An Analysis of Wind Fluctuation Statistics Collected under Stable Atmospheric Conditions at Three Sites in Alberta, Canada

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ABSTRACT

Wind fluctuation data collected under stable atmospheric conditions at two prairie sites and a site located near the Rocky Mountain foothills have been analyzed. Results of the analysis show a marked tendency for horizontal fluctuation angles to vary inversely with wind speed. In contrast, vertical fluctuation angles tended to be invariant with wind speed.

Atmospheric turbulence was much greater at the foothills site than at the prairie sites. This was mainly due to the fact that standard deviations of vertical wind angles were almost twice as great. Standard deviations of horizontal fluctuation angles were only about 20% greater.

1. Introduction

Increasing public awareness of risks associated with the accidental near-ground release of toxic gaseous material is causing more attention to be focused on turbulence under low wind speed stable atmospheric conditions. These are the situations that are usually associated with the highest hazard potential. This identification is often based upon use of the Pasquill-Gifford dispersion coefficients (e.g., Gifford 1968) which were obtained from the result of studies conducted at wind speeds of greater than about 2 m s^{-1} over flat terrain in Porton England (Pasquill 1961; Smith and Abbott 1961). These suggested that standard deviations of both horizontal and vertical wind fluctuation angles (σ_θ, σ_ϕ) decrease with decreasing wind speed and increasing stability. Results of recent more detailed investigations, however, do not support this conclusion.

An analysis of information by Hanna (1983) suggests that near the ground under stable flow and low winds the standard deviation of the horizontal wind speed, σ_V will tend to be constant, i.e.,

$$\sigma_V = A. \tag{1}$$

A consequence of Eq. (1) is that the standard deviation of the horizontal fluctuation angle σ_θ will increase with decreasing horizontal wind speed U ($\sigma_\theta \sim \sigma_V/U$). Evidence supporting the use of Eq. (1) has been supplied by various authors (e.g., Leahey and Halitsky 1973; Sagendorf and Dickson 1976; Hanna 1981, 1983; Schacher et al. 1982; Eidsvik 1985; Leahey and Hansen 1985a). Hanna (1983) found that values of A range from about 0.3 to 1.0 m s^{-1} depending on conditions such as averaging time, topography, synoptic situations and coastal influences. For a flat plain area in Idaho, he derived a value for A from hourly average σ_θ data, of about 0.5 m s^{-1}. This is in close agreement with the value of 0.55 m s^{-1} that Leahey and Hansen (1985b) found from an analysis of Doppler radar information collected over level prairie at Ellerslie, Alberta.

Investigations and dimensional analyses have also shown that the standard deviation of vertical wind σ_W under stable conditions tends to vary directly with wind speed, i.e.,

$$\sigma_W = BU. \tag{2}$$

The proportionality coefficient appears to be a slowly varying function of surface roughness, mixing depth, and height above ground (e.g. Pasquill and Smith 1983). Its magnitude is typically in the order of 0.1. Because vertical turbulence tends to decrease with decreasing wind speed it is difficult to evaluate using standard wind measuring devices under near-calm stable situations. It would be useful if Eq. (2) could be established for use at very low wind speeds where the sensitivity of the device for measuring vertical wind is limiting.

Horizontal and vertical wind fluctuation angles (σ_θ, σ_ϕ) are related to atmospheric turbulence by the relations

$$\sigma_\theta \sim \sigma_V/U \tag{3}$$

$$\sigma_\phi \sim \sigma_W/U. \tag{4}$$

From Eqs. 1–4 it follows that

$$\sigma_\theta \sim A/U \tag{5}$$

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and

$$\sigma_\phi \sim B \tag{6}$$

(Angles σ_θ, σ_ϕ expressed in Eqs. 3–6 are in radians).

Equations (5) and (6) were assessed using hourly averaged data collected at three sites in Alberta: two on the open prairie and the other near the foothills.

2. Description of sites and instrumentation

The first prairie site at which turbulence was measured was located near Mazeppa which is a small hamlet located about 30 km south of Calgary, Alberta. Terrain immediately adjacent to the location is grass covered and relatively flat. There are 100–150 m high hills at distances of about 10 and 15 km west and north of the site, respectively.

Terrain in the immediate vicinity of the second measurement site was similar to that surrounding the first. This site was located on the prairie about 1.5 km east of the city of Calgary, which has a population of 600 000 people. A large hill rises to an elevation of about 150 m at a distance of 14 km to the northwest.

The third and final site was located in the foothills of the Canadian Rockies about 100 km northwest of Calgary. The immediate vicinity of the site is characterized by open fields. Most of the region, however, is forested. Topography is irregular with many small hills. These rise to heights of up to 150 m within a distance of 5 km.

Devices used for measuring atmospheric parameters were identical at all three sites. They consisted of a Gill UVW anemometer located at 10 m for measuring horizontal and vertical wind speeds, and two temperature sensors placed at distances of 13 and 3 m above the ground. Propellers used in the wind instrument had a distance constant of 1 m. Sensing threshold for the wind measurement was 0.1 m s^{-1}. Temperature sensors were accurate to within ±0.1°C.

Readings were obtained from wind and temperature sensors about once a second and automatically processed into hourly values of U, σ_θ, σ_W and vertical temperature differences through use of an on-site computer.

TABLE 1. Observed median values of σ_θ and σ_ϕ as a function of wind speed under stable atmospheric conditions for a prairie site south of Calgary.

	Autumn			Winter		
U (m s^{-1})	σ_θ (deg)	σ_ϕ (deg)	N	σ_θ (deg)	σ_ϕ (deg)	N
0.6	52.0	2.8	121	47.0	2.5	245
1.5	23.0	2.6	412	24.0	2.8	443
2.5	15.0	3.3	161	15.0	2.9	331
3.5	9.5	3.2	132	12.0	2.9	183
4.5	10.0	3.3	53	10.5	3.0	100
5.5	8.0	3.1	34	9.0	3.3	85
6.5	9.0	3.8	31	8.0	3.0	41
7.5				6.0	2.9	35

TABLE 2. As in Table 1, except for a prairie site east of Calgary.

	Westerly winds			Easterly winds		
U (m s^{-1})	σ_θ (deg)	σ_ϕ (deg)	N	σ_θ (deg)	σ_ϕ (deg)	N
0.3	52.5	2.5	2			
1	29.0	2.5	44	30.0	2.5	29
2	13.0	2.5	152	18.0	2.5	61
3	10.0	2.5	126	9.0	2.5	85
4	8.0	3.0	107	9.0	3.0	65
5	8.0	3.5	81	7.0	4.0	24
6	8.0	4.0	52	6.5	4.3	8
7	9.0	4.0	33	7.5	4.3	6
8	8.5	4.0	14	7.5	4.0	2
9	7.0	4.0	11	7.0	3.5	1
10	7.0	3.8	4			
11	10.0	4.0	3			
12	6.0	3.5	1			
13	11.0	4.0	1			
14	6	3.5	1			

Time periods over which observations were collected depended on anticipated requirements set by regulatory agencies.

3. Analyses of data

Tables 1 to 3 give median hourly average values of σ_θ, σ_ϕ for each site, and the number of data, N, upon which they are based as functions of wind speed. Information is presented only for stable atmospheres, as determined by the requirement that the vertical temperature gradient $\geqslant -0.5$°C/100 m.

Data are shown classified according to season in Table 1 but according to wind direction in Tables 2 and 3. These classifications were not determined by the requirements of the present study but for purposes of meeting regulatory needs. Seasonal information at site 1 was needed for incinerator stack design purposes. Information at site 2 was divided according to whether the wind was from or toward the city of Calgary (westerly and easterly winds, respectively). At site 3, the data were assessed according to the diurnal wind flow pattern which is usually northwesterly (katabatic) during the night and southeasterly (anabatic) during the day.

a. *Variations of σ_θ with wind speed*

Values of A were calculated for each wind speed from Eq. (5). These were studied to determine the wind speed range over which they tended to be constant. This range was found to vary from about 0.5 to 5 m s^{-1} for the two prairie sites. For the foothills site, it was about 1 to 4 m s^{-1} under katabatic flow and only from 1 to 2.5 m s^{-1} under anabatic flow conditions.

The limited applicability of Eq. (5) under very low wind speeds was expected because the prediction of infinitely great values of σ_θ as wind speeds approach

TABLE 3. As in Table 1, except for Foothills Site.

	Northwesterly winds				Southeasterly winds			
U (m s^{-1})	σ_θ (deg)	N	σ_ϕ (deg)	N	σ_θ (deg)	N	σ_ϕ (deg)	N
0.2	60.0	11	4.3	10	61.0	17	5.2	7
0.5	54.0	246	4.3	192	57.5	122	5.2	88
1.0	33.0	289	7.6	225	34.5	176	9.3	121
1.5	23.0	165	7.0	117	25.0	92	9.3	53
2.0	21.0	77	6.3	51	19.0	68	9.9	41
2.5	19.0	64	7.4	40	17.5	36	9.9	25
3.0	16.0	61	7.7	38	23.5	20	11.8	18
3.5	15.0	29	6.2	21	21.0	15	8.1	14
4.0	12.5	18	7.9	10	20.0	12	9.7	12
4.5	14.0	11	7.8	7	18.5	8	8.9	7
5.0	14.0	7	5.7	4				
5.5	14.0	10	7.5	6				
6.0	20.5	2	7.9	2				

zero is obviously unreasonable. The limited applicability at wind speeds greater than a given threshold is also reasonable. This is because, at higher wind speeds mechanically generated turbulence should cause σ_V to increase significantly contrary to the assumption expressed in Eq. (1).

Values of A as estimated for the three sites did not seem to vary significantly with season or wind direction. Average values for each site are shown in Table 4. The one-to-one correlation coefficient R between predicted and observed values of σ_θ and the number of data N upon which it is based is also shown. This was calculated according to the relation

$$R^2 = 1 - \frac{\mathrm{SE}^2}{\mathrm{SD}^2}$$

where

SE = standard error of sample
SD = standard deviation of sample.

Values for A of 0.65 and 0.56 found for the prairie sites are similar to those found by previous investigators for flat terrain. They are only marginally less than the value for A of 0.73 found for the foothills site.

Figure 1 illustrates the agreement obtained between values of σ_θ observed at the two prairie sites and those predicted using an average value for A of 0.6 (radians). (This is equivalent to 34°). Substantial agreement is evident.

TABLE 4. Values of A and B as derived for the indicated site. The correlation coefficients are also shown.

Site	A	N	R	B	N	R
South of Calgary	0.65	10	0.92	0.056	10	0.95
East of Calgary	0.56	10	0.98	0.066	17	0.98
Foothills	0.73	11	0.79	0.140	18	0.89

b. Variations of σ_W with wind speed

Information shown in Tables 1–3 was analyzed to determine the applicability of Eq. (2). The wind device used in the studies, as previously mentioned had a threshold of about 0.1 m s^{-1}. Wind speed values of about this amount or less would have been underestimated by the measuring procedure. For this reason, only values of σ_W of greater than 0.15 m s^{-1} as obtained from Tables 1–3 through the relation $\sigma_W = U\sigma_\phi$ were used. This effectively limited the analysis to wind speeds

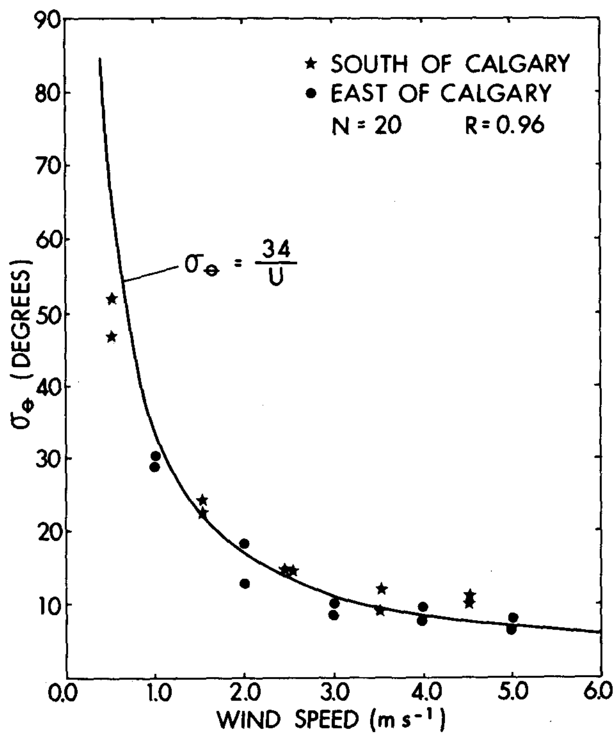

FIG. 1. Comparison between predicted and observed values of σ_θ.

greater than 3.5 m s^{-1} and 1 m s^{-1} at the prairie and foothill sites, respectively.

Results of the analysis for values of B are given in Table 4. Values of B for the two prairie sites are both about 0.06. The value applicable to the foothills site is over twice as large. Relative differences in values of B obtained for the prairie and foothills sites are thus much greater than differences in comparable values of A. This implies that topography and/or surface roughness exerted its greatest influence on the standard deviation of the vertical wind fluctuations.

The very substantial agreement between values of σ_W observed on the prairie sites and predictions using Eq. (2) with an average value for B of 0.06 is shown in Fig. 2. Values of σ_W obtained from observations at low wind speeds and not used in the correlation are also shown. The apparent tendency for the relationship to underpredict σ_W at high wind speeds is explainable by the fact that the value for B is an average obtained from data collected at two different sites. Agreement between predicted and observed σ_W data is nonetheless substantial. This demonstrates that values of σ_ϕ under stable atmospheric conditions should tend not to vary with wind speed.

4. Conclusion

An analysis of standard deviations of horizontal fluctuation angles has shown that they vary inversely with wind speeds ranging from about 0.5 to 5 m s^{-1} (i.e., $\sigma_\theta = A/U$) over relatively flat prairie. The constant A is about 0.6. The relationship is somewhat poorer for moderately irregular forested terrain and more restricted in its wind speed range. The constant A under these circumstances is about 0.75.

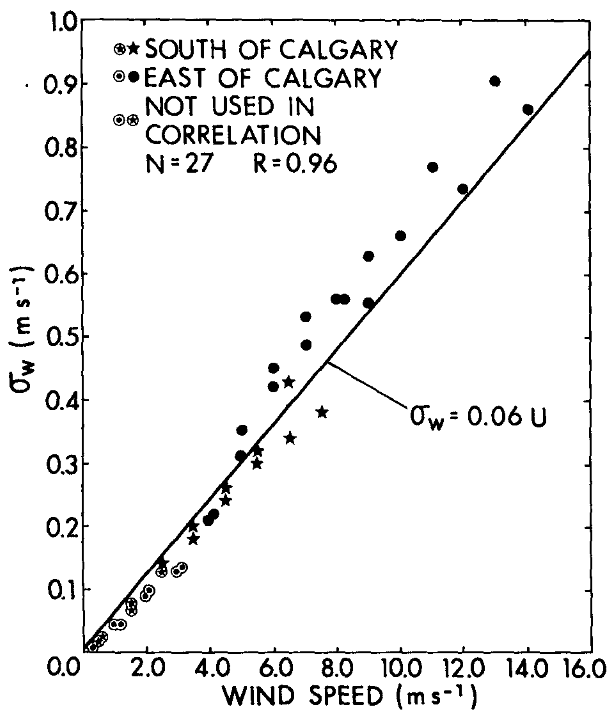

FIG. 2. Comparison between predicted and observed values of σ_W.

The assumption that under stable conditions the standard deviation of vertical wind speed is proportional to wind speed appears to be acceptable for both flat and irregular terrain. The proportionality constant B was found to be about 0.06 for prairie sites and 0.14 for the foothills region. This assumption, which implies that σ_ϕ is constant with wind speed, should be very useful under low wind speed situations when most wind devices cannot accurately measure vertical air fluctuations.

Results of this study indicate that forested, moderately irregular terrain under low wind speed stable conditions may lead to slightly increased values of σ_Θ. The terrain appears to have a much greater influence on values of σ_ϕ. These were observed to be over twice as great at the foothills site as at the prairie sites.

It should be stressed that values of A and B presented in this paper were derived from values of σ_θ and σ_ϕ calculated for hour-long periods. They should not be applied to directly estimate standard deviations of turbulent wind fluctuations for other time periods.

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