Variations of Wind Fluctuations Observed at 10 m over Flat Terrain under Unstable Atmospheric Conditions

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ABSTRACT

Turbulence data collected at the 10-m level during convective conditions at a site located amid flat terrain in Alberta have been analyzed with respect to wind speed U and normalized static stability S'_n. These two parameters have been assumed to respectively represent mechanical and thermal forces that engender atmospheric turbulence at ground level.

Observations of atmospheric turbulence show wide scatter in the value of the standard deviations of transverse, longitudinal, and vertical wind fluctuations (σ_v, σ_u, σ_w) for the same apparent conditions of mechanical and thermal forces (i.e., wind speed and static stability). It has been assumed that the large scatter is attributable to random localized effects such as those caused by the breaking of internal gravity waves. For this reason the present analysis has been restricted to median values of σ_v, σ_u, and σ_w in an effort to discern a pattern of behavior that may be explained in terms of U and S'_n. Equations have been empirically developed for median standard deviations of wind fluctuations in terms of wind speed and static stability. One-to-one correlation coefficients between predicted and observed data were typically in excess of 0.90.

Results of this study complement findings of a previous study done with the same database except for stable atmospheric situations. Information from the two studies allows for the estimation of parameters (σ_v/U, σ_u/U, σ_w/U) for use in plume dispersion models under a wide range of wind and stability conditions. Estimation procedures depend upon easily measured meteorological variables (U, S'_n). Illustrations of the dependencies have been provided.

1. Introduction

It has been the practice to estimate plume dispersion based upon schemes whereby atmospheric stabilities are categorized into discrete classes using such parameters as wind speed, cloud cover, and gustiness (e.g., Pasquill 1961; Cramer 1957; Smith and Singer 1966; Martin 1979). Plume dispersion parameters, usually in the form of standard deviations of plume spread, are then assigned to each stability category. These are then used in a Gaussian plume model to calculate ground-level contaminant concentrations resulting from emission sources. Categorization schemes, while of practical use, are not theoretically satisfying because they implicitly assume that atmospheric turbulence occurs in distinct subgroups. In actuality, of course, turbulence should tend to occur as a continuous function of meteorological variables.

Dispersion models have more recently been developed that employ values of standard deviation of wind fluctuations in order to assess ground-level consequences associated with stack emissions. Values of these standard deviations are usually calculated using parameters such as mixing height or sensible heat flux, which are difficult to estimate (e.g., Hanna and Chang 1993).

Leahey et al. (1994) have developed a series of equations that present half-hourly average standard deviations of transverse, longitudinal, and vertical wind fluctuations (σ_v, σ_u, σ_w) as functions of two easily measured parameters: wind speed and static stability. Their equations apply to turbulence at the 10-m level as observed over flat terrain under stable atmospheric conditions. Mechanical and thermal forces are implicitly parameterized in their equations by wind speed and static stability. Wind speed is commonly employed in most evaluations of atmospheric behavior. Static stability, which is less readily understood, may be defined as the restoring force to which a unit mass is subjected when displaced vertically by a unit distance. The force per unit mass whose potential temperature θ differs by $\Delta\theta$ from the surroundings on being displaced a distance Δz is (e.g., Scorer 1958)

$$S = -\frac{1}{\theta} g \frac{\Delta\theta}{\Delta z}, \quad (1)$$

where g is acceleration due to gravity. Static stability has a negative sign because it is in the opposite direction to Δz. Atmospheric conditions are defined as stable,

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neutral, or unstable according to whether the value of S is negative, zero, or positive, respectively.

Observations show that actual wind fluctuation data vary by more than a factor of 2 under what appears to be identical meteorological conditions. Leahey et al. (1994) assumed that this variation is attributable to nonhomogeneous, nonstationary phenomena such as the breaking of internal gravity waves, which are not a function of thermal or mechanical forces generated at ground level. As a consequence they developed and tested their predictive equations using median data in the belief that this would allow for the discernment of a behavior pattern that would be applicable over the full trajectory of a plume. This approach of basing predictive methods for atmospheric dispersion on mean or median data has met with general acceptance and success (e.g., Pasquill 1961; Smith and Singer 1966; Pasquill and Smith 1983; Martin 1979; Briggs 1973; Hanna et al. 1982; Leahey and Hansen 1985). The analysis presented in this paper uses the same data studied by Leahey et al. (1994). The distinction between this and the previous study lies in the type of atmospheric stability to which the data were restricted. The first paper addressed the subject of stable atmospheres ($\Delta\theta/\Delta z \geqslant 0.0$), whereas this paper presents results of studies relating to unstable atmospheres ($\Delta\theta/\Delta z \leqslant 0.0$). As indicated, both studies include data collected under neutral atmospheric conditions because at the associated singular value $\Delta\theta/\Delta z = 0.0$ their conclusions must be the same.

The major cause of atmospheric instability is solar heating of the earth's surface. Other secondary causes of atmospheric instability may be due to movement of cold air over warm ground, longwave radiation from clouds that are warmer than the earth's surface, and latent heat release from freezing water. All of these secondary causes of instability may be occasioned, for example, by an outburst of a shallow layer of arctic air. Equations developed and tested in this study have been restricted to periods of instability caused by solar heating. Analysis of data associated with cold-air advection has been left to another study.

The main objective of this study, as in the prior one, is to present equations that describe patterns of behavior between turbulence parameters, wind speed, and static stability. A quantitative understanding of these patterns should provide insights that will help in the formulation of physical explanations for their occurrence. For the sake of simplicity, the equations used to describe the patterns have been limited to linear or exponential expressions. In the limit as static stability approaches zero (i.e., neutral atmospheres), results of studies into stable and unstable atmospheres must agree. It is necessary for this reason to consider the equations empirically derived for stable atmospheric conditions by Leahey et al. (1994):

$$\sigma_v = \begin{cases} 0.25, & U < 0.75 \quad (2) \\ 0.37, & 0.75 \leqslant U \leqslant 3.0 \quad (3) \\ 0.37 + 0.068(U - 3.0), & U > 3.0 \quad (4) \end{cases}$$

$$\sigma_u = \begin{cases} 0.27, & U < 0.75 \quad (5) \\ 0.41, & 0.75 \leqslant U \leqslant 3.0 \quad (6) \\ 0.41 + 0.18 \\ \quad \times (U - 3.0)e^{-0.45S_n}, & U > 3.0 \quad (7) \end{cases}$$

$$\sigma_w = 0.04 + 0.075Ue^{-0.45S_n}, \quad U > 0.0, \quad (8)$$

where U is the wind speed (m s^{-1}) and S_n is the static stability normalized by its average observed value of -0.0032 s^{-2}.

A perusal of the Eqs. (2)–(8) shows that values of σ_v, and σ_u decrease abruptly as wind speed decreases below 0.75 m s^{-1}. At low wind speeds, both these parameters are apparently independent of local surface-generated mechanical and thermal forces. This may be because at these wind speeds atmospheric turbulence is more related to macroscale phenomena, such as gravity, pressure, and Rossby waves, than to surface-related disturbances. Both σ_u and σ_w have the same exponential dependency on S_n for wind speeds greater than 3.0 m s^{-1}.

When plume dispersion models employ the standard deviations of wind fluctuations they are usually divided by wind speed. The resulting ratios σ_v/U, σ_u/U, σ_w/U, referred to as standard deviations of the horizontal, longitudinal, and vertical wind angles, are denoted as σ_θ, σ_φ, and σ_ϕ. (These parameters are also sometimes referred to as turbulence intensities.) Many values of these parameters are cited in the literature for unstable atmospheric conditions. Gifford (1976) suggests values of σ_θ for slightly, moderately, and very unstable atmospheric conditions of 15°, 20°, and 25°, respectively. Briggs (1973) recommends standard deviations of plume dispersion that effectively assume values for σ_θ for the same meteorological situations of 6°, 9°, and 13°. Both Gifford and Briggs assume that σ_θ is constant with wind speed. Cramer (1957) recommended a constant value for σ_ϕ of 10° for extremely unstable conditions. Briggs (1973) effectively assumes about the same value.

There is little information available about σ_φ, but it is usually assumed to be proportional to σ_θ. This is because σ_u is commonly assumed to be proportional to σ_v (e.g., Panofsky et al. 1977; Panofsky and Dutton 1984; Leclerc et al. 1988). The proportionality constant varies from unity to about 1.3.

Results presented in this paper show relationships between wind fluctuations, wind speed, and static stability from data collected over flat terrain at Kathyrn, Alberta, from October 1988 to September 1989 inclusive by the Alberta Energy Resources Conservation Board (ERCB). Kathyrn lies about 20 km northeast of Calgary. The information was collected as part of theoretical and observational studies designed to better delineate risks associated with sour gas (i.e., gas containing hydrogen sulfide) pipeline ruptures. Temperature gradient data were collected between the 10- and 2-m levels using copper–constantan thermocouple junctions. A Kaijo Denki Co. Ltd. model DAT 310 sonic anemometer with the TR61A probe situated at the 10-m level was used for wind measurements. All information was collected in the form of 3-min averages. These were subsequently used to estimate half-hourly average values of parameters discussed in this paper. More details as to site location, instrumentation, and data collection and analyses procedures may be found elsewhere (ERCB 1990; Leahey et al. 1994).

2. Results of data analyses

This study evaluates wind fluctuation data for unstable atmospheres ($\Delta\theta/\Delta z \leqslant 0.0$) as a function of static stability and wind speed. There were 5435 half-hourly average values of each turbulence parameter (σ_v, σ_u, σ_w) available for analyses.

Static stability varies inversely with ambient temperature (K) and directly with vertical potential temperature gradient (K m^{-1}). Annual average and standard deviations of ambient temperatures in the Kathyrn area are about 277 and 12 K, respectively. Comparable information for $\Delta\theta/\Delta z$ as they relate to unstable atmospheres are −0.04 and −0.02 K m^{-1}. The average value for static stability observed under unstable atmospheric conditions is about 0.0014 s^{-2}.

Static stabilities used in the data analyses were normalized by their average observed value of 0.0014 s^{-2}. They are differentiated from static stabilities for stable atmospheres by a prime (′). Thus in this paper primed values of S_n always refer to unstable atmospheric conditions, unprimed values always refer to stable situations; the subscript *n* always means normalized static stability. Values for S'_n of 0.5, 1.0, and 2.0, for example, indicate static stabilities in unstable atmospheres that are one-half, same, and twice as great as the average values observed in unstable atmospheres at Kathyrn, Alberta, from October 1988 to September 1989 inclusive.

As mentioned, the purpose of this paper is to describe the behavior of turbulence associated with unstable atmospheres caused by solar heating of the ground. An examination of the data showed that there were three periods in early spring during which unstable conditions tended to occur throughout the day. All the periods were associated with northerly winds, indicating an advection of arctic air into the region. The first outburst of arctic air (9–11 March) resulted in a 20°C drop in maximum afternoon temperatures. The later periods (24 March–1 April; 6–9 April) were characterized by temperature drops of about 4° and 7°C, respectively. These two later periods were associated with precipitation with above and below freezing temperatures in the afternoon and evenings, respectively. The nocturnal events of instability that characterized these periods could have been caused by a combination of heat conduction from the ground, longwave radiation from warm clouds that might have existed above a shallow layer of arctic air, and/or latent heat releases caused by evening freezing of surface groundwater.

There was a total of 551 half-hourly periods during the outbursts of arctic air in which potential temperature gradients were negative during evening and early morning hours. Magnitudes of these gradients tended to be four to five times larger than those observed during other times of the year. They were not considered as being representative of unstable atmospheres caused by solar heating. This means that about 10% of all available data were rejected for purposes of this study. Turbulence information collected during the remaining periods of atmospheric instability was assessed as functions of static stability and wind speed. Table 1 presents percentile values of $\Delta\theta/\Delta z$ along with associated static stabilities, normalized by the average value of 0.0014 s^{-2} and rounded to the nearest 0.05. Values of S'_n ranged over about an order of magnitude from 0.10 to 2.65. By comparison the values of S_n used to develop equations that describe the behavior of stable atmospheric turbulence ranged over two orders of magnitude from 0.05 to 5.00.

Equations have been empirically developed for σ_v, σ_u, and σ_w. The form of the equations has been constrained by the requirement that when $S'_n = 0$, they must be identical to Eqs. (2)–(8) when $S_n = 0$. For equation development, values of σ_v, σ_u, and σ_w were divided into 10 subsets according to associated temperature gradients. There were approximately 490 half-hourly average values for each turbulence parameter with associated wind speed in each subset. The first subset was associated with the 0–10 percentile values of potential temperature gradients; the second set was associated with the 10–20 percentile values of potential temperature gradients. The 5 percentile value of potential temperature gradient was considered representative of the first subset of data, the 15 percentile value for the second subset, etc.

a. Variations of σ_v with wind speed and static stability

Figure 1 presents a plot of median half-hourly average σ_v values corresponding to three values of S'_n (0.10, 1.10, 2.65) as a function of wind speed. The graph illustrates average σ_v values for the wind speed range 1–3 m s^{-1}. Lines are shown indicating increases of σ_v at wind speeds greater than 3 m s^{-1}. They are based upon the assumption that the increase is given by the relation $B_v(U - 3.0)$, where the value of B_v has been determined by least-squares methods. The number of data upon which each median, shown in this figure, is based was arbitrarily restricted to values equal to or greater than 10. This procedure was adopted for all medians discussed in this paper. The consequential number of data upon which medians were based ranged from 10 to 54 with an average value of 28.

TABLE 1. Values of indicated percentiles of $\Delta\theta/\Delta z$ (K m^{-1}) with associated values of the normalized static stability.

Percentile	$\Delta\theta/\Delta z$ (K m^{-1})	S'_n
5	−0.003	0.10
15	−0.009	0.20
25	−0.016	0.40
35	−0.025	0.60
45	−0.033	0.80
55	−0.043	1.10
65	−0.054	1.35
75	−0.064	1.60
85	−0.079	2.00
95	−0.106	2.65

A perusal of Fig. 1 shows that

- σ_v associated with $S'_n = 0.10$ at very low wind speeds ($U = 0.5$ m s^{-1}) has about the same value as that observed during stable conditions (i.e., 0.25 m s^{-1}).
- Average values of σ_v for the wind speed range 1–3 m s^{-1} increase with increasing S'_n values.
- Values of σ_v tend to increase with wind speed when $U > 3.0$ m s^{-1}.
- Large instabilities ($S'_n = 2.65$) tended not to occur at wind speeds of less than 2.5 m s^{-1}.

Equation (3) shows that at low wind speeds when $S'_n = 0$ (or alternatively $S_n = 0$), σ_v has a value of 0.37 m s^{-1}. It was assumed for simplicity that departures from this value were directly proportional to S'_n; that is, $\sigma_v - 0.37 = A_v S'_n$, where A_v is a proportionality constant.

Table 2 presents the mean and standard deviations (SD) of observed values of σ_v for the wind speed range 1–3 m s^{-1}. It also shows associated values of A_v. The means increased with increasing S'_n values. Values of A_v were usually about 0.30. They did not appear to vary in a systematic fashion with S'_n. For assessment purposes it was arbitrarily decided to accept the value for A_v of 0.33 corresponding to a middle S'_n range value of 1.10.

Values of σ_v for wind speeds greater than or equal to 3 m s^{-1} were approximated by the relation

$$\sigma_v = 0.37 + 0.33 S'_n + B_v(U - 3.0). \qquad (9)$$

Values of B_v, shown in Table 2 as a function of static stability, were obtained by least-squares methods. Values of B_v tended to decrease with increasing S'_n. The correlation coefficient R between observed σ_v values for wind speeds greater than 3 m s^{-1} and those predicted using Eq. (9) is also given in Table 2.

This one-to-one correlation coefficient R was calculated using the expression

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

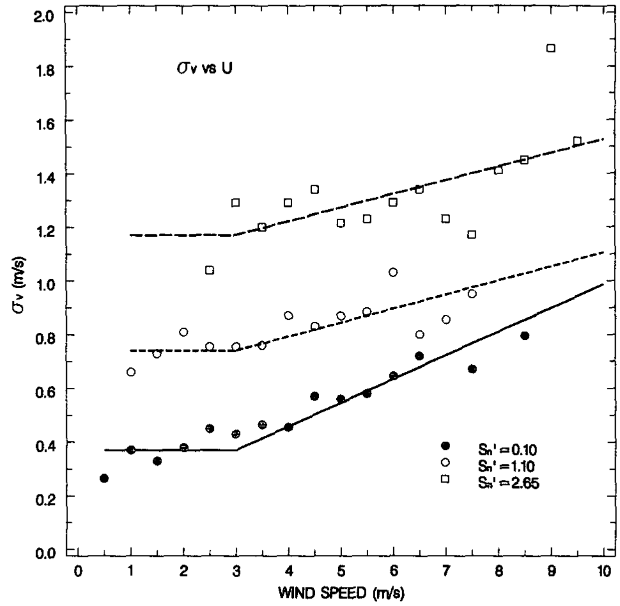

FIG. 1. Median values of σ_v as a function of wind speed for three different static stability conditions (0.10, 1.15, 2.65). Descriptions of the straight lines are given in the text.

where SE is the standard error of estimate and σ is the standard deviation of sample.

Table 2 shows that R has a value of 0.00 when S'_n is equal to 1.10 and 1.60. The failure to achieve finite values of R for all data should not be surprising when it is recognized that the data contain perturbations due to random phenomena.

It was assumed for purposes of simplicity that B_v decreased exponentially with decreasing static stability; that is,

$$B_v = C_1 e^{-C_2 S'_n}.$$

Because of the boundary conditions imposed by Eq. (4) when $S'_n = 0$, C_1 must be equal to 0.068. A value

TABLE 2. Mean and standard deviations (SD) of median σ_v values for the wind speed range $1.0 \leq U \leq 3.0$ m s^{-1} under indicated stability conditions. Values for A_v, B_v, and correlation coefficient R are also shown.

S'_n	Mean (m s^{-1})	SD (m s^{-1})	A_v (m s^{-1})	B_v	R
0.10	0.39	0.043	0.20	0.078	0.93
0.20	0.43	0.051	0.30	0.088	0.93
0.40	0.51	0.041	0.35	0.077	0.86
0.60	0.56	0.052	0.32	0.069	0.22
0.80	0.66	0.046	0.36	0.072	0.84
1.10	0.74	0.049	0.33	0.056	0.00
1.35	0.81	0.039	0.33	0.043	0.63
1.60	0.86	0.088	0.31	0.048	0.00
2.00	0.98	0.024	0.31	0.020	0.57
2.65	1.17	0.130	0.30	0.029	0.55

for C_2 of 0.18 was derived such that B_v was 0.056 when S'_n had a value of 1.10 (see Table 2). For assessment purposes C_2 was subsequently rounded to 0.20.

The following equations are consequently recommended for purposes of estimating σ_v:

$$\sigma_v = \begin{cases} 0.25, & U < 0.75 \text{ m s}^{-1} \\ \frac{1}{3}(S'_n + 1.1), & 0.75 \leq U \leq 3.0 \text{ m s}^{-1} \\ \frac{1}{3}(S'_n + 1.1) + 0.068(U - 3.0)e^{-0.20S'_n}, & U > 3.0 \text{ m s}^{-1}. \end{cases}$$

The value of 1.1 in the aforementioned equations ensures, in keeping with the constraint imposed by Eq. (3), that $\sigma_v = 0.37$ when $S'_n = 0.0$.

Figure 2 shows a comparison between 130 median observed σ_v values and those predicted using the aforementioned equations. The correlation coefficient was 0.96 and the standard error of estimate was 0.08 m s^{-1}. Values of σ_v associated with $S'_n = 1.10$ were not included in the values shown in Fig. 2. This is because they could not therefore be considered part of an independent dataset, as they were used to obtain values of A_v and B_v used in the prediction scheme.

b. *Variations of σ_u with wind speed and static stability*

Figure 3 presents a plot of median σ_u for three values of S'_n (0.10, 1.10, 2.65) as a function of wind speed. The figure shows lines illustrating the average σ_u for the wind speed range 1–3 m s^{-1}. Lines are also shown indicating increases of σ_u at wind speeds greater than 3 m s^{-1}. These are based upon the assumption that the increase is given by the relation $B_u(U - 3.0)$, where the value of B_u has been determined by least-squares methods.

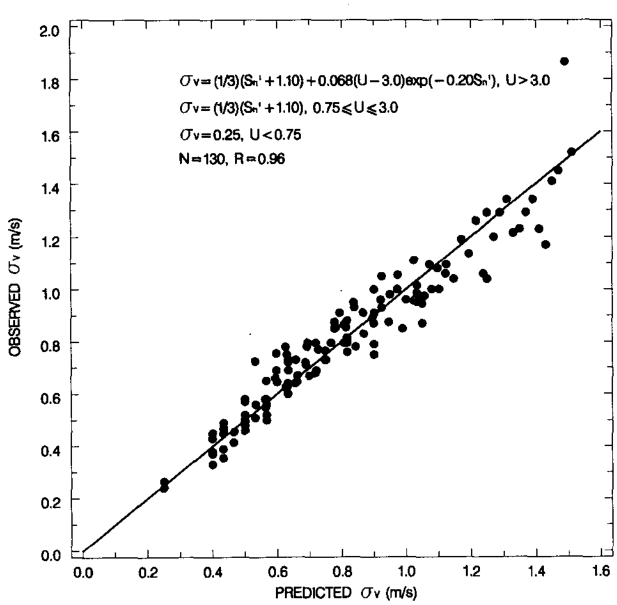

FIG. 2. Comparison between predicted and observed σ_v. The straight line shows the one-to-one relationship.

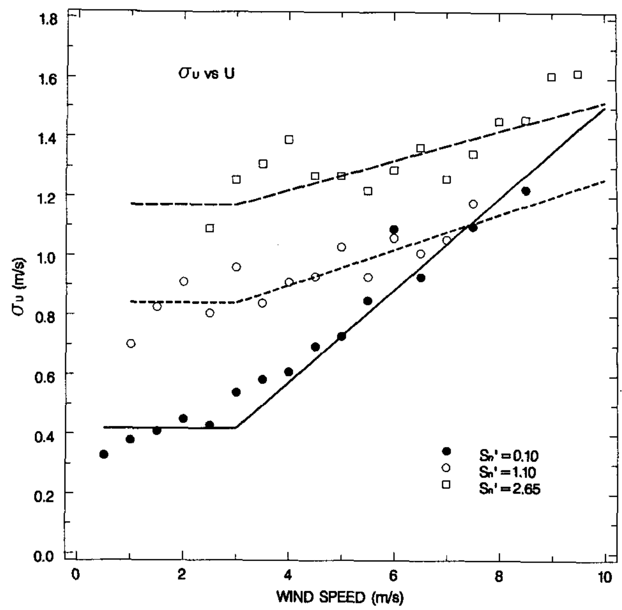

FIG. 3. Median values of σ_u as a function of wind speed for three different static stability conditions (0.10, 1.15, 2.65). Descriptions of the straight lines are given in the text.

A perusal of Fig. 3 shows that

- At very low wind speeds with a value of $S'_n = 0.10$, σ_u was 0.33 m s^{-1}. This is somewhat larger than the value of 0.27 m s^{-1} associated with stable atmospheres.
- Average values of σ_u for the wind speed range 1–3 m s^{-1} increased with increasing S'_n values.
- Increases of σ_u for winds greater than 3 m s^{-1} tended to be given by the relationship $B_u(U - 3.0)$.

Analyses to show the variation of σ_u with wind speed and static stability were conducted in the same fashion as those used for σ_v. Table 3 presents mean and standard deviations of median σ_u for the wind speed range 1–3 m s^{-1}. It also shows values of A_u and B_u, which are analogous to the A_v and B_v parameters given in Table 2. Values of A_u are similar to A_v. There is a steady decrease of B_u values with increasing S'_n.

It was assumed for assessment purposes that $A_u = A_v = 0.33$. At $S'_n = 0.0$ the value of B_u is constrained by Eq. (7) to be 0.18. It was assumed that it decreased exponentially with increasing S'_n with an exponent 0.74 derived such that $B_u = 0.080$ when $S'_n = 1.10$. For assessment purposes the exponent was subsequently rounded to 0.75.

The following equations are consequently recommended for purposes of estimating σ_u:

TABLE 3. Mean and standard deviations (SD) of median σ_u values for the wind speed range $1.0 \leq U \leq 3.0$ m s^{-1} under indicated stability conditions. Values for A_u, B_u, and correlation coefficient R are also shown.

S'_n	Mean (m s^{-1})	SD (m s^{-1})	A_u (m s^{-1})	B_u	R
0.10	0.42	0.06	0.10	0.155	0.95
0.20	0.48	0.10	0.35	0.148	0.96
0.40	0.56	0.03	0.38	0.142	0.97
0.60	0.60	0.06	0.32	0.125	0.94
0.80	0.69	0.10	0.35	0.095	0.84
1.10	0.84	0.09	0.39	0.080	0.86
1.35	0.91	0.15	0.37	0.077	0.36
1.60	0.97	0.10	0.35	0.054	0.75
2.00	1.03	0.05	0.31	0.028	0.60
2.65	1.17	0.08	0.29	0.021	0.64

$$\sigma_u = \begin{cases} 0.27, & U < 0.75 \text{ m s}^{-1} \\ \frac{1}{3}(S'_n + 1.24), & 0.75 \leq U \leq 3.0 \text{ m s}^{-1} \\ \frac{1}{3}(S'_n + 1.24) + 0.18(U - 3.0)e^{-0.75 S'_n}, & U > 3.0 \text{ m s}^{-1}. \end{cases}$$

The value of 1.24 in the aforementioned equations ensures that $\sigma_u = 0.41$ when $S'_n = 0.0$. This is in accordance with the boundary condition imposed by Eq. (6).

Figure 4 shows a comparison between 130 median observed σ_v values and those predicted using the aforementioned equations. The correlation coefficient and the standard error of estimate were 0.96 and 0.08 m s^{-1}, respectively. Values of σ_v associated with $S'_n = 1.10$ were excluded from the analyses because they were used to derive the exponential form for B_u.

c. *Variation of σ_w with wind speed and static stability*

Figure 5 presents a plot of median σ_w for three values of S'_n (0.10, 1.10, 2.65) as a function of wind speed. The figure shows lines, fitted by least-squares methods, illustrating the manner in which σ_w increases with wind speed. They show that σ_w tended toward a maximum value of about 0.70 m s^{-1} as wind speed increased toward 9 m s^{-1}.

It was assumed that

$$\sigma_w = 0.04 + A_w + B_w U.$$

The value of 0.04 was included in the aforementioned equation because of boundary requirements imposed by Eq. (8) at $U = 0.0$. This boundary condition additionally requires that $A_w = 0.0$ when $S'_n = 0.0$. Values of A_w and B_w as determined by least-squares methods are shown in Table 4; A_w increased with increasing values of S'_n while B_w decreased. Table 4 also shows

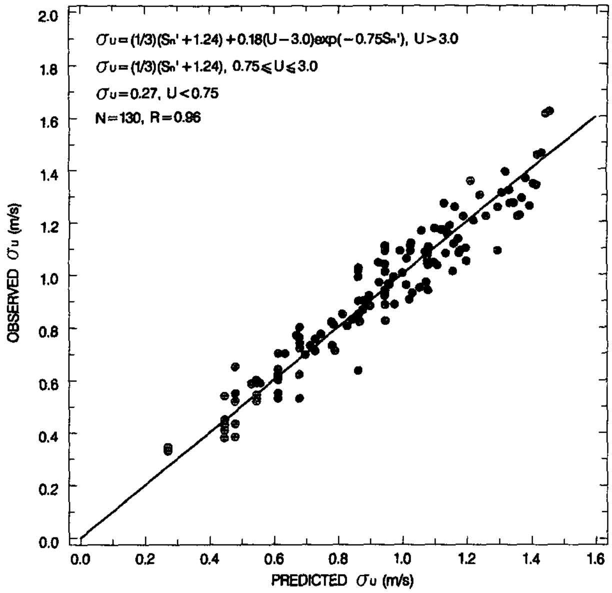

FIG. 4. Comparison between predicted and observed σ_u. The straight line shows the one-to-one relationship.

that correlation coefficients between median observed and predicted σ_w values were usually greater than 0.95.

Values of A_w were assumed to increase exponentially with S'_n according to the relation

$$A_w = C_3(1 - e^{C_4 S'_n}).$$

It was arbitrarily decided to derive parameters C_3 and C_4 using A_w values shown in Table 4 for $S'_n = 0.40$

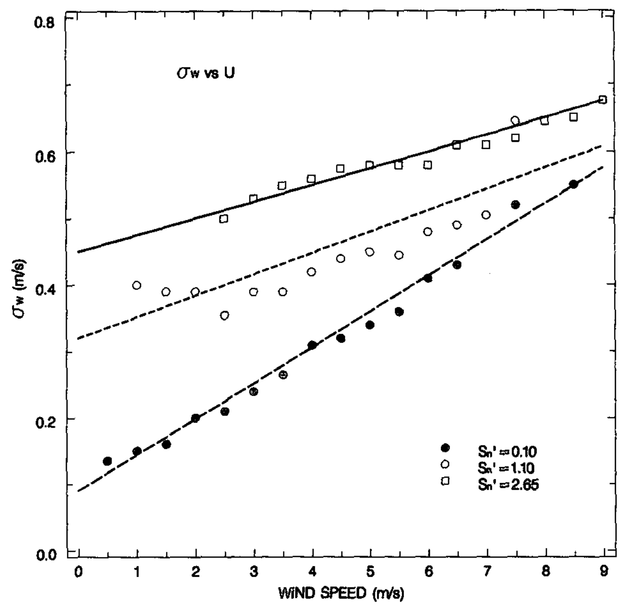

FIG. 5. Median values of σ_w as a function of wind speed for three different static stability conditions (0.10, 1.15, 2.65). Descriptions of the straight lines are given in the text.

TABLE 4. Values of A_w and B_w for the indicated stability conditions. Values for the correlation coefficient R are also shown.

S'_n	A_w (m s^{-1})	B_w	R
0.10	0.05	0.054	0.99
0.20	0.06	0.056	0.99
0.40	0.12	0.049	0.98
0.60	0.18	0.038	0.96
0.80	0.23	0.030	0.97
1.10	0.28	0.032	0.96
1.35	0.35	0.017	0.88
1.60	0.36	0.022	0.91
2.00	0.38	0.022	0.95
2.65	0.41	0.025	0.97

and 1.60. (This means that C_3, C_4 were obtained from the 25 and 75 percentile values of S'_n.) They were subsequently rounded to the nearest 0.05 value. It followed that

$$A_w = 0.70(1 - e^{-0.45S'_n}).$$

Values of B_w must equal 0.075 when $S'_n = 0.0$ [see Eq. (8)]. They were assumed to decrease exponentially with increasing S'_n. The exponent of 0.77, determined such that $B_w = 0.022$ when $S_n = 1.60$, was subsequently rounded to 0.75.

The following equation is consequently recommended for purposes of estimating σ_w:

$$\sigma_w = 0.04 + 0.70(1 - e^{-0.45S'_n}) + 0.075Ue^{-0.75S'_n}.$$

Figure 6 shows a comparison between 115 median observed σ_w values and those predicted using the aforementioned equations. The correlation coefficient and standard error of estimate were 0.95 and 0.04 m s^{-1}, respectively. Values of σ_w associated with S'_n values of 0.40 and 1.60 were excluded from the evaluation because they were used in deriving parameters used in the prediction equation.

d. Derived values of σ_θ, σ_φ, and σ_ϕ

Equations have been derived for σ_v, σ_u, and σ_w as a function of wind speed and degree of stability (S'_n) for unstable atmospheric situations. They are in agreement with corresponding equations previously developed for stable atmospheres at $S_n = 0$. The two sets of equations allow estimates to be made of standard deviations of wind fluctuations for a full range of atmospheric conditions. Ratios of these standard deviations to wind speed define values of σ_θ, σ_φ, and σ_ϕ.

Figures 7, 8, and 9 illustrate the behavior of σ_θ, $\sigma_\varphi/\sigma_\theta$, and σ_ϕ as functions of stability and wind speed. In keeping with observations, the range of values of S_n is shown as being twice as great as that for S'_n.

Figure 7 presents estimates of the standard deviations of the transverse wind angle σ_θ for three wind speeds (2, 4, 6 m s^{-1}) as a function of atmospheric stability.

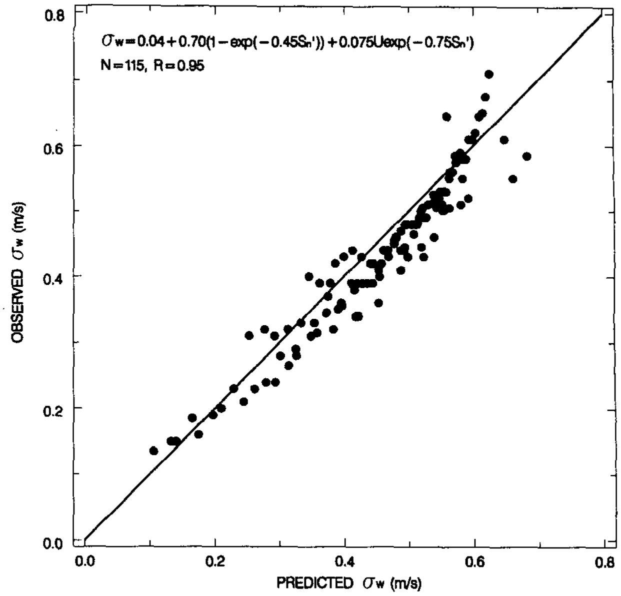

FIG. 6. Comparison between predicted and observed σ_w. The straight line shows the one-to-one relationship.

Values of σ_θ do not vary with the degree of stability (S_n) under stable atmospheric situations. They increase almost linearly with increasing values of instability (S'_n). The rate of increase is greatest at the lower wind speeds.

Figure 8 shows calculated values of the ratio $\sigma_\varphi/\sigma_\theta$ for three wind speed conditions. This ratio tends to be close to unity at low wind speeds but becomes appre-

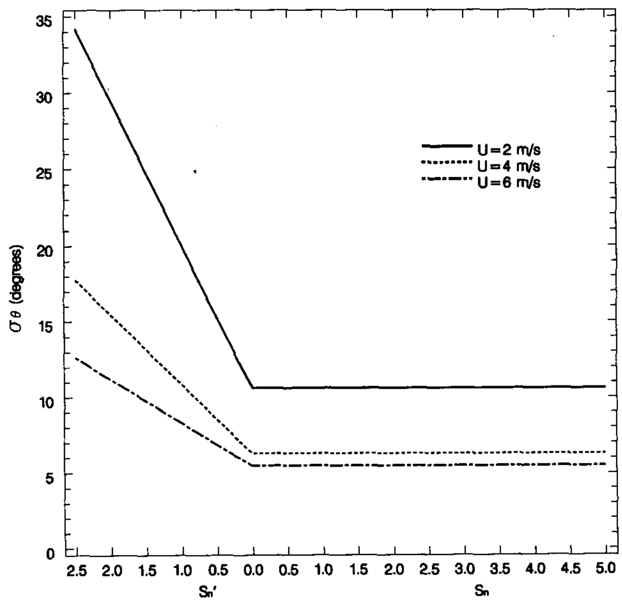

FIG. 7. Median values of σ_θ as a function of atmospheric stability for three wind speed conditions (2, 4, 6 m s^{-1}).

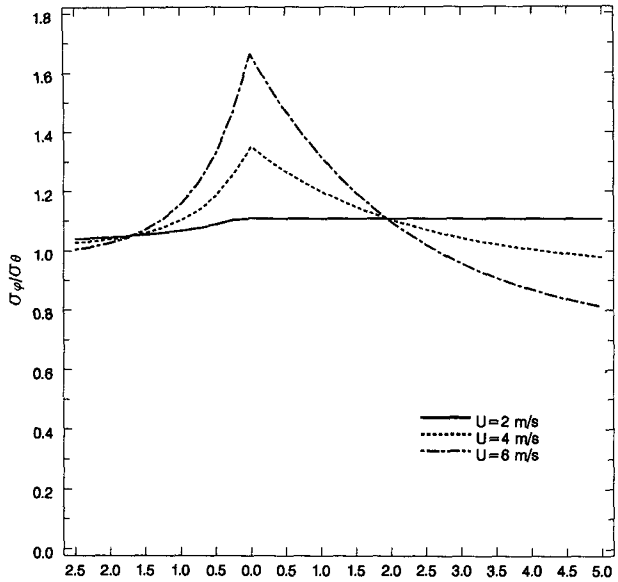

FIG. 8. Median values of $\sigma_\varphi/\sigma_\theta$ as a function of atmospheric stability for three wind speed conditions (2, 4, 6 m s^{-1}).

ciably greater than unity under conditions of near neutral atmospheres and high wind speeds. It becomes less than unity at high wind speeds and moderate to very stable atmospheric conditions.

Figure 9 presents estimates of σ_ϕ as a function of wind speed and atmospheric stability. They are much more sensitive to wind speed under unstable than under stable atmospheric conditions. Values of σ_ϕ become insensitive to S_n' with increasing wind speed. Under very stable atmospheric conditions, and moderately high wind speeds, σ_ϕ values approach 1°.

3. Summary and conclusions

Analyses of median σ_v, σ_u, and σ_w data collected over flat terrain at Kathyrn, Alberta, have shown predictable patterns attributable to mechanical and thermal forces as parameterized by wind speed and static stability. The patterns expressed in equation form as part of these analyses depend upon whether atmospheric conditions are stable or unstable.

Stable atmospheric conditions:

- Horizontal and vertical turbulence have background values manifested at low wind speeds, which are independent of mechanical and thermal forces.
- Transverse turbulence (σ_v) generated by mechanical forces is not affected by static stability.
- Longitudinal and vertical turbulence (σ_u, σ_w) generated by mechanical forces are progressively dampened in the same manner by increasing static stability.

Unstable atmospheric conditions:

- Horizontal and vertical turbulence have constant background values similar to those that exist during stable atmospheric conditions.
- The amount of turbulence generated by mechanical forces is progressively dampened by increasing static instability. The longitudinal and vertical components are dampened to the same degree and appreciably more than the transverse component.
- Thermal forces generate longitudinal and transverse components of turbulence to the same degree.
- As static instability increases values of σ_w exponentially approach a constant value indicating an upper bound to the degree of vertical turbulence sustainable by thermal forces.

Dampening effects of static stability (or instability) on the levels of longitudinal and vertical turbulence generated by mechanical forces are similar. The fact of similar dependencies suggest a close physical relationship between σ_u and σ_w. There does not appear, however, to be as close a relationship between these components of turbulence and σ_v.

Plume dispersion will depend upon patterns of turbulence behavior. Equations developed for turbulence intensities as a result of the studies conducted at Kathyrn, Alberta, allow for straightforward assessments of plume dispersion for a wide range of wind speeds and atmospheric stabilities.

It should be noted that values of static stability used in these studies have been normalized by the average value of static stability observed in the Kathyrn area under stable and unstable atmospheric conditions. It

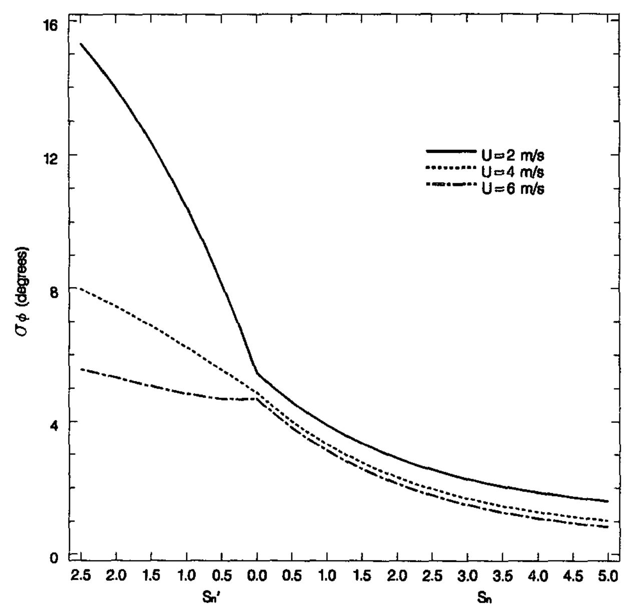

FIG. 9. Median values of σ_ϕ as a function of atmospheric stability for three wind speed conditions (2, 4, 6 m s^{-1}).

is, however, a simple matter to adjust the equations and graphs presented in this paper for any other desirable normalizing factor. For this reason the selection of the normalizing factor does not restrict the general applicability of results presented in this paper.

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