Horizontal Variability in 10 m Wind Velocities as Observed at Two Prairie Sites Separated by a Distance of 7.5 km*

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ABSTRACT

It is important to assess the representativeness of mesoscale wind data because most short range pollution models assume that wind velocity will remain constant over distances in the order of 10 km. Previous observational studies have shown that average hourly mesoscale differences in wind directions and speeds might be typically about 25 degrees and 1 m s^{-1}.

Initial results of this study using all available data, tended to agree with the above findings. Further analyses, however, were performed for periods to which most pollution models are restricted. These periods are usually characterized by the absence of mesoscale wind phenomena and terrain effects associated with katabatic winds. Hourly wind direction differences for these periods were found to be typically only about 10 degrees regardless of atmospheric stability. Wind speed differences were still typically about 1 m s^{-1}.

Differences of both wind speed and direction were normally distributed, suggesting that horizontal mesoscale wind velocity differences occur randomly. For this reason it may be impractical to attempt the development of short-range plume dispersion models that physically account for horizontal inhomogeneities.

1. Introduction

Short range models for predicting the transport and diffusion of atmospheric pollution over distances of about 10 km often assume that horizontal wind velocities are constant during plume travel times. Errors introduced into model estimates by this assumption are not usually evaluated. Assessment of these errors should take into account the degree and nature of horizontal variabilities.

While many observations and modeling efforts have been made with respect to vertical variations in wind speed (e.g., Hanna et al. 1982), comparatively little has been done to assess horizontal variability. It is known, however, that appreciable variations can occur over relatively short distances even under flat terrain conditions. This is because of mesoscale phenomena associated with internal gravity waves, synoptic disturbances, thunderstorms, and differing surface radiational effects. Variability in wind velocities can also occur because of the sheltering and channelling effects of terrain and associated katabatic and anabatic winds which are gravity driven (e.g., Munn 1966). Effects of terrain features can exhibit themselves at distances that seem to be very large in terms of their heights. Leahey and Hansen (1982), for example, showed that 300 m high hills can influence air flows at distances of up to at least 70 km.

Slade (1968) has reported the results of horizontal variability studies conducted near San Antonio, Texas, and Oak Ridge National Laboratory. The San Antonio study involved hourly wind data collected at four standard weather stations with an average separation distance of about 19 km. The average standard deviations of wind direction and wind speed differences between the six possible pairs of unlike station combinations were about 37 degrees and 2 m s^{-1}, respectively. Similar data were studied in the hilly area around the Oak Ridge National Laboratory. In this case a central station was compared to 16 satellite stations at an average distance of 4 km from the central station. Directions between stations agreed on average within 22.5 degrees about 40 and 70 percent of the time during night- and daytime periods, respectively.

Hanna (1982) discusses an unpublished report by Lockhart and Irwin (1980) in which the authors showed, from data collected in the St. Louis area, that standard deviations of differences in wind speed and direction between stations would increase with the natural logarithms of their separation distance. For the observational sites considered in this paper, which are separated by a distance of 7.5 km, they would predict standard deviations of about 25 degrees and 1.0 m s^{-1}.

Hanna (1982) also reports results of studies by

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C. J. Nappo which were based on hourly data collected at 25 monitoring stations in the St. Louis area. Nappo found that the standard deviation in spatial wind directions σ_θ (spatial) was virtually independent of stability. Values of the standard deviation of spatial wind speeds σ_U (spatial), however, tended to increase by about 35 percent as atmospheric stability increased from unstable to stable. Empirical equations derived by Nappo give σ_θ (spatial) and σ_U (spatial) as functions of wind speed:

$$\sigma_\theta\,(\text{spatial})^2 = (5)^2 + (60/U)^2 \tag{1}$$

$$\sigma_U\,(\text{spatial})^2 = U^2[(0.15)^2 + (0.6/U)^2] \tag{2}$$

where σ_θ (spatial) and σ_U (spatial) are given in degrees and m s^{-1}.

Results of the above studies suggest that predictions of short-range pollution models could be in appreciable error because of horizontal variability in the wind field. Uncertainties of 25 degrees in wind direction would introduce, for example, differences of about 4 km in the predicted position of a plume axis at a downwind distance of 10 km.

Analyses have been made of data collected at two sites located on the prairie in order to obtain a better understanding of the reasons for horizontal variability in the wind field. Frequency distributions of differences in hourly average wind speeds and directions were examined for purposes of evaluating effects of "normal" conditions, mesoscale phenomena and terrain influences.

2. Description of sites and instrumentation

Differences were assessed in 10 m wind velocities as measured at two stations designated as Crossfield West (CW) and Crossfield East (CE). They are located in Alberta amid slightly irregular, virtually treeless terrain, in an area about midway between the town of Crossfield (population 1500) and the city of Airdrie (population 10 000). A topographical map showing locations of the monitoring sites and a major highway is given in Fig. 1. Elevations are shown in meters above mean sea level. The altitude difference between the two stations, which are separated by 7.5 km, is about 50 m. Terrain is shown as sloping from about 1200 m in the southwest to about 1000 m in the northeast over a distance of about 20 km. The CE station lies in a shallow valley with a SE–NW orientation. Low hills rise about 15 m above the CE station at a distance of 1 km.

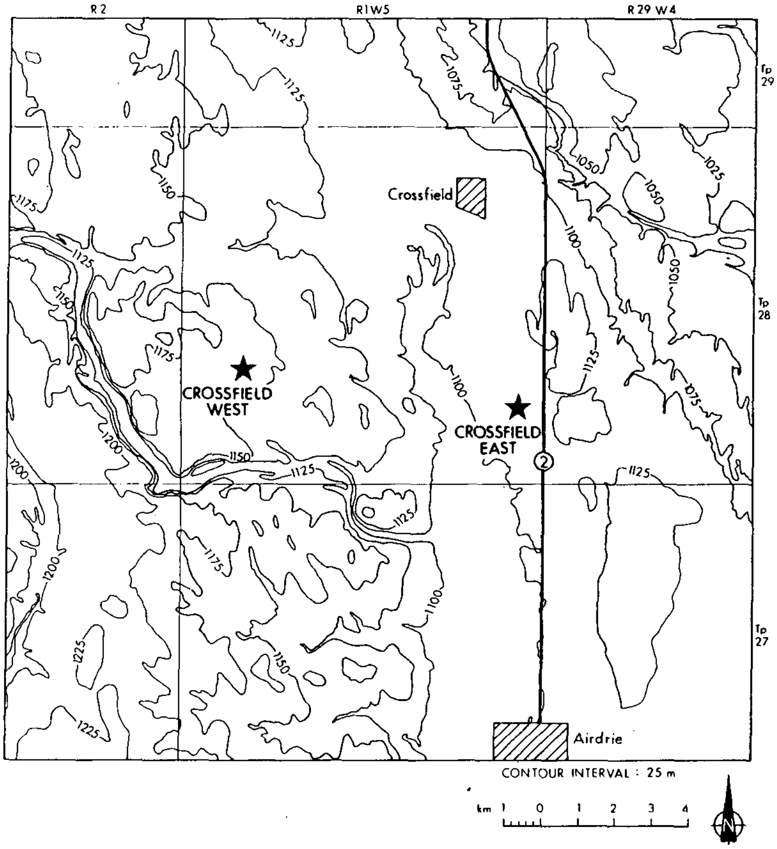

FIG. 1. Topographical map showing the locations of the Crossfield West (CW) and Crossfield East (CE) monitoring sites.

A Weathertronics 2020 Micro Response vane with a resolution of less than 1 degree was used for measuring wind directions. It has a threshold wind speed of 0.8 km h^{-1} (0.22 m s^{-1}) with a distance constant of 1.07 m. Wind speed was measured to the nearest 1 km h^{-1} (0.28 m s^{-1}) using the Weathertronics 2031 Micro Response Anemometer which has a threshold wind speed of 1 km h^{-1} and a distance constant of 1.5 m. Wind measuring devices were placed at the end of 1 m booms for purposes of minimizing wind shadow effects of the tower. They were overhauled on a 6 month basis. This involved detailed component assessment, routine replacement of ball bearings and associated lubrications.

Ambient stability was determined through the use of Weathertronics 4480A thermistors placed at the 3 and 13 m levels of the meteorological tower located at CE. These temperature measuring devices were accurate to within about ±0.1°C. They had motor aspirated temperature shields (Weathertronics model 8152 A) to provide protection against sunlight and the elements.

Output channels of the monitoring instruments were scanned by the control component of a data acquisition system approximately every five seconds. Responses were summarized and processed into vector averages of wind direction, wind speed and arithmetic averages of vertical temperature gradients. Observations extended over about a 20 month period from 13 March 1986 to 31 October 1987. Collection efficiency for concurrent wind and temperature data was about 87 percent. Most of the downtime was due to power failure, maintenance procedures, and short term problems related to the data acquisition system.

3. Analyses of data

For purposes of analysis, wind data were separated according to whether they were collected during stable, neutral or unstable atmospheric conditions. Stable and unstable atmospheres were associated with the requirement that the vertical temperature gradient be greater than or equal to $-0.5°C/100$ m or less than $-1.5°C/100$ m, respectively. Neutral atmospheres were associated with temperature gradients lying between these two values. This screening criteria should have effectively separated stable from unstable atmospheres. The delineation of neutral atmospheres is only approximate because they would often have been associated with small negative differences between the 13 and 3 m temperatures which could not have been adequately resolved by the measuring devices. For this reason data associated with neutral atmospheres will also incorporate some information from slightly stable and unstable atmospheric conditions.

a. Horizontal wind direction differences

Wind direction frequencies observed over the two-year study period at the two locations were very similar during neutral and unstable conditions, with no apparent evidence of terrain influences. Wind direction frequencies occuring at the two sites under stable atmospheric situations were, however, markedly different. Figure 2 shows that the predominant wind direction at CW was west-southwesterly while at CE it was southerly. The number of data *N* upon which the graph is based is shown. It appears as though stable air flowing east-northeasterly towards CE is directed northerly by the low hills which lie east of the station.

Values of wind direction differences, $\Delta\theta$, derived by subtracting directions at CE from those observed at CW were obtained to the nearest degree. Values of $\Delta\theta$ ranged from about -180 to 180 degrees. Standard deviation of the $\Delta\theta$ values for unstable, neutral and stable atmospheric conditions were 26, 22 and 32 degrees respectively. They thus tended to be of the same magnitude as those reported by Lockhart and Irwin (1980).

Frequencies of wind direction differences were examined to determine if there were patterns which might suggest physical explanations for the $\Delta\theta$ behavior. Figure 3 presents frequencies observed over the range from -60 to $+60$ degrees as classified by stability. The solid lines are normal curves with standard deviations of 10 degrees. They were subjectively fitted to the data by a process of trial and error. Values for the number of data shown on the graphs refer to all $\Delta\theta$ data within the -180 to 180 range.

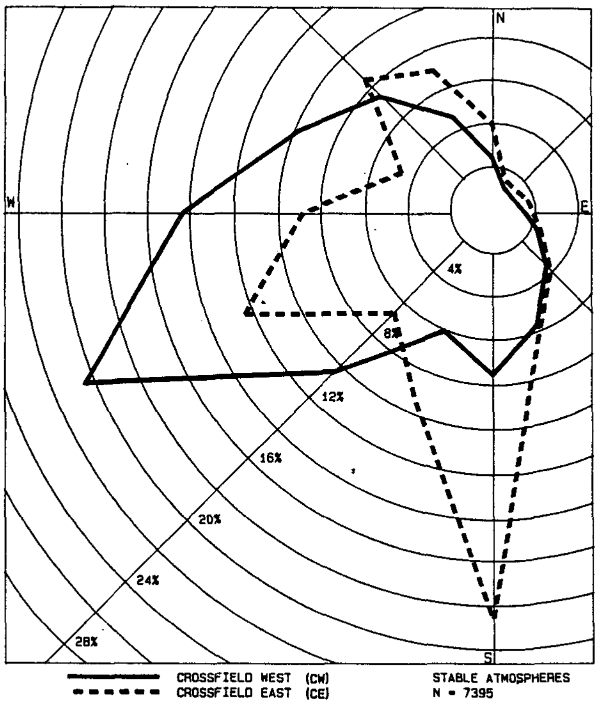

FIG. 2. Frequency of occurrence of wind directions (in percent) at Crossfield East and Crossfield West under stable atmospheric conditions.

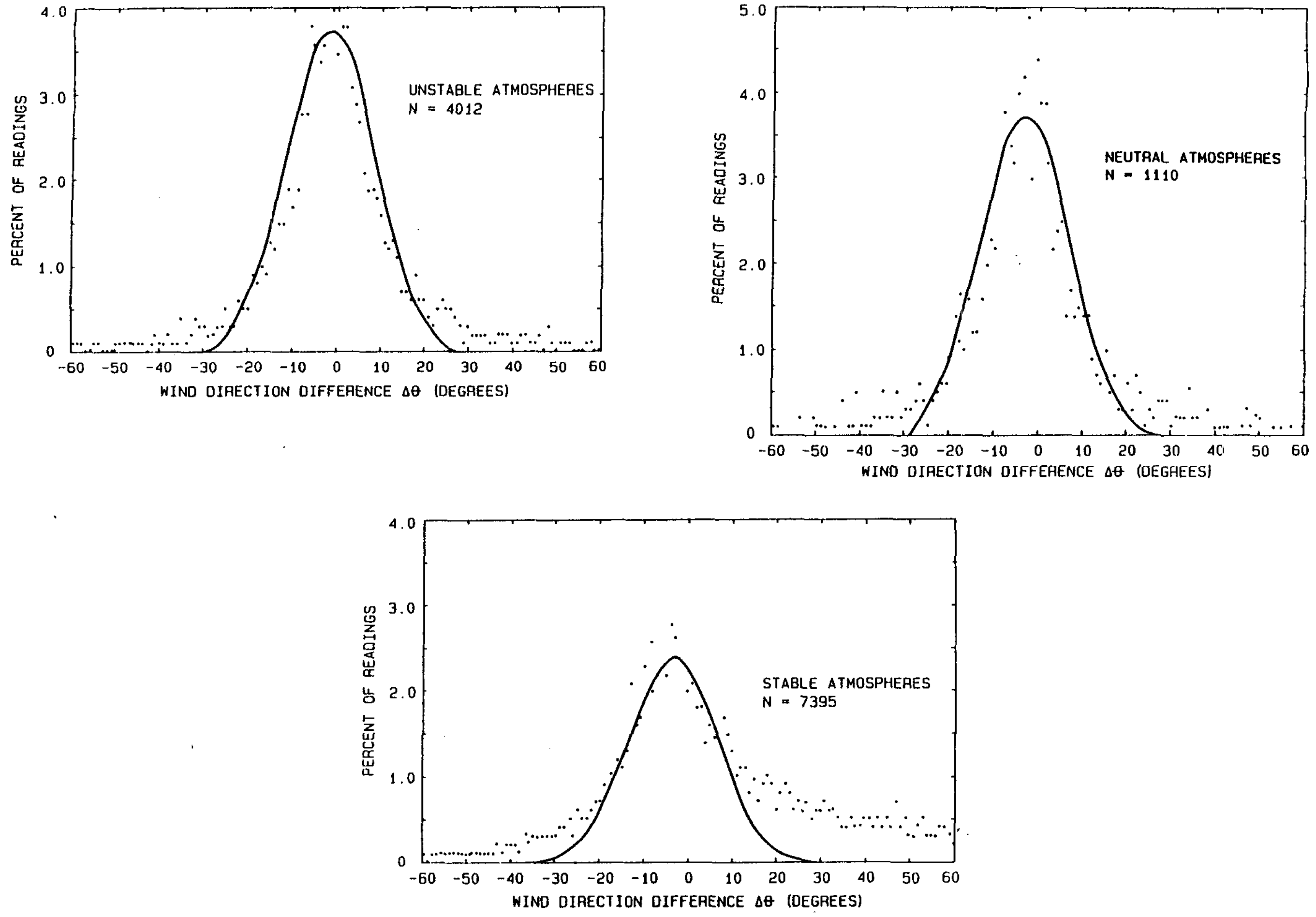

FIG. 3. Percent of readings for each degree of wind direction difference for the range −60 to 60 degrees for the indicated stability condition. The number of hours N upon which the data are based is shown.

Frequency distributions of $\Delta\theta$ were similar under neutral and unstable conditions. Under both stability conditions more than 85 percent of the data appears to be adequately described by the normal curve. The median $\Delta\theta$ value was zero for both cases. Values from −25 to +25 degrees are described by the same Gaussian curve with an amplitude of 3.75 percent to a significance in excess of the 99 percent confidence level. Values of $\Delta\theta$ less than −25 degrees occurred for a total of 6.6 and 6.8 percent of the time during unstable and neutral conditions, respectively. Values in excess of 25 degrees occurred 7.5 and 6.1 percent of the time, respectively. There was no obvious bias for $\Delta\theta$ to have either large positive or negative values. The fact that the median value for $\Delta\theta$ was zero suggests that there was no instrumentation bias in wind direction measurements.

Figure 3 also shows that distributions of $\Delta\theta$ were markedly different under stable situations than those observed during the other stabilities. Observations were skewed in favor of positive values. The tendency for large positive values of $\Delta\theta$ is understandable in terms of the channelling of stable west-southwesterly winds experienced at CW to southerly airflows at CE by low hills in the area. The normal curve with a standard deviation of 10 degrees and amplitude of 2.4 percent appears to adequately explain the data from only about −25 to 15 degrees. About 31.6 and 7.8 percent of $\Delta\theta$ data had values greater than 15 degrees or less than −25 degrees, respectively. Thus only about 60 percent of the data is described by the Gaussian curve.

Further analyses were performed for three sets of data. The first set consisted of $\Delta\theta$ values whose frequencies appear to be adequately described by the Gaussian curves. It was deemed to represent "normal" conditions. The second set consisted of positive $\Delta\theta$ values whose magnitudes were sufficiently large as to preclude them from the normal dataset. The third set was similar to the second except that it contained the large negative $\Delta\theta$ values. There were 8966, 2632 and 919 data in the first, second and third sets, respectively.

An examination was done to determine how the

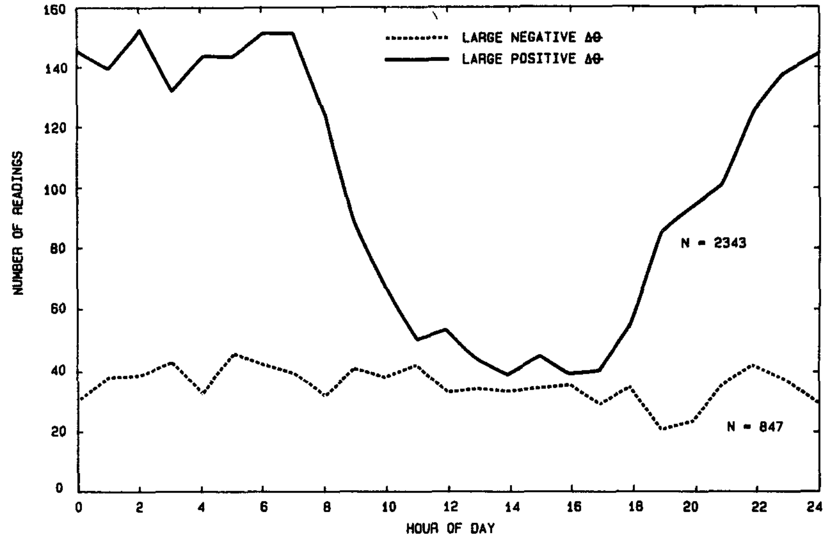

FIG. 4. The number of readings of large positive and negative values of $\Delta\theta$ as a function of time of day. The total number of readings N upon which the graphs are based is shown.

large positive and negative values of $\Delta\theta$ varied with time of day. Magnitudes of the large positive and negative $\Delta\theta$ values tended to remain nearly constant throughout the day with median values of about 38 degrees.

Figure 4 shows the number of occurrences of the large positive and negative $\Delta\theta$ values as functions of time of day. Frequencies of the large negative values appear to be independent of the time of day. This contrasts with the behavior of the large positive values which were much more frequent during the night than during the day. This diurnal variation can be traced to terrain-induced katabatic winds.

It was assumed on the basis of the data shown in Fig. 4 that the occurrence of large negative values of $\Delta\theta$ was not caused by terrain but rather by mesoscale phenomena that are not functions of atmospheric stability. It seems reasonable to assume further that these phenomena would cause large positive and negative $\Delta\theta$ values with the same frequency under all stability conditions. This assumption is supported by information collected during neutral and unstable atmospheric conditions when terrain influences were not evident (Fig. 3). The number of large positive $\Delta\theta$ values attributable solely to terrain can now be estimated by subtracting the lower from the upper curve shown in Fig. 4. Results of the subtraction expressed in percentage of total observations is presented in Table 1. It shows that terrain tended to noticeably influence wind directions at the observational stations about 20 percent of the time during nighttime hours. As might have been expected, terrain influences during daytime periods were comparatively negligible.

Further analyses showed that wind direction differences between the two prairie stations tended to occur with frequencies consistent with normal distributions about 75 percent of the time. Terrain influences noticeably affected the $\Delta\theta$ values about 10 percent of the time. Mesoscale phenomena, which are not functions of stability, resulted in large negative or positive values of $\Delta\theta$ about 15 percent of the time.

An examination showed that median wind speeds associated with large positive $\Delta\theta$ values were the same as those associated with large negative $\Delta\theta$ values. These speeds were about 2.5 and 1.5 m s^{-1} at the CW and CE stations, respectively. Median winds at CW and CE associated with "normal" $\Delta\theta$ values were appreciably higher at 4.0 and 3.4 m s^{-1}, respectively.

Table 2 shows the manner in which standard devia-

TABLE 1. Percentage of time terrain influence affected wind direction differences as a function of time of day.

Hour (MST)	Portion of time terrain influences evident (percent)	Hour (MST)	Portion of time terrain influences evident (percent)
00	23.7	13	1.7
01	21.3	14	1.1
02	23.6	15	2.0
03	18.9	16	6.6
04	23.8	17	5.4
05	20.7	18	6.4
06	23.4	19	12.2
07	23.5	20	13.7
08	18.7	21	13.1
09	9.6	22	17.0
10	5.6	23	20.3
11	1.7	24	23.7
12	3.8		

TABLE 2. Standard deviations of "normal" wind direction difference data as a function of wind speed measured at Crossfield East (CE)

Wind speed ($\mathrm{m\ s^{-1}}$)	Observed standard deviation of direction differences (deg)	N	Standard deviation of direction differences predicted from Eq. (1) (deg)
0.3	12	70	240
0.5	12	286	120
1.0	12	383	60
1.5	12	646	40
2.0	11	818	30
2.5	11	461	25
3.0	11	964	21
3.5	10	898	18
4.0	9	759	16
4.5	9	664	14
5.0	9	294	13
5.5	9	567	12
6.0	9	473	11
6.5	8	346	10
7.0	7	314	10
7.5	8	120	9
8.0	7	211	9
8.5	6	177	9
9.0	6	124	8
9.5	6	98	8
10.0	5	22	8
10.5	6	66	8
11.0	6	56	7
11.5	7	39	7
12.0	8	25	7
13.0	5	45	7
14.0+	6	40	7

tions from the "normal" $\Delta\theta$ dataset varied with wind speed. The number of data upon which the standard deviations are based is also shown. The standard deviation shown for 14.0 $\mathrm{m\ s^{-1}}$ pertains to data collected at this and all greater wind speeds. Standard deviations of $\Delta\theta$ decreased from 12 to 6 degrees as wind speeds increased from 0.25 to 8.5 $\mathrm{m\ s^{-1}}$. They then tended to remain constant as wind speeds increased.

Table 2 also presents standard deviations of wind direction differences as predicted using Eq. (1) developed by Nappo (Hanna 1982). The predictions appreciably overestimate the observed values at wind speeds of less than about 5 $\mathrm{m\ s^{-1}}$. This is probably because at these speeds Nappo was working with data that would have included the effects of mesoscale wind phenomena and katabatic winds. It is interesting to note the good agreement between predicted and observed standard deviations at the higher wind speeds where these influences should have been relatively uncommon.

Median magnitudes of large positive and negative $\Delta\theta$ values varied in a similar fashion with wind speed. They decreased from 50 to 35 degrees as wind speeds increased from 0.25 to 1.5 $\mathrm{m\ s^{-1}}$. They then tended to remain constant as wind speeds increased.

b. Horizontal wind speed differences

Analyses were done of wind speed differences, ΔU between CW and CE. Standard deviations of all ΔU data collected under unstable, neutral and stable atmospheres were 1.0, 1.0 and 1.3 $\mathrm{m\ s^{-1}}$, respectively. They were thus similar in magnitude to those reported by Lockhart and Irwin (1980).

Median wind speeds at CW were the same as those at CE during unstable and neutral atmospheric conditions, suggesting that there was no instrumentation bias in wind speed measurements. Under stable conditions median winds at CW were about 0.5 $\mathrm{m\ s^{-1}}$ greater than at CE. This tendency for greater wind speeds at the CW station may be due to its higher elevation compared to the CE station (Fig. 1).

Frequencies of ΔU were determined for 1 $\mathrm{km\ h^{-1}}$ (0.28 $\mathrm{m\ s^{-1}}$) classes. These are presented for different stability conditions in Fig. 5. The solid lines represent Gaussian curves with standard deviations of 2.4, 2.8 and 4.4 $\mathrm{km\ h^{-1}}$ (0.7, 0.8, 1.2 $\mathrm{m\ s^{-1}}$) respectively for unstable, neutral and stable atmospheric conditions. Amplitudes of these curves are respectively 16.0, 14.5 and 10.0 percent.

The Gaussian distribution describes about 98 percent of the information with a significance in excess of the 99 percent confidence level. As may be seen, differences in wind speeds tended to be much smaller under unstable than under stable conditions.

As in the case of $\Delta\theta$ data, the ΔU information was divided into three sets. The first consisted of data whose frequencies appear to be well described by the Gaussian curves. For unstable, neutral and stable atmospheres they lay in the range -2 to 2.2, -2.2 to 2.5 and -3.3 to 4.2 $\mathrm{m\ s^{-1}}$, respectively. The second dataset consisted of positive ΔU values whose magnitude were sufficiently large as to exclude them from the normal dataset. The third set was similar to the second except that it contained large negative ΔU values. There were 12 808, 112 and 80 data in the first, second and third sets, respectively.

Data in the second and third sets were analyzed to determine their behavior with respect to time of day. The set of large positive ΔU values did not show a diurnal pattern in their frequency of occurrence. Large negative ΔU values, however, occurred more frequently during the afternoon and evening (1200–2400 local time) than during the morning (0000–1200 local time). Frequencies of occurrence were respectively 68 and 32 percent. Reasons for this diurnal change, which effects only about 0.7 percent of the observations, are not evident.

Values for standard deviation of ΔU for the "normal" dataset, which comprised about 98 percent of the information, were examined to determine their relationship with wind speed. For this analysis data collected under unstable and neutral atmospheres were

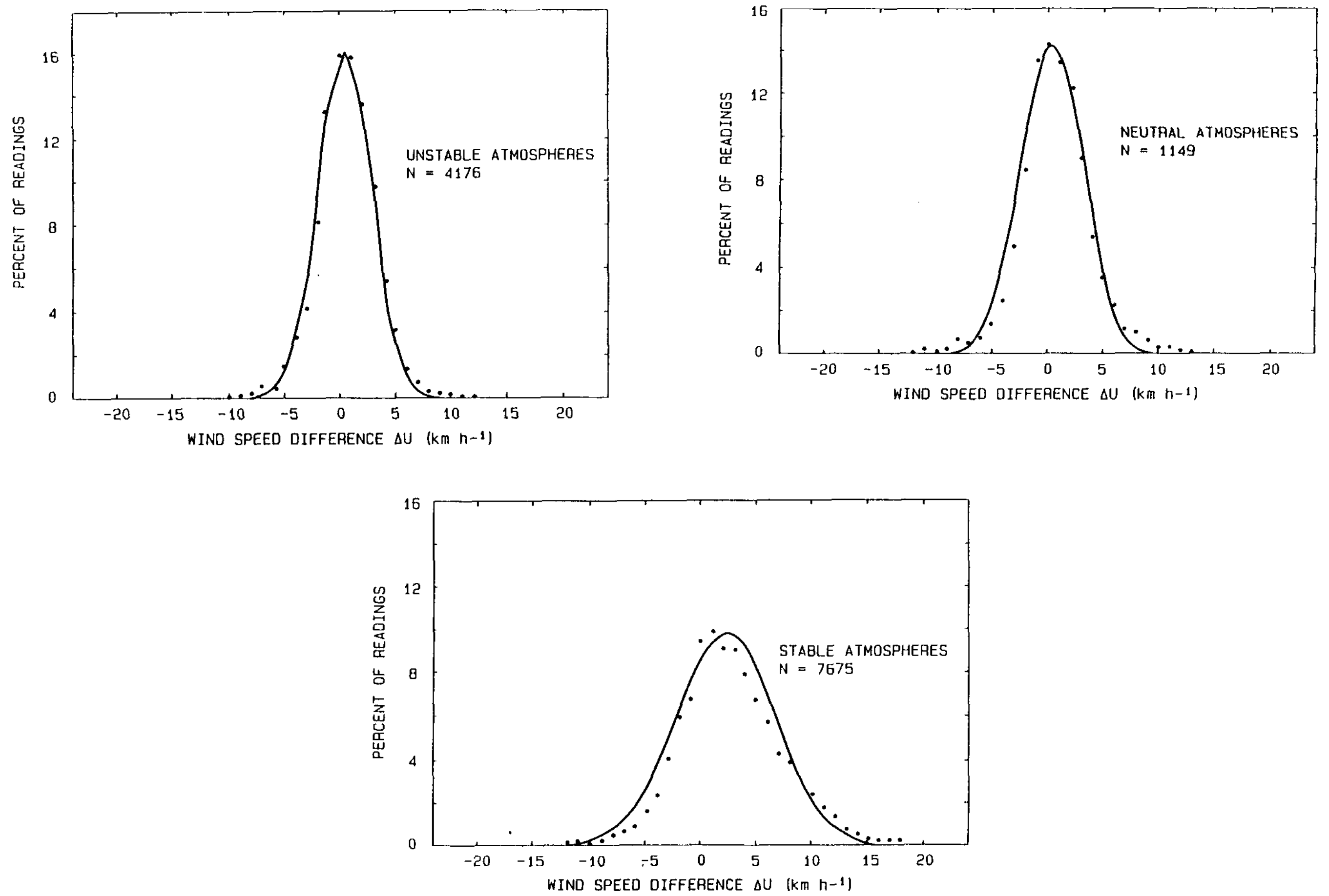

FIG. 5. Percent of readings for each km h^{-1} of wind speed difference for the range −20 to 20 km h^{-1} for the indicated stability conditions. The number of hours N upon which the data are based is shown.

grouped. Results of the evaluation are given in Table 3. The number of data N upon which the standard deviations are based is also shown. (The standard deviations shown for 14.0 m s^{-1} pertain to data collected at this and all greater wind speeds.) There are relative minimums in the number of data shown in Table 3 for winds of 2.5, 5.0, 7.5, 10.0 m s^{-1}. These minimums are artifacts due to conversion to m s^{-1} of the original data which were recorded to the nearest km h^{-1}.

Values of the standard deviation of wind speed differences under unstable and neutral atmospheres were about 0.7 m s^{-1} regardless of wind speed. Under stable atmospheric situations the standard deviation were about 1.2 m s^{-1} with no apparent variation with respect to wind speed.

Table 3 also presents values of the standard deviations of wind speed differences predicted using Eq. (2) developed by Nappo (Hanna 1982). Predictions agree with values observed under unstable and neutral atmospheres at wind speeds below about 4.5 m s^{-1}. Between this speed and 8.5 m s^{-1} they tended to agree with values observed during stable atmospheric conditions. Predicted values were large compared to observations at wind speeds greater than 8.5 m s^{-1}.

An examination of standard deviations of ΔU for the other two datasets also showed no systematic changes with wind speed.

4. Discussion and conclusions

Short range air pollution models usually apply to "normal" situations when obvious causes of mesoscale inhomogeneities such as katabatic winds and local weather systems are absent.

Significant horizontal inhomogeneities engendered by katabatic flows occurred about 10 percent of the time in the Crossfield area. They would presumably occur more frequently in regions where the terrain was less regular. Data demonstrate that horizontal variability is similar during unstable and neutral atmospheric conditions. This finding is valid even though our neutral category contains information from slightly stable situations. The reason is probably katabatic flows are not initiated until vertical gradients exceed about −0.5°C/100 m.

TABLE 3. Standard deviations of "normal" wind speed difference data as a function of wind speed measured at Crossfield East (CE)

Wind speed ($m\ s^{-1}$)	Observed standard deviation of wind speed difference ($m\ s^{-1}$) (unstable and neutral atmospheres)	*N*	Observed standard deviation of wind speed difference ($m\ s^{-1}$) (stable atmosphere)	*N*	Standard deviation of wind speed differences predicted from Eq. (2) ($m\ s^{-1}$)
0.3	0.6	31	1.1	402	0.6
0.5	0.6	217	1.1	787	0.6
1.0	0.6	290	1.1	625	0.6
1.5	0.7	408	1.2	755	0.6
2.0	0.8	458	1.1	818	0.7
2.5	0.7	235	1.2	421	0.7
3.0	0.7	501	1.1	796	0.8
3.5	0.7	490	1.1	654	0.8
4.0	0.7	450	1.1	476	0.8
4.5	0.7	390	1.2	402	0.9
5.0	0.7	159	1.0	169	1.0
5.5	0.8	325	1.1	288	1.0
6.0	0.7	262	1.0	246	1.1
6.5	0.7	188	1.0	178	1.1
7.0	0.8	185	0.9	145	1.2
7.5	0.7	70	1.1	56	1.3
8.0	0.7	127	0.9	104	1.3
8.5	0.8	104	1.3	76	1.4
9.0	0.8	79	1.0	51	1.5
9.5	0.6	62	1.0	38	1.5
10.0	0.5	11	0.9	11	1.6
10.5	0.8	36	1.1	32	1.7
11.0	0.8	36	1.2	22	1.8
11.5	0.7	28	1.3	12	1.8
12.0	0.7	17	1.5	9	1.9
13.0	0.7	25	1.3	16	2.0
14.0+	0.9	15	1.0	20	2.2

Appreciable horizontal inhomogeneities due to mesoscale phenomena that appeared to be independent of stability occurred about 15 percent of the time. They could be largely associated with internal gravity waves generated by the Rocky Mountains which lie about 75 km west of the study area. Such an explanation is particularly attractive because the existence of these gravity waves would not be dependent on atmospheric stability as measured near the ground. Convective storms in the study area would be another cause of mesoscale wind variations. These storms would also be largely independent of local measurements of near-ground stability.

Horizontal differences in wind speeds and directions under "normal" atmospheric conditions tend to have Gaussian distributions with standard deviations of about 1 $m\ s^{-1}$ and 10 degrees. The Gaussian distributions indicate that wind velocity differences may occur randomly. For this reason it may be undesirable to attempt the development of short term pollution models that physically account for horizontal inhomogeneities.

It should be relatively easy to estimate the range of errors that random variations in horizontal wind velocities will introduce into predictions of air pollution models. These errors would demonstrate discrepancies between observed and predicted concentrations that could not be overcome through improvements in plume parameters.

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