An Examination of Residual Wind Fluctuations Observed at 10 m over Flat Terrain

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(Manuscript received 25 January 1995, in final form 5 May 1995)

ABSTRACT

This study investigates the behavior of wind fluctuations observed at the 10-m level over a flat terrain site located some 100 km east of the Rocky Mountains. The purposes were to assess residual fluctuations in order to ascertain effects attributable to the nonhomogenous, nonstationary character of turbulence and to evaluate influences of gravity waves. Residual wind fluctuations were defined for purposes of this study as the differences between observed half-hourly average standard deviations of wind fluctuations (σ_v, σ_u, σ_w) and those that are expected to occur in association with simultaneous wind speeds and static stabilities. These latter fluctuations were estimated from equations developed by Leahey, Hansen, and Schroeder (LHS).

Results of the analyses showed, as expected, that residual distributions for nonwesterly wind conditions were nearly Gaussian. Standard deviations for residuals of horizontal fluctuations, attributable to the nonhomogenous, nonstationary nature of turbulence, were 0.165 and 0.210 m s^{-1} for stable and unstable situations, respectively. For residuals associated with vertical fluctuations they were, respectively, 0.065 and 0.075 m s^{-1}.

Residuals for horizontal and vertical wind fluctuations observed when winds were from the mountains showed a greater tendency for the positive bias associated with gravity waves. This tendency was most evident under unstable conditions when gravity wave influences on horizontal fluctuations were apparent about 25% of the time. These influences are explained as being associated with mountain lee waves occurring at the planetary boundary layer's capping inversion. They are evidenced at the 10-m level because atmospheric mixing processes occurring in thermally unstable atmospheric situations bring momentum generated from these waves downward to the ground.

Nonstationary and nonhomogenous atmospheric turbulence effects result in wind fluctuations whose half-hourly average standard deviations differ from those predicted by the LHS equations. Differences under stable atmospheres and low to moderate wind speeds are typically less than 50% of predicted values. They decrease as a percentage of predicted values with increasing wind speed and decreasing stability.

1. Introduction

Variations in wind fluctuations are usually attributed to either turbulence or gravity waves. Atmospheric flow is called turbulent if its vorticity is randomly distributed in time and space, whereas atmospheric modes of motion are called waves if they propagate with respect to a coordinate system advected with a velocity specified by the mean flow field (Busch et al. 1969).

Turbulence is generated mechanically in stable atmospheres usually by wind shears near the ground. Under unstable atmospheric conditions turbulence is generated by both mechanical and buoyancy forces. Its kinetic energy is dissipated under all conditions by viscous forces (Pasquill and Smith 1983). Equations have been developed that describe turbulence in terms of the standard deviations of the wind fluctuations. Mechanical and buoyancy forces are usually parameterized within these equations by locally occurring frictional and convective velocities (e.g., Stull 1988; Panofsky et al. 1977; Hicks 1985; Wyngaard 1989); Leahey et al. (1994, 1995) have developed equations in which they are parameterized by local wind speed and static stability. These equations, which forecast standard deviations of wind fluctuations attributable to locally generated turbulence, relate only to representative values such as the median or mean. They do not allow for the nonstationary, nonhomogenous nature of the atmosphere, which may result in levels of turbulence unattributable to local thermal and mechanical forces. Thus, if a steady strong wind should decrease, a relatively high level of mechanically generated turbulence could persist then slowly decay. Such a nonstationarity phenomenon, sometimes referred to as "fossil turbulence" (e.g., Woods et al. 1969), cannot be accounted for by the simultaneously occurring wind speed. Similarly, for example, uneven heating and cooling of the earth's surface because of variable cloudiness might result in a locally patchy pattern of turbulence. Consequential levels of turbulence in these horizontally nonhomogenous conditions may occur at a given site because of advection and be unrelated to local meteorological conditions. Because nonstationarity and nonhomogeneity effects tend to occur randomly, they

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should result in a Gaussian distribution of differences between actual levels of turbulence and those attributable to locally occurring generators.

Gravity waves can exist only when the atmosphere is stably stratified so that a fluid parcel displaced vertically will undergo buoyancy oscillations. They are apparent, not only near the ground, but also within the capping inversion surmounting the convectively active planetary boundary layer (PBL) (Hooke and Jones 1986). A wide variety of dynamic phenomena are causes of gravity wave excitation. These include wind shear, thunderstorm activity, and frontal passages (Finnigan et al. 1984; Stull 1976; Egger et al. 1993; Haase 1991). Mountain lee waves are also manifestations of gravity wave phenomena. They will tend to occur in the upper atmosphere at discontinuities in the temperature profile (e.g., Scorer 1958) such as occur at capping inversions under unstable atmospheric situations. It is not surprising given their many potential causes, that gravity waves have been found through use of acoustic echo sounders (Hooke and Jones 1986) and microbarographs (Gedzelman 1983) to be nearly ubiquitous within stable air. Their effects with respect to wind fluctuation behavior is, however, still largely unresolved.

Gravity waves are distinguished from turbulence because they are considered to be deterministic; we can in principle solve for their velocity and displacement at any location and time. Equations that describe turbulence, on the other hand, forecast only the statistics of the perturbation.

Analyses of wind fluctuation data collected in the presence of stable atmospheres are complicated by the fact that the two different kinds of motion (turbulence, gravity waves) are intermingled. There is no clear-cut distinction between the two. When turbulence exists in a stratified fluid, some of the energy is transformed into waves. On the other hand, the breaking of gravity waves, as the result of ground encounters or changes in governing conditions related to static stability or wind speeds, results in turbulence growth. It is not possible to clearly distinguish the portion of atmospheric energy attributable to turbulence or gravity waves when energy is constantly flowing between the two kinds of motion. It is recognized that there is a fuzzy ground between turbulence and wave phenomena. But as we are reminded by Stewart (1969), "Just because various shades of orange exist does not mean that we cannot distinguish between red and yellow."

This paper presents the results of an analysis of residual wind fluctuation data as observed at the 10-m level over flat terrain. Residual wind fluctuations have been defined as fluctuations that are unexplainable in terms of local mechanical and thermal forces associated with atmospheric behavior near the ground. They have been assessed in terms of the half-hourly average standard deviations of horizontal, transverse, and vertical wind fluctuations (σ_u, σ_v, σ_w). There was a twofold purpose to the investigation: first to estimate variances in wind fluctuation levels attributable to nonstationary, nonhomogenous atmospheric turbulence and second to assess effects attributable to gravity waves.

Information used in the residual analyses was 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, Alberta, and about 100 km east of the Rocky Mountains. The area was selected with a view to obtaining an observational site characterized by terrain as flat as practically achievable. The general area is very regular for at least 10 km in all directions with gently rolling hills. Within 2 km of the actual observational site, the terrain has negligible slopes in the south–north direction. The terrain rises from the east to the west with a slope of 0.015 (0.9°). It was covered with agricultural crops during summer months. The aerodynamic surface roughness varied from about 0.01 to 0.04 m for winter and summer months, respectively (ERCB 1990).

Temperature gradient data were collected between the 10- and 2-m levels using copper-constantan thermocouple junctions. A Kaijo Denki Co. Ltd. model DAT310 sonic anemometer with the TR61A probe situated at the 10-m level was used for wind measurements. It is designed to yield data with accuracy within ±1%. 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 instrumentation and data collection and analyses procedures may be found elsewhere (ERCB 1990; Leahey et al. 1994).

2. Theory

It has been assumed that any phenomenon that results in random occurrences of wind fluctuation data is effectively turbulence. Its presence is manifested in a Gaussian distribution of residual fluctuations R,

$$R = O - P, \tag{1}$$

where

O is the observed standard deviation of wind fluctuations (m s^{-1}) and

P is the standard deviation of wind fluctuations attributable to local mechanical and thermal forces (m s^{-1}).

As values of O are never less than 0, it follows from Eq. (1) that the lower bound for R is $-P$. In order that the distribution for R follow the "bell-shaped curve" it must also follow that the upper bound for R is $+P$. This means that the maximum observed standard deviation of wind fluctuations attributable to turbulence should not exceed twice the value of P.

Gravity waves, for purposes of this study, will be considered as a nonlocal phenomenon. This means that unlike turbulence, they will not be considered the result of local variations in wind speed and static stability. The presence of gravity waves will always express itself in greater wind fluctuations than would have occurred in their absence and, in consequence, be evident in a positive bias in values of R. Such a bias, for example, would be apparent when gravity waves occur on the PBL's capping inversion to the lee of the Rocky Mountains, which lie some 100 km west of the Kathyrn observational site. Thermal mixing within the PBL will bring momentum generated by these waves periodically toward the ground resulting in bursts of atmospheric activity reflected in greater wind fluctuations.

Equations developed by various investigators may be used to provide values of P. Many of these equations rely upon similarity theory and are expressed in terms of frictional and convective velocities and mixing depths (e.g., Stull 1988), which are difficult to measure. In addition, their parameterizations tend to be based on only limited field observations taken during relatively ideal conditions (Hanna and Chang 1992). Values of P, for this investigation were estimated from equations developed for half-hourly average values of σ_u, σ_v, and σ_w by Leahey et al. (1994, 1995) from a full year of information. Their equations are relatively easy to apply in so far as they parameterize turbulence on the basis of wind speed and static stability, which require a knowledge of easily available meteorological data. One-to-one correlation coefficients between predicted and observed median data were consistently large, being usually about 0.95.

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)

$$S = -\frac{g}{\theta}\frac{\Delta\theta}{\Delta z}, \qquad (2)$$

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

The Leahey–Hansen–Schroeder (LHS) equations relate to turbulence observed at the 10-m level over flat terrain under stable and unstable atmospheric conditions. They pertain to mechanical turbulence generated by the wind and to thermal turbulence caused by radiational cooling and heating. Equations for σ_v, σ_u, and σ_w (m s^{-1}) are as follows:

stable atmospheres ($\Delta\theta/\Delta Z \geqslant 0.0$):

$$\sigma_v = \begin{cases} 0.25, & U < 0.75 \text{ m s}^{-1} \\ 0.37, & 0.75 \leqslant U \leqslant 3.0 \text{ m s}^{-1} \\ 0.37 + 0.068\,(U - 3.0) & U > 3.0 \text{ m s}^{-1} \end{cases}$$

$$\sigma_u = \begin{cases} 0.27, & U < 0.75 \text{ m s}^{-1} \\ 0.41, & 0.75 \leqslant U \leqslant 3.0 \text{ m s}^{-1} \\ 0.41 + 0.18\,(U - 3.0)\,e^{-0.45 S_n}, & \\ \quad U > 3.0 \text{ m s}^{-1} & \end{cases}$$

$$\sigma_w = 0.04 + 0.075\,U\,e^{-0.45 S_n}, \quad U \geqslant 0.0 \text{ m s}^{-1}$$

unstable atmospheres ($\Delta\theta/\Delta Z \leqslant 0.0$):

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

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

$$\sigma_w = 0.04 + 0.70\,(1 - e^{-0.45 S'_n}) + 0.075\,U e^{-0.75 S'_n}, \quad U \geqslant 0.0 \text{ m s}^{-1}.$$

As indicated, equations for both stability conditions include neutral atmospheric situations because their predictions at the associated singular value $\Delta\theta/\Delta z = 0.0$ are the same. Static stability utilized in the equations (S_n, S'_n) has been normalized by average values of S observed at Kathyrn during stable and unstable conditions. These values are -0.0032 and 0.0014 s^{-2}, respectively. Normalized values for unstable atmospheres are differentiated from those for stable conditions by a prime ($'$). Thus, primed values of S_n always refer to unstable atmospheric conditions, and unprimed values always refer to stable situations; the subscript n always means normalized static stability. Wind speed is denoted in the equations by U.

An examination of the LHS equations shows that they predict background values of horizontal and vertical turbulence, which becomes manifest at low wind speeds. Thus, for example, under stable atmospheric

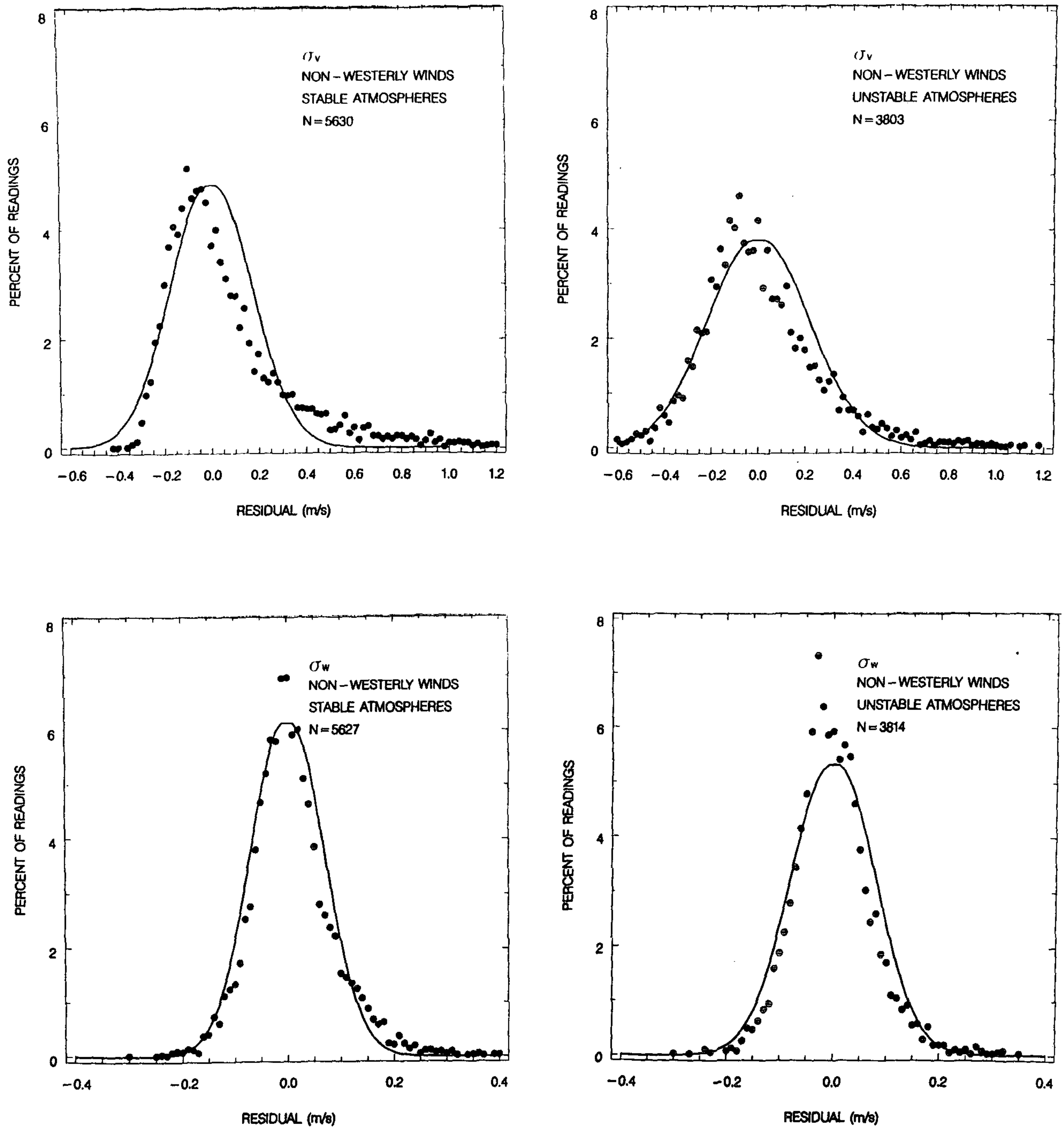

FIG. 1. Percent of readings for each 0.02 and 0.01 m s^{-1} increment of σ_v and σ_w residuals, respectively, as observed during nonwesterly winds. The number of data (N) upon which the data are based is shown.

conditions, the standard deviation of vertical wind fluctuations, σ_w, is predicted to approach a background value of 0.04 m s^{-1} as horizontal winds approach zero. These background values for turbulence were derived from the Kathyrn data without regard to wind direction.

3. Results of data analyses

Data concerning residuals were initially stratified according to atmospheric stability and wind direction. Stratification according to wind direction was made in order to assess any influence that might be evident in

TABLE 1. Values of A and B for straight-line relationships between standard deviations of residuals and wind speed. Values of the linear correlation coefficient R_1 are also shown.

	Atmospheric conditions					
	Stable			Unstable		
Residual	A (m s^{-1})	B	R_1	A (m s^{-1})	B	R_1
σ_v (m s^{-1})	0.185	−0.0075	0.87	0.230	−0.004	0.36
σ_u (m s^{-1})	0.130	0.0125	0.80	0.185	0.009	0.61
σ_w (m s^{-1})	0.025	0.0090	0.97	0.062	0.0045	0.48

the wind fluctuation data as a result of the presence of the Rocky Mountains. Frequency distributions of residual values were analyzed for stable and unstable atmospheric conditions as observed under westerly (southwest, west-southwest, west, west-northwest, northwest sectors) and nonwesterly wind direction conditions. Spring thaw episodes characterized by decreases of ambient temperatures from above to below freezing values were omitted from the analyzed dataset in order to eliminate latent heat of fusion influences from the assessments.

a. *Distribution of residuals observed under nonwesterly wind conditions*

It quickly became evident from the data analyses that residual frequencies tend to have Gaussian distributions under nonwesterly wind conditions. Negative residuals were in better agreement with the bell-shaped curve than were positive values. This was expected because of the bias toward positive values caused by gravity waves. Distributions of residuals for σ_v and σ_u were found to be similar.

Standard deviations for Gaussian distributions suitable for describing the nonstationary, nonhomogenous effects of atmospheric behavior were derived using negative residuals. For this purpose, data for σ_v and σ_u were combined to obtain Gaussian distributions suitable to both parameters. Median values for the negative residuals were obtained for the 11 nonwesterly 22.5° wind sectors. The average of these was then used to obtain the appropriate standard deviation under the assumption that 50% of all residuals should lie within 0.68 standard deviations from the mean (assumed to be zero). In this fashion, standard deviations for residuals—attributable to nonstationary, nonhomogenous atmospheric effects—of 0.165 and 0.065 m s^{-1} were, respectively, derived for σ_v (σ_u) and σ_w for stable atmospheric conditions. Corresponding values obtained for unstable atmospheric conditions were somewhat larger, being 0.210 and 0.075 m s^{-1}.

An examination of the agreement between predicted and observed frequencies for σ_w residuals for nonwesterly wind conditions showed a consistent tendency for observed distributions to lag predicted values by an abscissa value of about 0.02 m s^{-1}. To obtain better agreement for these wind direction conditions, the background value of 0.04 m s^{-1} contained in the LHS equations was reduced to 0.02 m s^{-1}.

Figure 1 presents the agreement between observed and predicted distributions for σ_v and σ_w residuals for nonwesterly winds. One-to-one correlation coefficients between predicted and observed frequencies are in excess of 0.95. Agreement is especially good for the σ_w values. The Gaussian distributions underestimate frequencies of large positive σ_v residuals, especially for stable atmospheric conditions. Though not shown on the graphs, because of space restrictions, residuals of σ_v and σ_w under stable atmospheric conditions extended to values up to about 3.5 and 1.5 m s^{-1}, respectively. They extended up to about 3.0 and 0.35 m s^{-1} under unstable conditions.

Residual data collected during nonwesterly winds were also analyzed for stable and unstable atmospheric conditions as functions of wind speed. Data were stratified into 1 m s^{-1} wind speed classes. Standard deviations were estimated, as previously, by dividing the median negative residual value obtained for a given wind speed class by 0.68. The number of data on which each median was based was arbitrarily restricted to values equal to or greater than 10. Consequential wind speeds used in the analyses ranged from about 1.0 to 12 m s^{-1}. Number of data used to derive the medians ranged from 10 to 700 with average values of 240 and 160 for stable and unstable atmospheric conditions, respectively.

Results of fitting the standard deviation data to the line $y = A + BU$ by least squares methods are presented in Table 1. Agreement between the straight-line relationship and the standard deviation of residuals was much better for stable than unstable atmospheric conditions. Standard deviations of residuals for all parameters were also more dependent on wind speed (i.e., B was larger) under stable than under unstable atmospheric situations. Standard deviations of residuals for σ_v decreased with increasing wind speed (B is negative), whereas the opposite was true for σ_u (B is positive).

b. *Distribution of residuals observed under westerly wind conditions*

Residuals occurring under westerly wind conditions had frequency distributions that were not as Gaussian

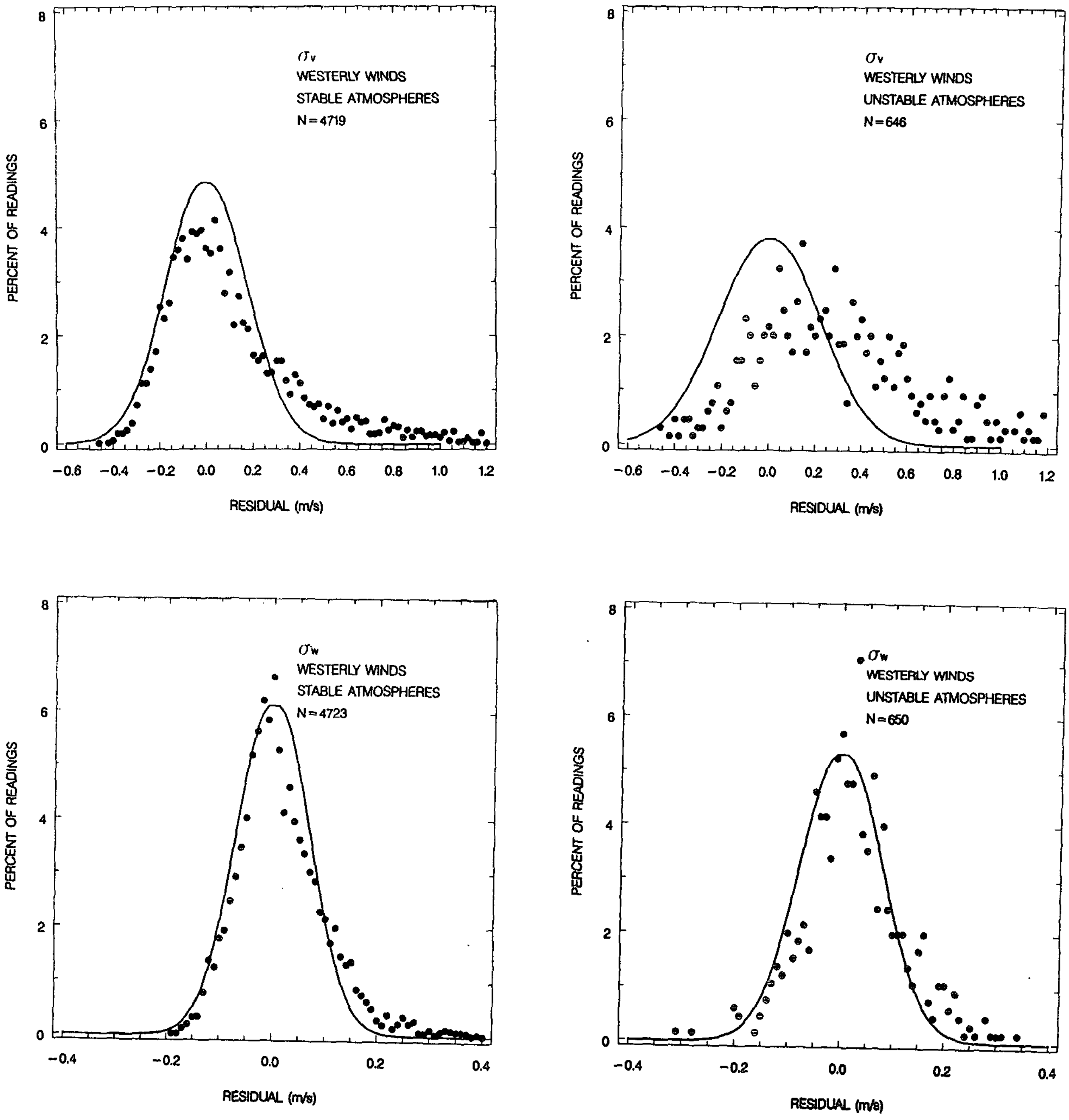

FIG. 2. Percent of readings for each 0.02 and 0.01 m s^{-1} increment of σ_v and σ_w residuals, respectively, as observed during westerly winds. The number of data (N) upon which the data are based is shown.

as those that occurred during nonwesterly wind situations. This is illustrated in Fig. 2, which compares observed frequencies with Gaussian distributions previously derived from nonwesterly winds. All observed distributions show a more marked bias toward positive values than those presented in Fig. 1. The bias was particularly noticeable under unstable conditions, especially for horizontal turbulence. Once again, the largest positive values for residuals for σ_v and σ_w are not shown because of space restrictions. They reached maximum values similar to those attained under nonwesterly wind conditions.

The background turbulence for σ_w of 0.04 m s^{-1} as predicted by the LHS equations appears to be suitable under westerly wind conditions. This conclusion was reached because observed and predicted frequency distributions for residuals do not show a consistent shift pattern.

TABLE 2. Ratios (%) of standard deviation of residuals to values of the standard deviations of turbulence predicted by the LHS equations for the indicated wind speed class and atmospheric stability condition.

	Wind speed class					
	0.00–0.75 (m s^{-1})		1.00–5.00 (m s^{-1})		5.00–10.00 (m s^{-1})	
Residual	Stable	Unstable	Stable	Unstable	Stable	Unstable
σ_v	70	90	45	30	20	20
σ_u	50	70	40	25	25	20
σ_w	80	20	40	20	30	15

c. *Estimates of gravity wave influence*

It was assumed that the frequencies of positive residual values of σ_v and σ_w in excess of those given by the appropriate Gaussian curve were caused by gravity waves. Derived differences were subsequently rounded to the nearest five percent. Under stable atmospheric conditions, the estimated occurrence of gravity wave influences on σ_v was about 10% and 15% of the time for nonwesterly and westerly winds, respectively. The increase of gravity wave influences with changing wind direction was thus quite small. Under unstable situations, however, the respective values were 5% and 25% of the time, indicating that wind changes from nonwesterly to westerly resulted in a fivefold increase in the apparent occurrence of gravity waves.

The gravity wave influence was less apparent on σ_w than on σ_v (σ_u) residuals. Under stable conditions, gravity waves were apparent about 5% and 10% of the time during nonwesterly and westerly wind conditions, respectively. The respective values for unstable atmospheric situations were about 0% and 10%.

d. *Uncertainties associated with use of the LHS equations*

Nonstationary and nonhomogenous atmospheric effects cause wind fluctuations whose standard deviations are not in agreement with median values as predicted by the LHS equations. Information contained in Table 1 was used to estimate consequential uncertainties that might arise in the estimations of σ_v, σ_u, and σ_w. Ratios of derived standard deviations of the residuals at given wind speeds to predicted values of σ_v, σ_u, and σ_w were obtained for typical stable and unstable situations ($S_n = S'_n = 1.0$). Results of the calculations rounded to the nearest five percent are presented in Table 2 for three wind speed classes. They show that uncertainties, under stable atmospheres and low to moderate wind speed (1–5 m s^{-1}), are typically less than 50% of predicted values. The uncertainties decrease as a percentage of predicted values with increasing wind speed and decreasing stability. When near-calm situations exist, the uncertainties in σ_v, σ_u, and σ_w may approach the magnitude of predicted values.

4. Discussions and conclusions

Half-hourly average standard deviations of residual wind fluctuation data obtained for nonwesterly winds should be generally representative of conditions existing over flat terrain at distances well removed from mountainous areas. This conclusion appears reasonable because influences of mountain lee waves on the data were apparent for no more than 10% of the time. Residuals were appreciably more dependent on wind speeds for stable than for unstable atmospheres. Such behavior suggests that spatial and temporal variations in wind fluctuations may be less sporadic and more organized under stable than unstable atmospheric situations. This conclusion also appears to be supported by the fact that nonhomogenous, nonstationary effects, as expressed by the residuals, are greater for unstable than for stable atmospheres.

The LHS equations indicate a background value of 0.04 m s^{-1} for values of σ_w. This value appears to be appropriate for westerly winds from the mountainous areas. A lower value of 0.02 m s^{-1} appears to be appropriate for other wind directions.

Gravity wave influences on wind fluctuations were apparent in horizontal data collected under conditions of westerly winds especially during unstable atmospheric conditions. The tendency for gravity wave influences to be most apparent during unstable conditions may be explained as being caused by mountain lee waves occurring on the capping inversion of the PBL. Thermal mixing of the atmosphere associated with unstable conditions will bring momentum generated by these waves toward the ground. Vertical fluctuation data tended not to show the influences of these gravity waves because they were obtained too close to the ground (10 m) to be able to reflect effects of any large-scale vertical motion. Occasional evidences of gravity wave influences under nonwesterly wind conditions is attributable to the fact that upper winds might be westerly (and thus from the mountains) even though 10-m winds indicate otherwise. The apparent gravity wave influences may also be attributable to frontal passages or effects of thunderstorm activity.

The LHS equations have been used in this paper to establish references from which residual wind fluctuations are calculated. The general appropriateness of the equations is supported by the near-Gaussian distribution obtained for residual turbulence under nonwesterly wind conditions. Standard deviations of the residual wind fluctuations will tend to be overestimated to the extent that the equations are not acceptable. Future investigators can presumably demonstrate better reference equations by showing that their estimates of residual turbulence are smaller than those reported in this paper.

Acknowledgments. The comments and suggestions of Mr. Randy Angle and Dr. Lawrence Cheng from Alberta Environmental Protection were very much appreciated.

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