model will give overestimates of pollutant concentrations, or conversely, the conditions under which the effects of sea breeze induced wind veering will not be significant. In higher latitudes (greater than 40°) the effects of sea breeze induced veering will become significant at downwind distances of 1 to 3 km, and thus span much of the range of applicability (0.2 to 10.0 km) of the Gaussian plume model. The foregoing analysis assumes that veering affects only the mean wind direction and, consequently, the position of the plume. If veering also affects the turbulent intensity, modification of σ_y may be required.

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