EXTREME VALUE ANALYSIS OF WIND GUSTS IN ALBERTA

Thomas K. Flesch[1]
John D. Wilson[1]

1993

Scientific Authority: S. Navratil

This is a joint publication of Forestry Canada and the Alberta Land and Forest Services pursuant to the Canada-Alberta Partnership Agreement in Forestry

[1]Geography Department
University of Alberta
Edmonton, Alberta T6G 2H4

Project No. A-8033-107

DISCLAIMER

The study on which this report is based was funded in part under the Canada-Alberta Partnership Agreement in Forestry.

The views, conclusions and recommendations are those of the authors. The exclusion of certain manufactured products does not necessarily imply disapproval nor does the mention of other products necessarily imply endorsement by Forestry Canada or the Alberta Land and Forest Services.

Catalogue No.: FO42-91/107-1993E
ISBN: 0-662-21153-7

Additional copies of this publication is available at no charge from:

Forestry Canada
Regional Development
5320 - 122nd Street
T6H 3S5
Telephone: (403) 435 - 7210

or

Forest Industry Development Division
11th Floor, Sterling Place
9940 - 106th Street
Edmonton, Alberta
T5K 2P6
Telephone: (403) 422 - 7011

ABSTRACT

An historical analysis of wind speed was conducted to assess the future likelihood of extreme wind gusts in Alberta. This likelihood was presented in terms of a return period, which represents the average length of time between gusts of given wind speeds. In addition, the directional history of maximum recorded gusts was examined. The study found that the speed of the maximum gust generally increased from north to south, while a directional analysis indicated extreme gusts come from a west to northwest direction across most of the province. A general tendency was found for shorter return periods when moving from north to south, confirming the greater potential for high winds in southern Alberta as compared with northern sections. Seasonally computed return periods show a slightly greater likelihood of higher wind gusts in the winter for the north and south, and in the summer for central portions of the province. The representativeness of the meteorological stations used in the study is of some concern. However, computed return periods can be extrapolated from the stations with some confidence.

EXECUTIVE SUMMARY

An extreme value analysis of wind speed was conducted to assess the future likelihood of extreme gusts in Alberta. This likelihood was presented in terms of a return period, which represents the average length of time between gusts of a given wind speed. The analysis was performed according to classical statistical methods. In addition, the directional history of maximum recorded gusts was examined.

Gust records at 14 stations in Alberta were used in the study. The maximum recorded wind speed ranged from 100 km/hr (Fort Smith and Peace River) to 171 km/hr (Lethbridge). The speed of the maximum gust generally increased from north to south in the province. A directional analysis indicates that extreme gusts come from a west to northwest direction across most of the province.

For a given wind speed, there is a general tendency for shorter return periods when moving from north to south across Alberta. This confirms the greater potential for high winds in southern Alberta compared with northern sections. Seasonally computed return periods show the same spatial trend, with a slightly greater likelihood of higher wind gusts in the winter for the north and south, and in the summer for central portions of the province.

The representativeness of the stations used in the study is of some concern. The measurement site at some locations is not "standard", which makes comparisons between the various stations difficult. Comparison of two nearby Edmonton sites indicates, however, that computed return periods can be extrapolated from the stations with some confidence.

FOREWORD

Boreal mixedwood forests represent about one third of the productive forest land base in the prairie provinces. Maintaining timber productivity and sustainability of conifer production and accommodating the diverse demands being placed on management of Boreal mixedwoods needs new, innovative approaches to their silviculture.

Recently Forestry Canada demonstrated, in cooperation with the provincial and industrial clients, the benefits and practical application of a silviculture and harvesting system that protects understory white spruce while harvesting overstory aspen. One of the risks associated with this silvicultural system is the instability and vulnerability of released white spruce to wind damage.

In managed and man-made forests all around the world, wind damage is a recurrent and serious problem due to the resultant changed stand conditions and structure. The extent of damage can be very high, ranging from 10% of annual allowable cut to as high as 100% in several European and other countries.

To reduce the risks of wind damage in the current and new silvicultural systems applied to the Boreal forest, the Northern Forestry Centre initiated measures to minimize wind-induced losses in the future. One of the first steps in wind risk management is the development of wind risk assessment and classification systems for use in silviculture and forest management planning and in highlighting areas requiring mitigating measures.

The analysis and summary of high wind speeds in Alberta presented in this report provide an important knowledge base for assessing wind risk and integrating it with the silviculture system. The calculated return periods of high wind speeds form the prerequisites for prescribing suitable and affordable silvicultural systems that consider the spatial and temporal arrangement of harvesting and silvicultural operations. Furthermore the critical wind statistics summarized in this report should be of interest to managers of other resources and to landscape planners.

S. Navratil
Research Scientist
Mixedwood Silviculture

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

A. INTRODUCTION

Determining the likelihood of high wind gusts across Alberta is clearly an extreme value problem. An extreme value is the largest or smallest value in a data set. All data sets contain extreme values. An extreme value analysis attempts to model the observed data extremes. Analysis of an observed sample of "high" wind gusts allows generalizations about the likely frequency of recurrence of events as large as we have seen, and perhaps extrapolations to the likely frequency of events we have not yet seen. An extreme value analysis has critical importance in many applications. An example is the design of dams, which relies on the analysis of precipitation amounts in order to predict the probability of flood frequencies.

The results of an extreme value analysis are commonly presented in terms of a return period (when time is a variable of interest). When designing a dam, the civil engineer wants to know the typical period between extreme rainfall events. The return period attempts to answer the question, "How long will I have to wait for an event?" The focus of this study will be on determining the return period for wind gusts in Alberta.

1. Return Period

For discussion we will assume a data set containing the annual maximum wind speed for each of 30 years: $U_1, U_2, \ldots, U_{30}$. It is assumed that U is drawn from a static but unknown parent population having a cumulative extreme value distribution function $F_U(u)$:

$$Prob\,[U \leq u] = F_U(u)\,.$$

The return period, T(u), of an event having wind speed u is by definition the reciprocal of the probability p(u) of that event occurring:

$$T(u) = \frac{1}{p(u)} = \frac{1}{1-F_U(u)}\,.$$

Upon analysis of our 30 year data set we might find that for a wind speed of 90 km/hr, T(90) is 13.8 years. This means that on "average" a wind speed of 90 km/hr will occur every 13.8 years. There is *at least* a 63% chance of an exceedance of this wind speed happening by or before the return period. The chance of exceedance varies with the length of the return period. Table 1 shows that for a T(90) of 13.8 years, there is approximately a 65% chance that in any 13.8 year period there would be an event as large as 90 km/hr.

Table 1. Cumulative probability of exceedance (C_{exc}) by or before the given return period (T).

T (yrs)	$C_{exc}(T)$	T (yrs)	$C_{exc}(T)$
2	0.750	50	0.636
5	0.672	100	0.634
10	0.651	200	0.633
20	0.642	1000	0.632

The return period can be crudely determined without making any assumptions about the form of the underlying statistical distribution of u, $F_U(u)$. For example, the largest value in the 30 year data set could be used as the estimate of the 30 year return period wind speed, with the second largest being the wind speed estimate for the 15 year return period, and so on. The problem with this approach is that the confidence interval of our estimates is very broad (Kendall 1959), for if we select the wind speed having a 10 year return period as described, it can be shown that the true return period would lie within the range of 3.7 to 50 years, for a confidence interval of 95%. Certainly there would be little confidence in such an estimate.

A superior estimate of return period can be made if the underlying statistical distribution, $F_U(u)$, can be determined. The advantage in assuming a form for $F_U(u)$ is that the complete data set is used to determine the parameters which describe $F_U(u)$. In determining the wind speed having a 30 year return period from our data set for example, all 30 values provide information (define $F_U(u)$), not just the single maximum value. The result is a much greater accuracy in estimating the return period when compared with the crude approach first described. The difficulty is in establishing the form of $F_U(u)$.

2. Extreme Value Distributions

Before proceeding to calculate return periods, it is necessary to choose the correct extreme value distribution, $F_U(u)$. It has been established (Fisher and Tippet 1928) that only three distributions can occur as asymptotic limit extreme value distributions (i.e., in the limit of a very large sample): the Exponential, the Cauchy, and the Weibull. For this study it is possible to eliminate the Weibull distribution from consideration since it describes a variable which has an upper limit, and we cannot ascribe a meaningful upper limit to wind speed.

The Exponential distribution (also known as the Gumbel) is the simplest of the two possible distributions. It has only two parameters, and is the most commonly used for meteorological variables. The Cauchy distribution is potentially no worse than an Exponential, but requires three parameters. It is expected that the Exponential distribution will satisfactorily describe wind speed extremes.

The Exponential distribution for the largest value of wind speed u can be written as:

$$F_e(u) = \exp[-\exp(-\frac{u-\lambda}{\delta})] ,$$

where λ and δ are the distribution parameters. The λ represents a measure of the central tendency of the distribution, and δ is a measure of the spread of the distribution (somewhat analogous to the mean and standard deviation of a Gaussian distribution). Often the variable of interest, in this case u, is transformed to a reduced variate,

$$y = \frac{u-\lambda}{\delta} ,$$

with the Exponential distribution becoming,

$$F_e(y) = \exp[-\exp(-y)] .$$

To compute return periods we require estimates of λ and δ.

There are several methods for calculating λ and δ (Lowery and Nash 1970). These include the graphical, moments, regression, and maximum likelihood methods. The simplest of these is the moments method, generally preferred for most applications. This method relates the easily calculated mean and standard deviation of an extreme value data set to λ and δ. For our example we would compute the mean extreme wind speed ($\overline{U}$) and standard deviation (σ_U), with the Exponential distribution parameters calculated as (Kinnison 1985),

$$\delta = 0.78\ \sigma_U \quad , \quad \lambda = \overline{U} - 0.577\delta .$$

3. Extreme Value Data Requirements

A critical issue in extreme value analysis is selecting a proper data set for study. As we have indicated, an extreme value analysis becomes an exercise in fitting an extreme value distribution to the variable of interest. Unfortunately, there is little useful information about extreme occurrences from measurements of the "general population", i.e., average hourly wind speed observations are of no use in determining the likelihood of wind extremes. An extreme value analysis requires that only data extremes be studied.

Classical statistical methods for analyzing extreme values place three requirements on the data of interest. The first is that the variable to be examined be a random statistical value. In essence this means that a probability function exists which associates probability to each possible value of the variable. The second requirement is that the parent distribution of the variable, from which the extremes were selected, remains constant from one set of samples to the next. In our case, this would dictate that no time trend be present in the wind record over the years. The final requirement is that the individual extremes be statistically independent. How the independence criterion might be violated can be illustrated by the following example of daily wind extreme data. A frontal passage occurs creating a sustained wind gust of 100 km/hr over the midnight hour. Because the meteorological day begins and ends at midnight, the gust is recorded as the maximum wind on two days. Because the gust was just a single event, the two recorded extremes are not independent.

B. OBJECTIVES

The objective of this report is to analyze wind gust data at stations across Alberta and to:

i) calculate the return period for wind gusts of 70, 90, 110, and 130 km/hr;

ii) calculate seasonally categorized return periods for the above wind speeds based on the following definitions,
   - Spring: April - June
   - Summer: July - September
   - Winter: October - March; and

iii) examine the directional frequency of maximum wind gusts.

In addition, we will examine the quality of the wind gust data as well as the representativeness of our results at specific sites to other areas in Alberta.

C. EXTREME VALUE ANALYSIS

1. Wind Gust Data

The analysis of extreme winds requires a data set of maximum wind speeds – average wind speed measurements are of no value. Such an analysis is limited by the availability of observations. Although there are over 300 locations in Alberta where meteorological data is routinely recorded, only a few measure wind speed, and fewer still record the maximum wind gusts. Only 19 sites in Alberta record maximum wind speed.

The variable length of the data record further reduces the number of stations available for our analysis. The recording of wind gusts in the province began in the mid-1950s, so the potential maximum record length of a station in Alberta is about 35 years. We would be confident that a station having 35 years of data would give useful information on return periods up to 35 years, and perhaps somewhat beyond. Unfortunately, most stations do not have such a long record. Some were only in operation for a short time (i.e., Rocky Mountain House, 1986-), or have changed locations substantially (i.e., Whitecourt) so that the assumption of a uniform wind population becomes questionable. We have arbitrarily selected a minimum record length of 15 years taken at the same location, as our criteria for station analysis. Table 2 lists the stations which meet this criteria and were used in our study. Figure 1 shows the station locations. Edmonton Municipal and Coronation also met the criteria, but were not used.

Table 2. Stations used in study and record lengths.

Station	Years of Record	Record Length (years)
Fort Smith	1958 - 88	31
High Level	1971 - 88	18
Fort McMurray	1956 - 88	33
Peace River	1960 - 88	29
Slave Lake	1972 - 88	15
Grande Prairie	1955 - 88	34
Cold Lake	1956 - 88	33
Edmonton Int'l Airport	1961 - 88	28
Edmonton Namao	1956 - 88	33
Edson	1971 - 88	18
Red Deer	1957 - 88	32
Calgary	1955 - 88	34
Medicine Hat	1960 - 88	29
Lethbridge	1955 - 88	34

Figure 1. Weather stations used in the study.

All of the stations in Table 2 measured wind speed with a U2A anemometer system, consisting of a wind vane and a three cup anemometer mounted approximately 10 m above the ground. Wind direction is reported to the nearest five degrees. Maximum wind speed was recorded using one of two methods. In the more reliable method, wind speed was continuously transmitted to a Monroe chart recorder, and the maximum wind determined from the chart. Otherwise the maximum wind speed was seen real-time on the U2A anemometer dial by an observer and recorded. Over time the Monroe recorder has become the standard, eliminating the uncertainty created by varying observer dedication. Weather records were eventually transferred from the site location to the Atmospheric Environment Service's (AES) Climate Centre for archiving. We have obtained the AES data up to 1988 from the Climate Centre. This data set contains the maximum wind speed (km/hr) and corresponding wind direction (in tens of degrees) for each day of the year for the length of record.

As mentioned earlier, the wind data used in an extreme value analysis should: i) be a random statistical variable, ii) come from a static population, and iii) be statistically independent. Certainly wind speed meets the first requirement. We have some uncertainty regarding the second requirement. A visual inspection indicates a time trend in the wind extremes at some stations. Figure 2 illustrates the annual maximum wind series for Red Deer and Fort Smith. Red Deer appears to have a decreasing maximum wind speed over time, while Fort Smith has no clear trend. Fort Smith is typical of most locations, where the large year-to-year variability and the relatively short record length make it difficult to confirm any trend, so that we are comfortable in assuming a static wind population. For Red Deer, however (and to a lesser extent the Edmonton stations), a trend seems possible. This trend could be due to: natural random variability, a change in measurement location or instrumentation, changes in the adjacent landscape (i.e., growing trees), or a true climatological change. Although the classical extreme value analysis can be modified to accommodate a time trend, we have not done so. In a predictive sense, the interpretation of a more sophisticated analysis which accounts for a time trend is problematic, as assumptions must be made as to the future trend. We do not feel it is possible to make such an assumption (as we are not certain of a trend or, if it exists, its cause and continued likelihood), and therefore the advantage of using techniques for analyzing data with a time trend is lost. As for the third requirement, we believe that it is highly unlikely that a problem exists with statistical independence. Given that only one maximum is selected each year makes it almost impossible that any event could be counted twice (the event would have to occur over midnight December 31). Even this could not occur in the Spring and Summer data sets. We believe, therefore, that the wind data in its present form can be used in a classical extreme value analysis, given some caution as to the possibility of a time trend at Red Deer.

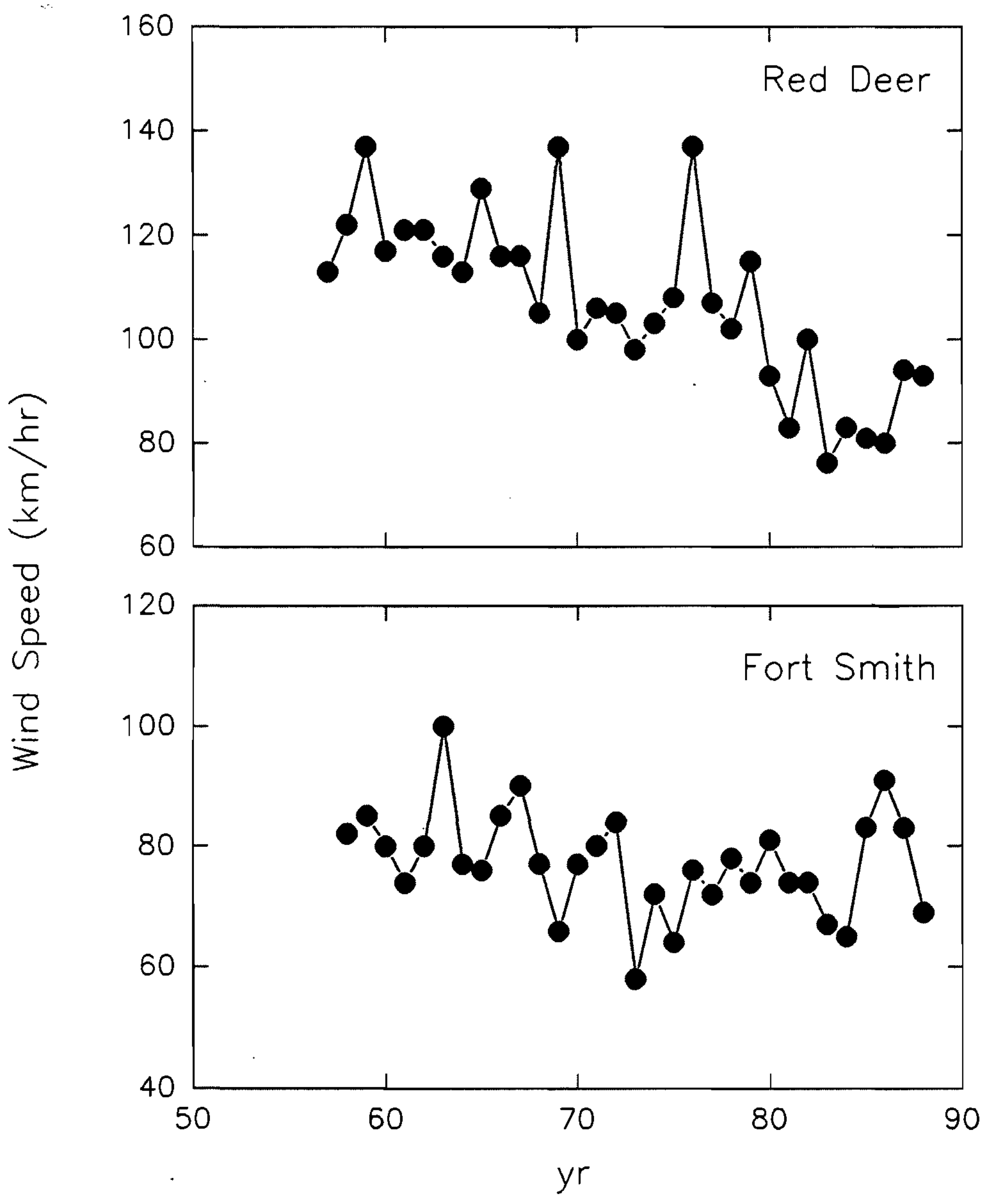

Figure 2. Time series of the annual maximum gust at Red Deer and Fort Smith.

One assumption in interpreting the analysis will be that the wind measurements at the given stations are representative of the surrounding areas. This would not be the case for wind speed recorded in a sharp valley, which is not likely to be an indication of the wind even 100 m distant. All of the sites in this study are located at airports. The level, generally extensive uniform grass surface, gives some degree of uniformity to the sites. We also want wind measurements to be made at a "standard" setting, so that comparisons can be made between the sites. In meteorological terms, standard refers to a wind measurement made 10 m above a short grass surface. Unfortunately, this standard has only recently been met throughout the province. At some stations the history of the anemometer location shows large and frequent changes. The anemometer height has always been 10 m at High Level, Peace River, Slave Lake, Edson, Cold Lake, Edmonton Namao, and Edmonton International. At Fort McMurray, Grande Prairie, Lethbridge, and Medicine Hat, the height varied over the years from 13 to 10 m. And at Fort Smith, Red Deer, and Calgary, the measurement height has dropped from 16-18 m to 10 m. As well as height, anemometer placement has changed, varying from the standard grass, to an airport control tower, to an airport hangar roof. This variability in measurement conditions create some uncertainty in station-to-station comparisons. If we were comparing average wind speed, the measurement height would be very important, as the average wind is strongly height dependent. But the height dependence of the maximum instantaneous wind speed is not clear, although we suspect there is less dependence here than with the average wind. The effect of the location of the anemometer, over grass or on a hangar roof, is even more unpredictable.

There is some question as to the effect of surrounding vegetation on site measurements. Stations in the southern portion of the province are generally surrounded by open farmland, and so measurements over a grass site are relatively representative of the area. In the north, however, the stations are often small clearings in an expansive forest. The average wind speed within a small clearing is reduced when compared with the wind over an extensive grass area. But as the clearing becomes larger, the wind speed 10 m above the ground approaches the wind speed 10 m above the grass site. A traditional meteorological rule of thumb is that a wind measurement should be located at least 100 m downwind for every upstream roughness change of one meter. So if the countryside surrounding a station is a 20 m tall forest, the wind measurement over grass should occur at least 2000 m from the forest edge. This criteria is quite conservative, and economically unrealistic, and a 10 to 1 rule is more accepted. In our discussions with AES, we learned that some northern stations do not, or have not in the past, satisfied a 10 to 1 ratio with the surrounding forest edge. These stations are High Level, Fort McMurray, and Edson. It seems likely that wind measurements at these stations were affected by the forest. Again, we cannot predict the effect of the forest edge on the maximum gust. It may seem that the maximum gust speed would be reduced (as the average speed would be), but the forest edge may create extreme turbulence in a gust event and actually increase the instantaneous speed.

The history of wind measurements in Alberta is far from ideal, with varying observation heights and location settings. This complicates any study of wind climatology. Because there is no means to adjust any of the data so as to make the individual station results representative of a standard site, some uncertainty must be attached to the interpretation of the study results.

2. Return Period Analysis

The calculation of return periods was outlined briefly in the Introduction. Table 3 shows a detailed example illustrating how return periods were calculated for High Level. As discussed, the Exponential extreme value distribution was used in our calculations. We performed a Kolmogorov-Smirnov goodness-of-fit test, using a null hypothesis that observations were selected from an Exponential distribution (this test is recommended because it is non-parametric, i.e., distribution-free, and is very easy to apply). The procedure is as follows:

i) Rank the observations by increasing wind speed (i=1,2,..N), and for each U_i calculate the empirical cumulative frequency ($S_i(X_i) = i/N$) and the theoretical frequency based on an Exponential distribution (Equation (1)).

ii) Find the largest difference, D = maximum $|S_i - F_E(U_i)|$

iii) Reject the Exponential distribution (with chosen small probability α of a Type I error) if for the given N and α, D exceeds the value given in Table 4.

Table 3. Extreme value calculations for High Level, Alberta.

Data:

Year	Max. Wind	Year	Max. Wind
1971	72	1980	80
1972	64	1981	102
1973	72	1982	74
1974	72	1983	78
1975	93	1984	87
1976	89	1985	120
1977	70	1986	74
1978	76	1987	74
1979	83	1988	78

Parameter Estimation (Moments Method):

Mean of Maximum Wind - 81.0
Standard Deviation (σ_U) - 13.4

$\delta = 0.78\ \sigma_U = 10.5$
$\lambda = U - 0.58\ \delta = 75.0$

Return Period for 90 km/hr Wind:

$T(90\ km/hr) = 1/[1 - F_e(90)]$
$F_e(90) = \exp[-\exp[-y(90)]]$
$y(90) = (90 - \lambda)/\delta = (90 - 75)/10.5 = 1.43$

T(90) = 4.7 years

Wind Speed Having a 10 Year Return Period:

$T(u) = 10$ years,
$F_e(u) = 1 - 1/T(u) = 0.9$
$y(u) = -\ln[-\ln(F_e(u))] = 2.25$
$u_{10yr} = \delta\ y(u) + \lambda = 98.6$ km/hr

$\mathbf{u_{10yr} = 98.6}$ **km/hr**

The Kolmogorov-Smirnov test is very conservative, i.e., it is relatively uncommon to reject the null hypothesis. For the above example, and all of our cases, we accepted the Exponential distribution with an α=0.10.

Table 4. Critical values for the Kolmogorov-Smirnov goodness-of-fit test.

N	α	
	0.10	0.05
10	0.368	0.410
15	0.304	0.338
20	0.264	0.294
25	0.240	0.270
30	0.220	0.240
35	0.210	0.230
> 35	$1.22\ N^{-0.5}$	$1.36\ N^{-0.5}$

We also calculated the wind speed associated with return periods (u_T) of 2, 5, 10, 20, and 50 years, as well as confidence intervals for these estimates of u_T (Lowery and Nash 1970). A standard deviation of u_T (σ_{uT}) can be calculated as follows:

$$\sigma_{uT} = \frac{\sigma_u}{\sqrt{N}} \sqrt{1 + 1.14 K_T + 1.10\, K_T^2}\,,$$

where,

$$K_T = 0.78(y_T - 0.58)\,.$$

With 95% confidence we can say that the true magnitude of u_T would lie within the interval $u_T \pm 2\sigma_{uT}$. For the above example from High Level, the 95% confidence interval for a u_{10} is 85.3 to 111.7 km/hr. As the sample size increases, this confidence interval will decrease. Appendix 1 gives a complete listing of the return period calculations for 70, 90, 110, and 130 km/hr gusts, and the wind speed for return periods of 2, 5, 10, 20, and 50 years, for the stations used in this study.

3. Wind Direction Analysis

In this study, information on the directional characteristics of maximum wind gusts was examined. We would have liked to have calculated return periods for different directions, but the measurements did not permit this. Our data set consisted only of daily maximum wind speeds and the corresponding direction. To calculate the return period for different directions, e.g., east winds, a data set of maximum *east* winds is required. It is impossible to extract such information from the AES data. For example, we may know that the maximum wind speed for a given year was 98 km/hr from the southeast, but on the same day an annual maximum east wind of 95 km/hr may have occurred and would not have been reported. The only analysis possible from the gust data is to compute the directional frequency of maximum winds, i.e., 35% of the recorded annual maximum winds were from the west, 23% from the northwest, and so on.

We considered wind direction based on the eight cardinal points of the compass (N, NE, E, SE, S, SW, W, NW), and calculated the percentage annual wind maximums in each direction. A wind direction of N means that the wind was blowing from the north to the south. The original AES data gives wind direction to the nearest 10 degrees (310, 320, etc.). The reduction from tens of degrees to eight points results in a bias such that the cardinal directions (N, E, S, W) represent a larger sector of the compass than the intermediate directions. Each of the four cardinal direction sectors span 50 degrees, while the intermediate sectors span 40 degrees. This bias usually results in higher frequencies in the cardinal directions than in the intermediate directions. The AES Climatic Atlas of Canada (1988) reports that the errors created by this bias are generally small, and they do not consider them significant. We did not make any attempt to account for this bias, although we believe it does result in some error in our calculations.

Appendix 1 lists the directional characteristics for the stations used in this study.

D. RESULTS

1. Maximum Recorded Wind Speeds

Figure 3 shows the maximum wind speeds recorded at the study locations within Alberta. The values range from 100 km/hr at Fort Smith and Peace River, to 171 km/hr at Lethbridge. There is a general tendency for increasing maximum speed from north to south. Beyond this, it is difficult to identify a spatial pattern, or even to characterize an "extreme event". At some locations the event occurred in a thunderstorm, during a snowstorm or during a chinook.

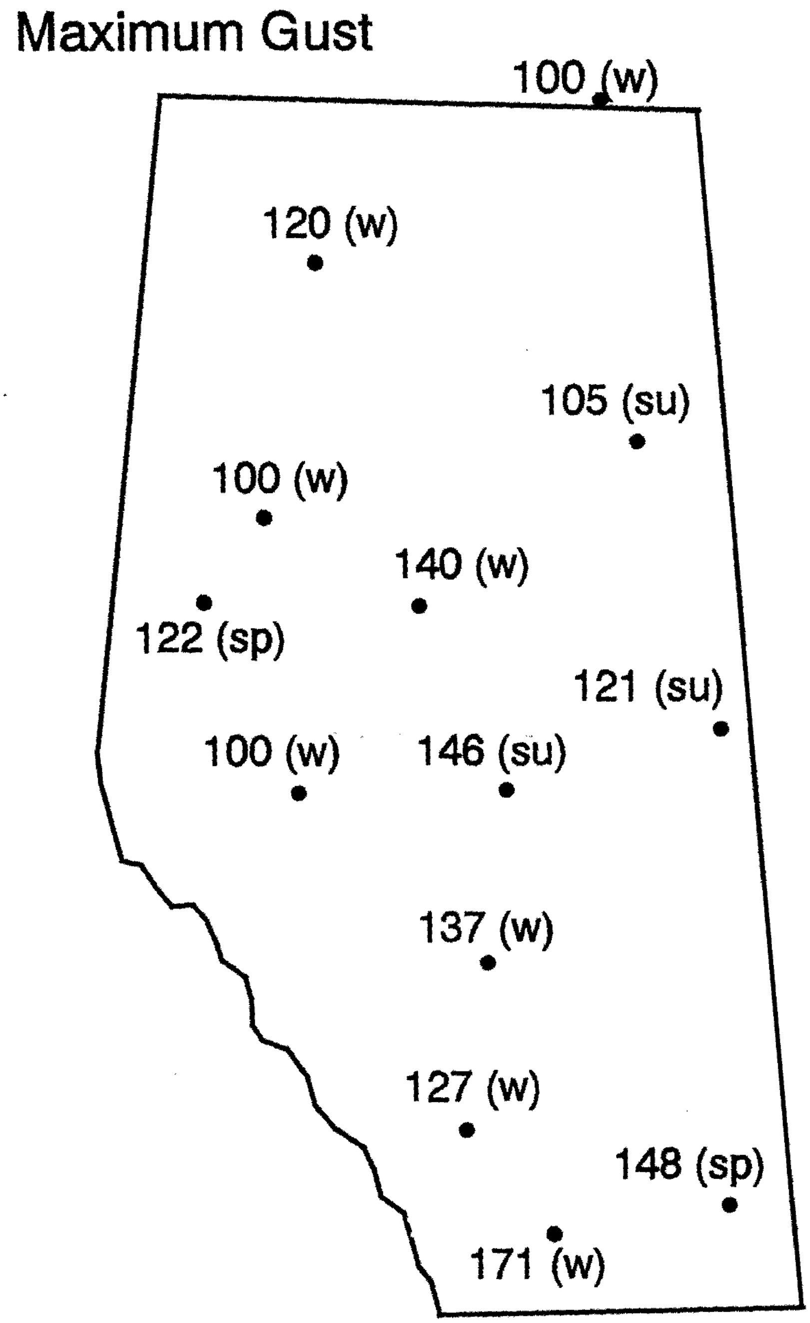

Figure 3. Maximum recorded wind gust (km/hr) at the study sites. The season in which the maximum gust occurred is indicated in parenthesis: w = winter, su = summer, sp = spring.

2. Return Period Analysis

a) Uncategorized return periods

The uncategorized return periods (all seasons) clearly show increasing gust magnitudes as one moves south in Alberta. Figure 4 shows the return periods for 70, 90, 110, and 130 km/hr gusts at the study sites. The analysis shows that wind speeds of 70 km/hr are common throughout Alberta, as the return period falls below 1.5 years at all locations. This means that on average, all stations would expect to see a 70 km/hr gust every year or two. In fact, only in the far north (return period > 1 yr) would such an event not be expected every year.

The return period increases significantly for a 90 km/hr event in the north, reaching 12.3 years at Fort Smith. But in the southern half of the province a 90 km/hr wind is still expected every year. It is not until a speed of 110 km/hr that a gust can be considered rare, and then only in the northern part of the province. From the calculated return period we would say that such a gust is extremely rare (not historically seen) in Fort Smith and Peace River (a low confidence should be placed on return periods greater than the record length). The return period for a 110 km/hr wind decreases as one moves south in the province, reaching a low of 1.1 years in the chinook country of Lethbridge.

In the northern portion of the province, the return period for a 130 km/hr gust has little meaning. In Fort Smith, High Level, Fort McMurray, Peace River, and Edson, we cannot accurately predict such an event. We can only say that it is very unlikely that such an event will occur within an individual's lifetime. Moving south, a 130 km/hr gust becomes a rare event at Grande Prairie (64 yr return period), an infrequent event in Red Deer (10.9 yr return period), and a common event at Lethbridge (2.7 yr return period).

b) Seasonally categorized return periods

An examination of seasonally categorized return periods indicates that across Alberta the stations are about equally split between having higher summer or higher winter gusts. This is indicated by the season having the shorter return periods (Figures 5A, 5B, and 5C). Very generally, higher wind gusts occur in the winter in the north and adjacent to the mountains, while in central portions of the province (Edson, Grande Prairie, Edmonton, Fort McMurray, Cold Lake) and Medicine Hat, the summer has higher gusts. Spring seems to have lower gust speeds than the other seasons in the northern part of the province, but in the south the return periods are similar between the seasons.

It is tempting to attribute the seasonal characteristics of the maximum wind gusts to a climatological feature. For instance, we might speculate that the occurrence of

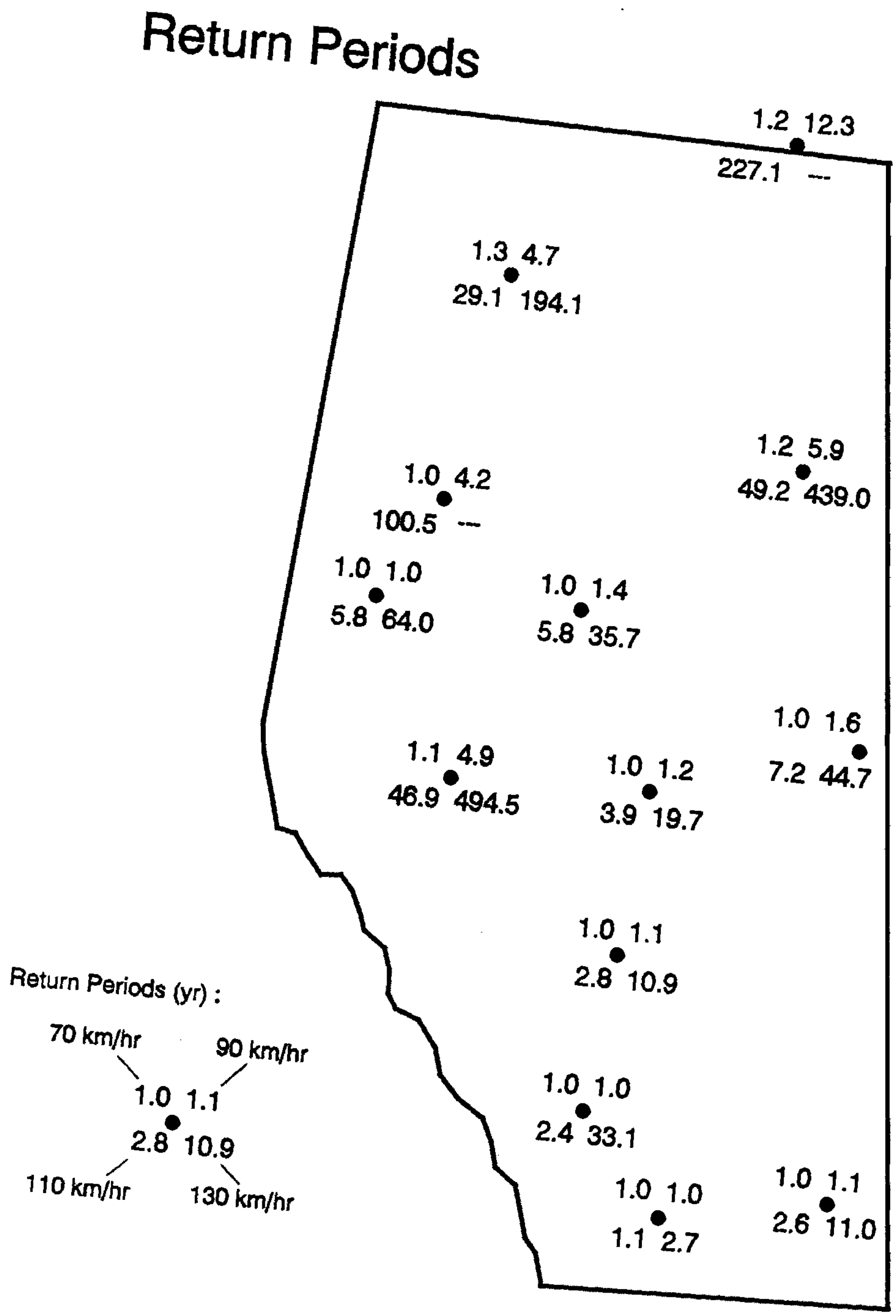

Figure 4. Calculated return periods (no seasonal categorization) for 70, 90, 110, and 130 km/hr gusts. A dash indicates a return period > 500 yr.

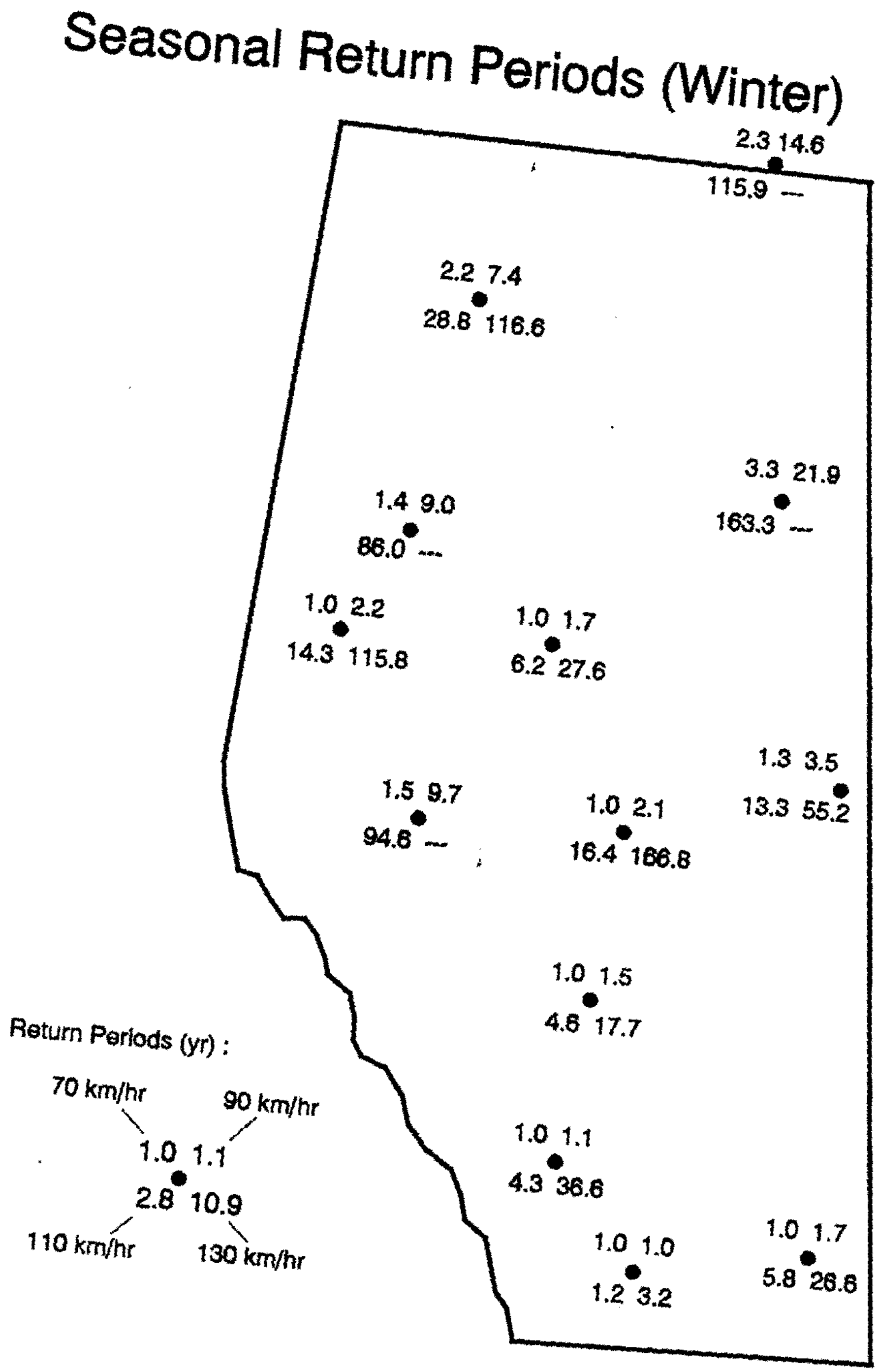

Figure 5A. Seasonal return periods for winter (Nov. - Mar.) for 70, 90, 110, and 130 km/hr gusts. A dash indicates a return period > 500 yr.

Seasonal Return Periods (Spring)

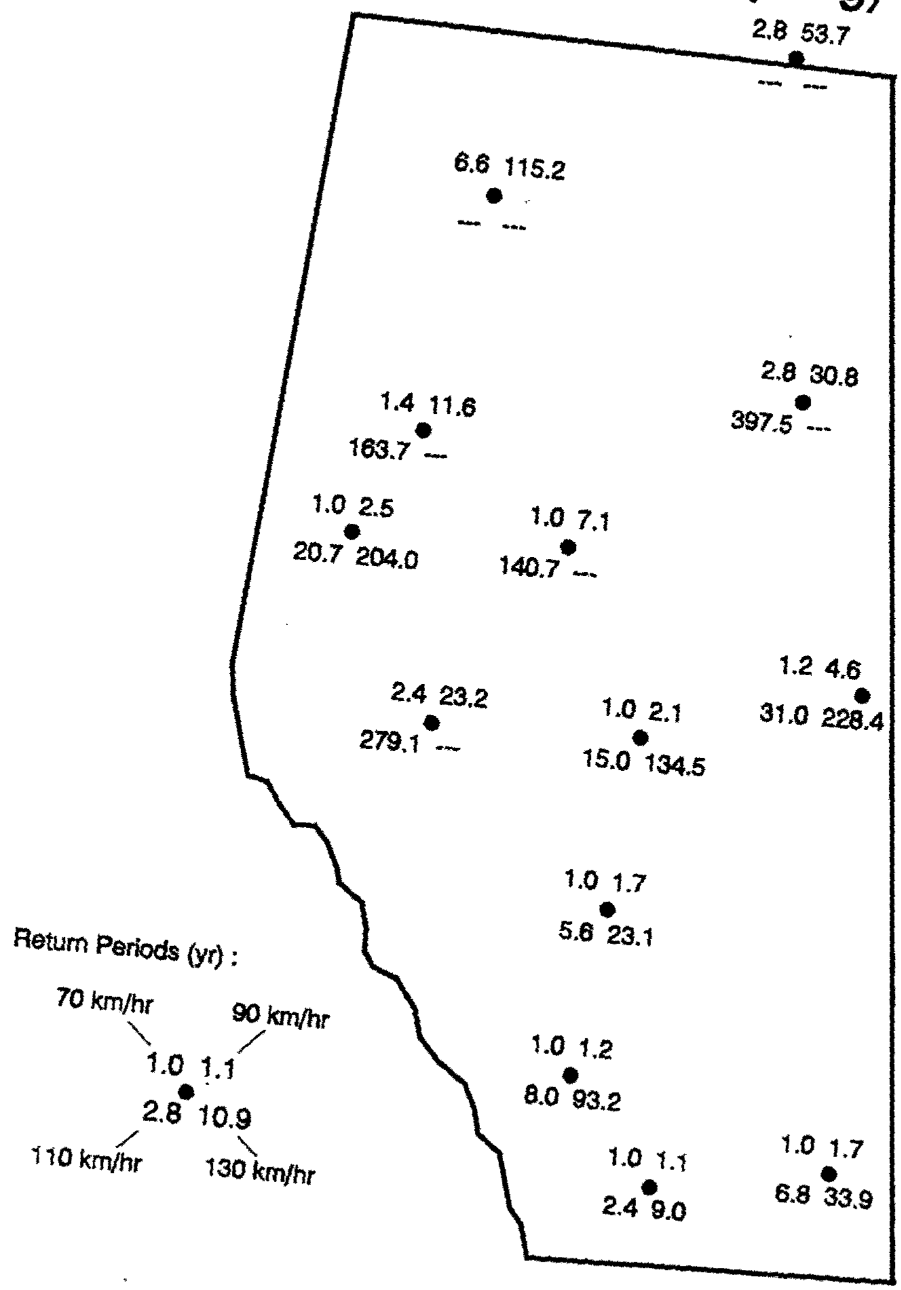

Figure 5B. Seasonal return periods for spring (Apr. - June) for 70, 90, 110, and 130 km/hr gusts. A dash indicates a return period > 500 yr.

Seasonal Return Periods (Summer)

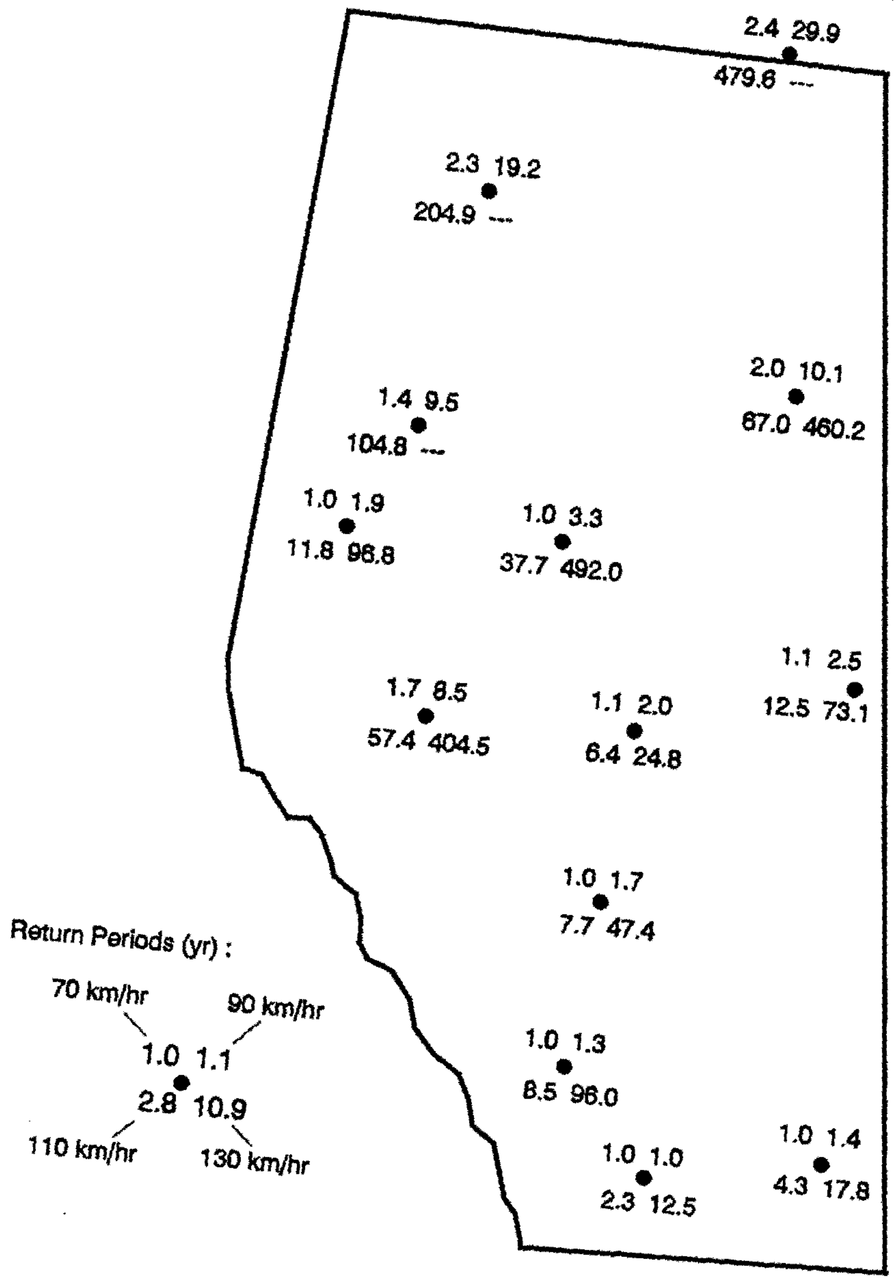

Figure 5C. Seasonal return periods for summer (July - Oct.) for 70, 90, 110, and 130 km/hr gusts. A dash indicates a return period > 500 yr.

summer maximum gusts in the central region are related to the more common occurrence of thunderstorms, while in the north thunderstorms are not common and the maximum gust occurs in winter storms. Such an explanation may be correct (although Longley (1972) shows the maximum number of thunderstorm days occurs in the north), but in the absence of a very long record, chance may provide much of the explanation for the apparent seasonal patterns. The pattern of a winter or summer maximum may be simply due to the random chance of a thunderstorm passing over the station in the summer.

3. Directional Analysis

a) Annual wind extremes

Our analysis of the directional characteristics of annual maximum winds shows quite clearly the predominance of extreme winds from the N - NW - W directions (Figure 6). At each station in Alberta, the large majority of maximum gusts occurred from these directions. We can further say that at most locations the annual maximum gust came from the NW - W directions. Only in Calgary and Red Deer were there large contributions from the north. If we were to restrict our analysis to only the "extremes-of-the-extremes" we would conclude even more strongly that the extreme gusts were oriented in a NW - W directions.

The characteristic direction of maximum gusts contrasts with the direction of the prevailing average wind, which is from the north and east across northeastern sections of Alberta, and the south and west in southwestern portions of the province (Longley 1972). The average mean wind direction is the result of average weather patterns. In late-fall through early-spring the mean position of the arctic front through North America lies NW - SE across Alberta, with northeasterly winds north of the front and southwesterly winds to the south. But these average patterns are not important factors in the direction of the extreme gusts. The annual maximum wind in Alberta typically occurs during intense storms or during frontal passages. The nature of these events is usually strong winds from the N - NW - W. The exception is along the foothills, where chinooks often bring extreme wind events, but also from a westerly direction.

Throughout most of the province we believe that the annual maximum wind will occur from the NW - W. However, we are uncertain as to the validity of this statement adjacent to the mountains, which may impose unique wind flow characteristics. Indeed, of the study locations, the one closest to the mountains (Calgary) had the most wind maximums from the north (parallel to the mountains). The lack of reporting stations adjacent to the mountains makes it impossible for us to generalize about this region.

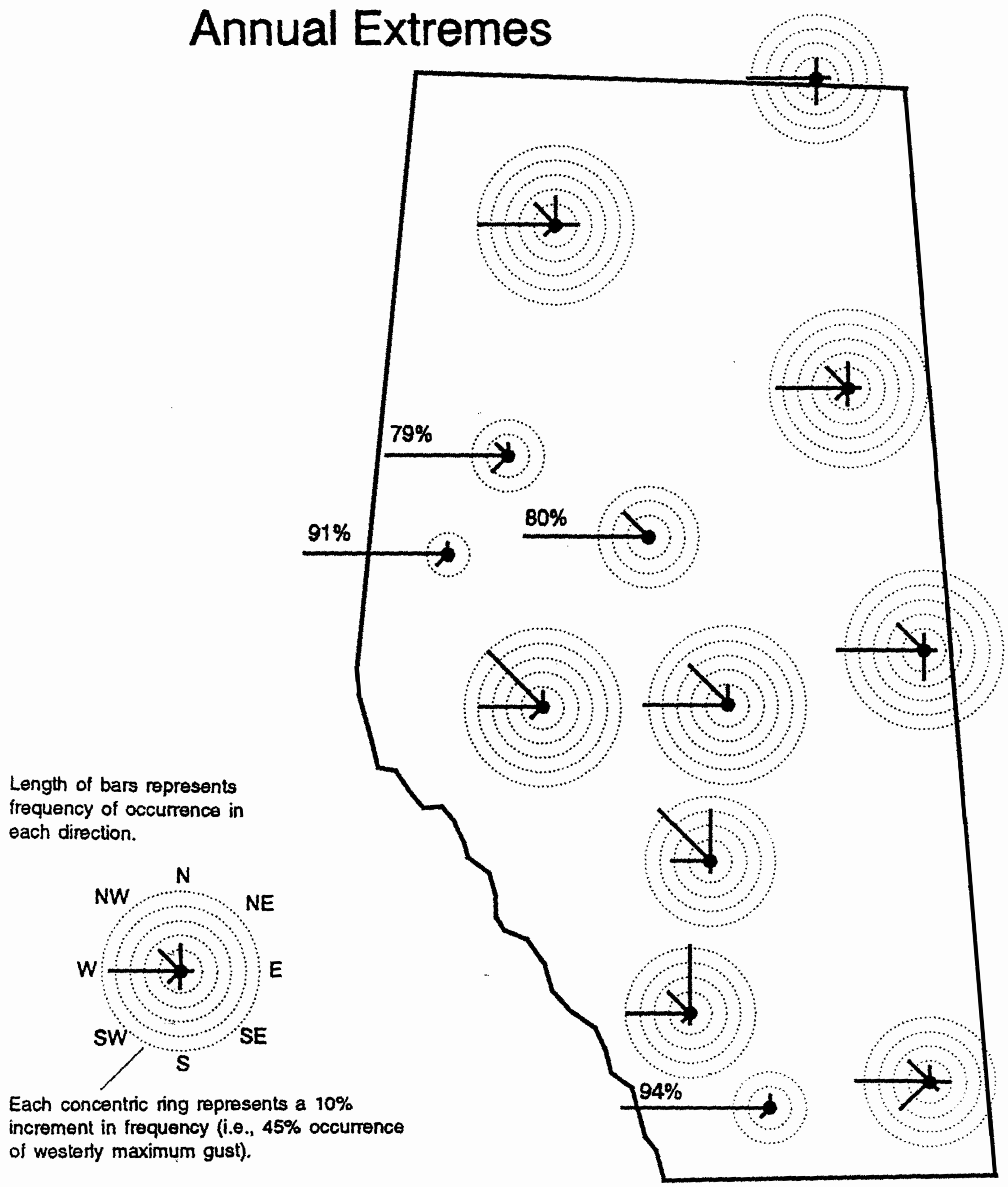

Figure 6. Directional frequencies (wind rose) for the annual extreme wind gusts.

b) Seasonal wind extremes

The seasonal characteristics of the direction of the maximum gust are similar to the annual characteristics: most of the extreme gusts occur from the NW - W directions (Figures 7A, 7B, and 7C). There appears to be a tendency for a larger range in the seasonal gust direction than in the annual range. This is likely due to the fact that on a seasonal basis there are fewer "true" extremes than in the annual record, and many relatively low wind gusts. Considering only the "extremes-of-the-extremes" again confirms that the maximum seasonal gust usually occurs from the NW - W directions.

4. Spatial Extrapolation of Results

The underlying assumption in undertaking this study is that the results of the analysis of 14 stations can be extrapolated to estimate the likelihood of wind gusts throughout Alberta (excluding the mountains). We have already discussed the problems associated with non-uniformity in the layout of the measurement sites and differences between the site and surrounding terrain/vegetation. There is also a question regarding the scale of the gust events. Can two "ideal" measurement locations, located near each other, have substantially different return periods? There is an opportunity to examine this question because of the existence of two recording sites in the Edmonton area (International Airport and Namao). We compared results from the two similar sites located outside the city. Both have anemometers located within extensive areas of maintained grass. The surrounding area at both locations is farmland interspersed with woodlots. The two stations are approximately 30 km apart.

Figure 8 shows the annual maximum gust record at the two stations. Surprisingly, there is quite a difference when comparing the two on a year-to-year basis. In 1974 there was a 138 km/hr gust at Namao (thunderstorm) while the maximum gust at the International was 84 km/hr. These differences certainly show that maximum gust events are spatially limited. But what effect does the limited scale have on the extreme value statistics of a location? From these two stations it appears that it has a minimal effect. Table 5 shows the uncategorized return periods for different wind speeds at both stations. There is good agreement between the calculated return periods (even T(130) is relatively close, considering the range seen across the province). This is encouraging in that it suggests that it is acceptable to extrapolate and interpolate our results.

Figure 9 shows the winter and summer maximum gust records at the two stations. Again there is quite a bit of year-to-year difference between the two stations. Table 5 shows the winter and summer categorized return periods for the two locations. Although the two are similar in the summer, in the winter the difference between the 110 and 130 return periods is large. Large differences also exist between the two in

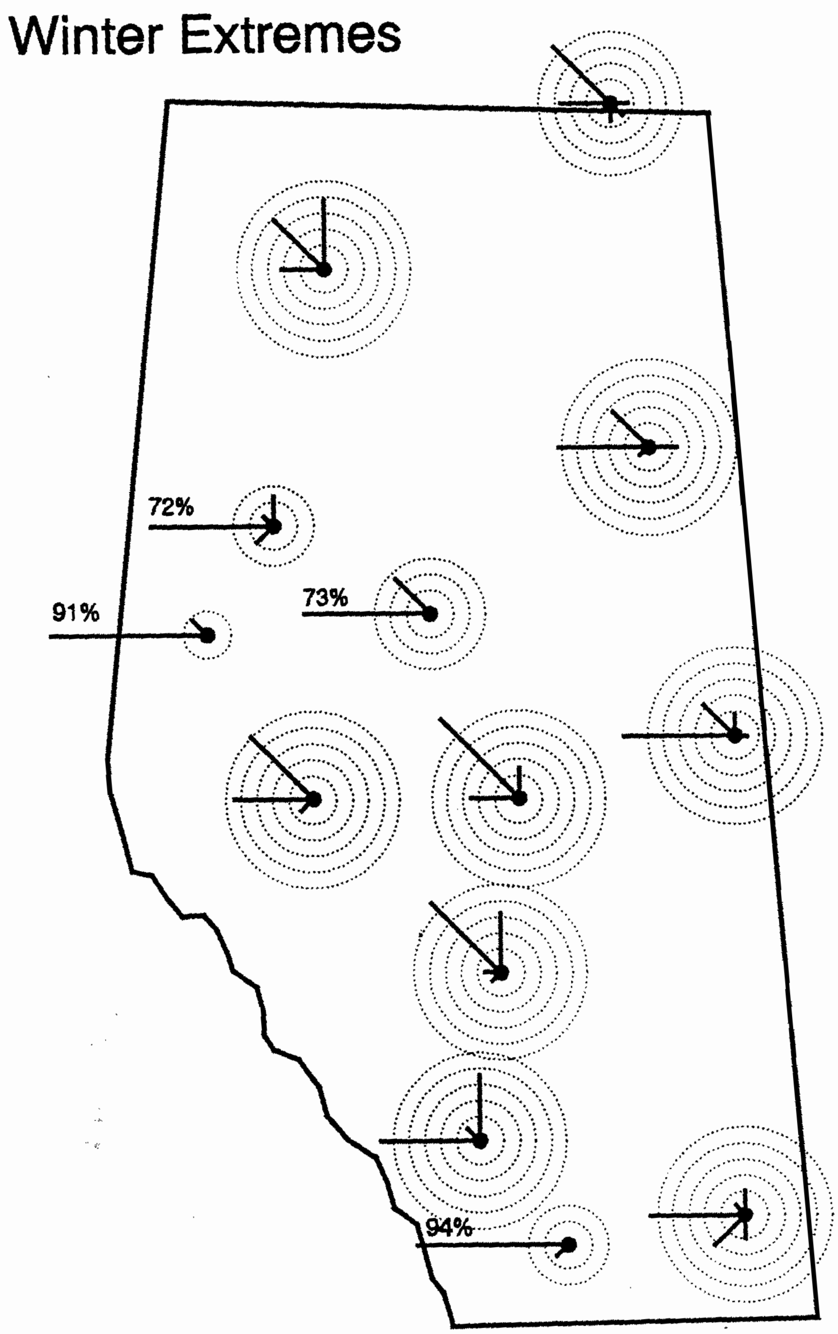

Figure 7A. Directional frequencies for the annual winter (Nov. - Mar.) extreme wind gusts.

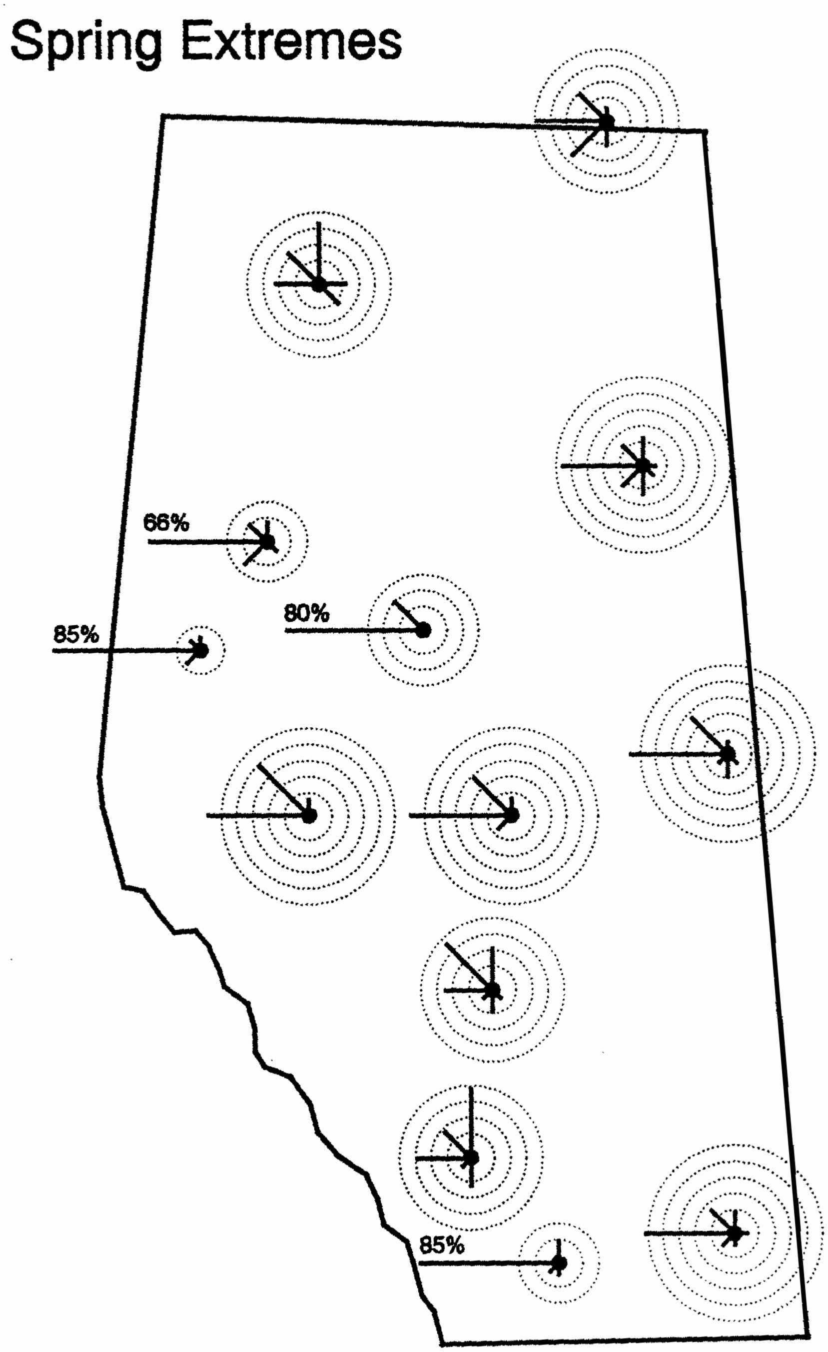

Figure 7B. Directional frequencies for the annual spring (Apr. - June) extreme wind gusts.

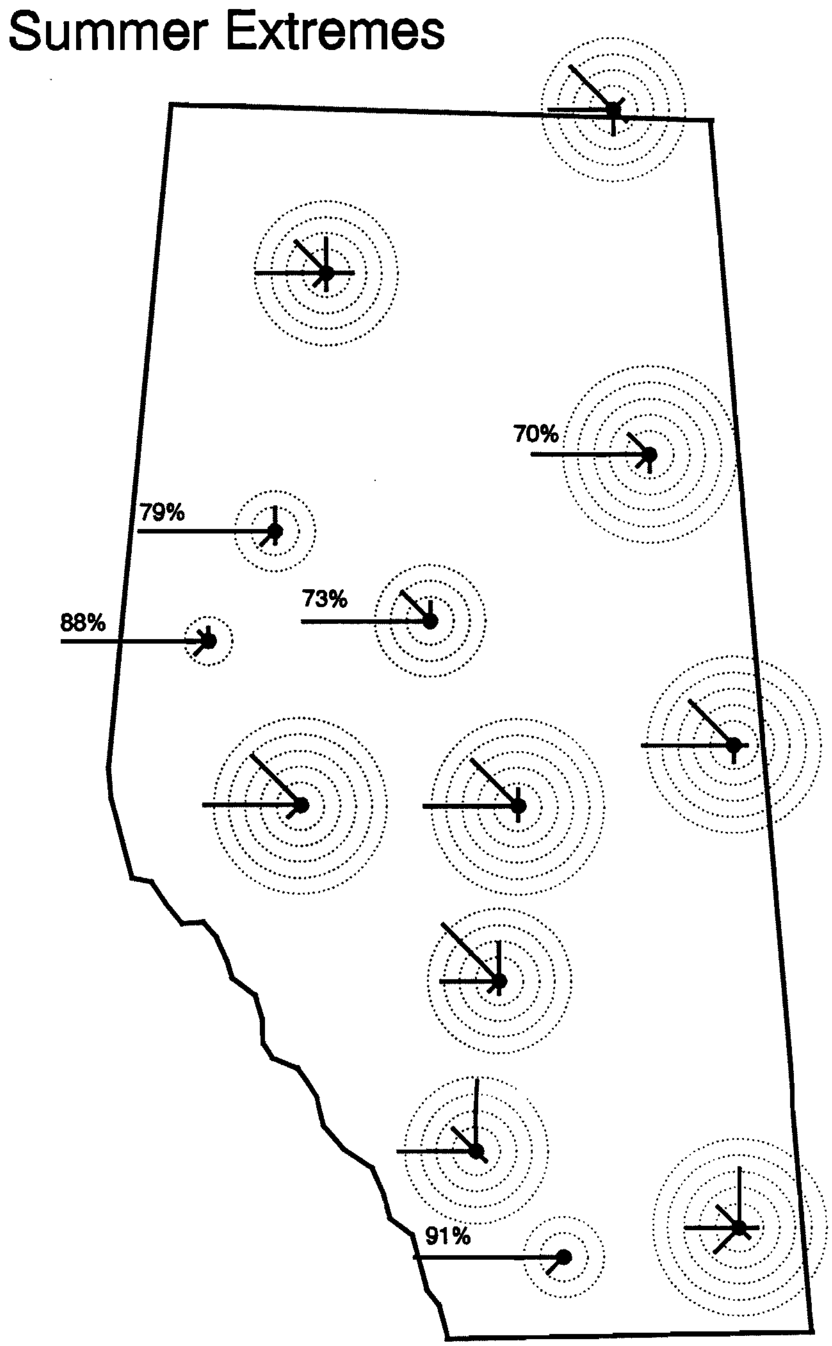

Figure 7C. Directional frequencies for the annual summer (July - Oct.) extreme wind gusts.

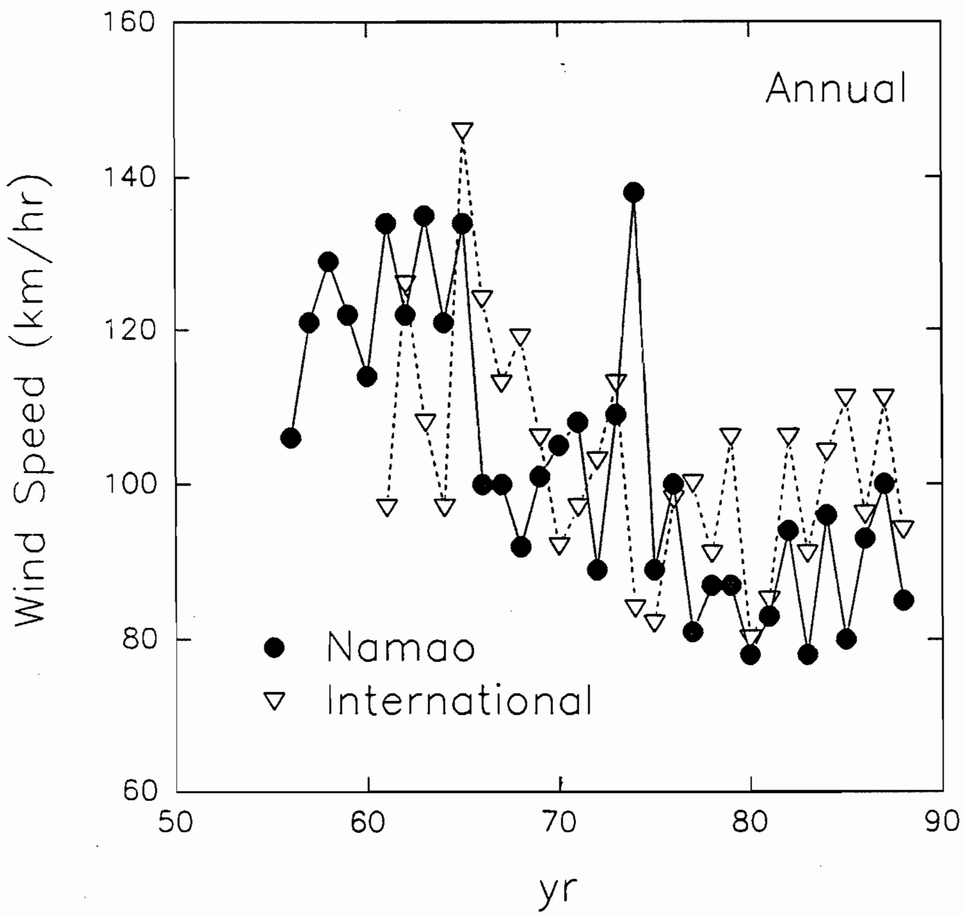

Figure 8. Time series of the annual maximum gust at Edmonton Namao and Edmonton International.

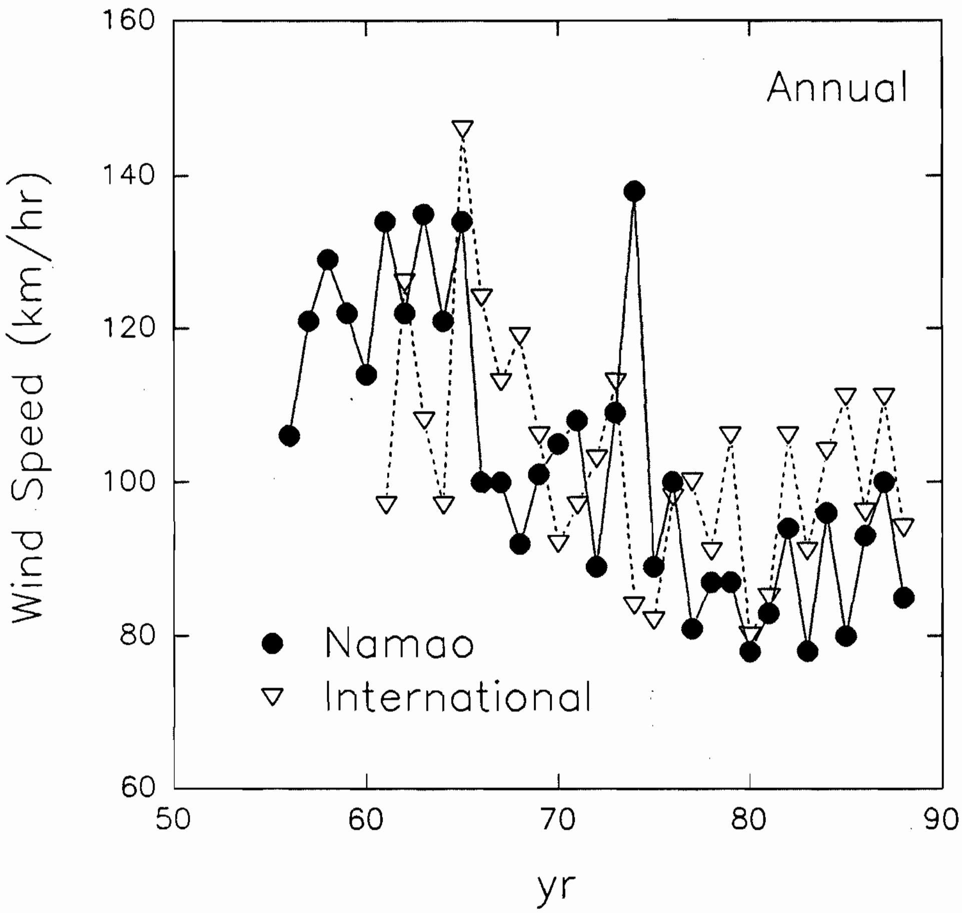

Figure 9. Time series of the annual maximum winter and summer gust at Edmonton Namao and Edmonton International.

the spring statistics (not shown). We conclude that on a seasonal basis caution is advised when extrapolating the infrequent, larger gust extremes (> 10 yr return periods). We believe that the added uncertainty in the seasonal results (as compared with the non-categorized annual results) is due to the smaller data pool used to construct the seasonal maximum record. Our study has shown that a record gust can occur over a large part of the season, and looking at roughly 1/3 of the data when selecting seasonal maximums necessarily increases the uncertainty in the analysis results (as well as extrapolation errors).

Table 5. Return periods for Edmonton Namao and Edmonton International Airport.

Wind Speed km/hr	Uncategorized Return Period		Winter Return Period		Summer Return Period	
	Namao	Int'l	Namao	Int'l	Namao	Int'l
70	1.0	1.0	1.1	1.0	1.0	1.1
90	1.3	1.2	2.1	2.1	1.8	2.0
110	3.4	3.9	7.8	16.4	5.1	6.4
130	12.1	19.7	33.8	166.8	17.9	24.8

E. SUMMARY AND CONCLUSIONS

Gust records at 14 stations in Alberta were examined and several features observed. The maximum recorded wind speeds range from 100 km/hr (Fort Smith and Peace River) to 171 km/hr (Lethbridge). The speed of the maximum gust generally increased from north to south across the province. A directional analysis indicates that across most of the province the extreme gusts come from a west to northwest direction.

Classical extreme value statistics were used to estimate the probability of extreme gusts. Results were presented in terms of return periods, which represent an average length of time between gusts of a given wind speed. There is a general tendency for shorter return periods when moving from north to south across Alberta. This confirms the greater potential for high winds in southern Alberta as compared with northern sections. Seasonally categorized return periods show the same spatial trend, and a slightly greater likelihood of higher wind gusts in the winter in the north and south, and in the summer in central portions of the province.

The representativeness of the results at the select locations is a matter of concern. The measurement site at some locations is not "standard", which makes comparisons between the various stations difficult because we do not know the effect that the non-standard observations have on the extreme winds. It is important to note that the results for a standard location in this study extrapolate to the wind at 10 m above a grass surface, with some similarity to the wind speed 10 m above a thick uniform forest canopy. Comparison of two nearby sites indicates that the uncategorized annual results can be extrapolated from the stations with some confidence. However, caution is advised for the extrapolation of seasonally categorized results.

The following is a list of our recommendations in planning for extreme gust events in Alberta.

1. The results of this study should not be extrapolated to areas of non-uniform terrain (i.e., foothills area).

2. Expect the most frequent and extreme gust events to have a west to northwest direction.

3. Expect considerable inaccuracy in the calculated return periods with values near, or larger, than the length of the station record. This is generally about 30 years.

4. Assign less accuracy to the seasonally categorized results than the uncategorized results. This is particularly true in looking at the more extreme gusts (return periods > 10 years).

5. For return periods at unmeasured locations, it would be preferable to interpolate between stations as opposed to extrapolating from any one station.

REFERENCES

Atmospheric Environment Service. 1988. Climatic atlas of Canada, Map Series 5 - Wind. Environment Canada, Canadian Government Publishing Centre, Ottawa, ON.

Fisher, R.A.; Tippett, L.H.C. 1928. Limiting forms of the frequency distributions of the largest or smallest member of a sample. Proc. Cambridge Phil. Soc. 24:180-190.

Kendall, G.R. 1959. Statistical analysis of extreme values. In Proc. of Symposium No. 1, Spillway Design Floods. National Research Council of Canada.

Kinnison, R.P. 1985. Applied extreme value statistics. MacMillan Publishing Company, New York, NY.

Longley, R.W. 1972. The climate of the prairie provinces. Atmospheric Environment Climatological Studies No. 13. Toronto, ON.

Lowery, M.D.; Nash, J.E. 1970. A comparison of methods of fitting the double exponential distribution. J. Hydrology, 10:259-275.

APPENDIX 1

The following pages give the detailed results of the extreme value analysis for each of the 14 stations used in this study. At the top of each page is the AES station number and station name. The following line gives the length of the station record and the number of *complete* years of data. The results given are self-explanatory, broken down into annual and seasonal calculations. At the bottom of each page are the parameters used in the exponential extreme value distribution.

FILE NO. 2202200 STATION: FORT SMITH
Period Of Record: 1958 - 1988 (31 years data)

	Annual	Winter	Spring	Summer
Maximum Wind Speed	100 km/hr	100 km/hr	87 km/hr	90 km/hr

Directional Frequency (%) of Maximum Winds (31 Years)

Dir	Annual	Winter	Spring	Summer
N	10	10	3	13
NE	0	0	0	3
E	6	6	0	0
SE	0	6	3	6
S	13	6	10	10
SW	3	0	26	0
W	42	26	39	35
NW	26	45	19	32

Return Periods

Return Period (years)

Wind Speed	Annual	Winter	Spring	Summer
50 km/hr	1.0	1.0	1.0	1.0
70 km/hr	1.2	2.3	2.8	2.4
90 km/hr	12.3	14.6	53.7	29.9
110 km/hr	227.1	115.9	-999.0	479.6
130 km/hr	-999.0	948.0	-999.0	-999.0

Wind Speed (km/hr)

Return Prd	Annual (sd)	Winter (sd)	Spring (sd)	Summer (sd)
2 yr	75.8 (1.4)	68.4 (2.0)	67.1 (1.3)	68.4 (1.5)
5 yr	83.5 (2.4)	79.2 (3.4)	74.3 (2.3)	76.5 (2.6)
10 yr	88.5 (3.3)	86.3 (4.6)	79.1 (3.0)	81.9 (3.4)
20 yr	93.4 (4.1)	93.1 (5.8)	83.6 (3.8)	87.1 (4.4)
50 yr	99.7 (5.2)	102.0 (7.4)	89.5 (4.9)	93.7 (5.6)

Average and Standard Deviations of Sample Data

	Annual	Winter	Spring	Summer
Average	77.2	70.39	68.48	69.90
SD	8.7	12.18	8.12	9.19
Delta	6.8	9.50	6.33	7.17
Lambda	73.3	64.90	64.83	65.77

FILE NO. 3073146 STATION: HIGH LEVEL
Period of Record: 1971 - 1988 (18 years data)

Maximum Wind Speed	Annual	Winter	Spring	Summer
	120 km/hr	120 km/hr	81 km/hr	93 km/hr

Directional Frequency (%) of Maximum Winds (18 Years)

Dir	Annual	Winter	Spring	Summer
N	17	39	33	17
NE	0	0	0	0
E	11	0	11	11
SE	0	0	11	0
S	0	0	0	6
SW	6	0	0	6
W	50	22	22	39
NW	17	39	22	22

Return Periods

	Return Period (years)			
Wind Speed	Annual	Winter	Spring	Summer
50 km/hr	1.0	1.1	1.0	1.0
70 km/hr	1.3	2.2	6.6	2.3
90 km/hr	4.7	7.4	115.2	19.2
110 km/hr	29.1	28.8	-999.0	204.9
130 km/hr	194.1	116.6	-999.0	-999.0

	Wind Speed (km/hr)			
Return Prd	Annual (sd)	Winter (sd)	Spring (sd)	Summer (sd)
2 yr	78.8 (2.9)	67.8 (3.9)	60.2 (1.9)	68.6 (2.3)
5 yr	90.6 (4.9)	83.9 (6.6)	67.9 (3.2)	78.1 (3.9)
10 yr	98.5 (6.6)	94.5 (8.9)	73.0 (4.3)	84.3 (5.3)
20 yr	106.0 (8.3)	104.7 (11.3)	77.9 (5.4)	90.3 (6.7)
50 yr	115.7 (10.6)	117.9 (14.4)	84.3 (6.9)	98.1 (8.5)

Average and Standard Deviations of Sample Data

	Annual	Winter	Spring	Summer
Average	81.0	70.78	61.67	70.33
SD	13.4	18.18	8.72	10.73
Delta	10.5	14.18	6.80	8.36
Lambda	75.0	62.59	57.74	65.51

FILE NO. 3062693 STATION: FORT MCMURRAY
Period of Record: 1956 - 1988 (33 years data)

	Annual	Winter	Spring	Summer
Maximum Wind Speed	105 km/hr	97 km/hr	97 km/hr	105 km/hr

Directional Frequency (%) of Maximum Winds (33 Years)

Dir	Annual	Winter	Spring	Summer
N	12	6	12	6
NE	0	0	0	0
E	3	12	3	0
SE	0	0	3	0
S	9	0	12	6
SW	9	3	12	6
W	48	52	45	70
NW	18	27	12	12

Return Periods

Return Period (years)

Wind Speed	Annual	Winter	Spring	Summer
50 km/hr	1.0	1.1	1.0	1.0
70 km/hr	1.2	3.3	2.8	2.0
90 km/hr	5.9	21.9	30.8	10.1
110 km/hr	49.2	163.3	397.5	67.0
130 km/hr	439.0	-999.0	-999.0	460.2

Wind Speed (km/hr)

Return Prd	Annual (sd)	Winter (sd)	Spring (sd)	Summer (sd)
2 yr	78.0 (1.9)	63.5 (2.0)	66.3 (1.6)	70.4 (2.1)
5 yr	88.3 (3.1)	74.6 (3.4)	75.1 (2.7)	82.1 (3.6)
10 yr	95.1 (4.2)	82.0 (4.6)	81.0 (3.6)	89.9 (4.8)
20 yr	101.7 (5.4)	89.1 (5.8)	86.6 (4.6)	97.3 (6.1)
50 yr	110.1 (6.8)	98.3 (7.4)	93.8 (5.8)	106.9 (7.8)

Average and Standard Deviations of Sample Data

	Annual	Winter	Spring	Summer
Average	79.9	65.55	67.97	72.55
SD	11.7	12.63	9.97	13.27
Delta	9.1	9.85	7.77	10.35
Lambda	74.6	59.86	63.48	66.57

FILE NO. 3075040 STATION: PEACE RIVER
Period of Record: 1960 - 1988 (29 years data)

Maximum Wind Speed	Annual	Winter	Spring	Summer
	100 km/hr	100 km/hr	94 km/hr	96 km/hr

Directional Frequency (%) Of Maximum Winds (29 Years)

Dir	Annual	Winter	Spring	Summer
N	3	14	7	10
NE	0	0	0	0
E	0	0	0	0
SE	0	0	3	0
S	0	0	0	3
SW	10	10	14	7
W	79	72	66	79
NW	7	3	10	0

Return Periods

	Return Period (years)			
Wind Speed	Annual	Winter	Spring	Summer
50 km/hr	1.0	1.0	1.0	1.0
70 km/hr	1.0	1.4	1.4	1.4
90 km/hr	4.2	9.0	11.6	9.5
110 km/hr	100.5	86.0	163.7	104.8
130 km/hr	-999.0	857.6	-999.0	-999.0

	Wind Speed (km/hr)			
Return Prd	Annual (sd)	Winter (sd)	Spring (sd)	Summer (sd)
2 yr	84.4 (1.3)	74.6 (1.9)	74.8 (1.6)	75.1 (1.8)
5 yr	91.2 (2.2)	84.4 (3.2)	83.2 (2.7)	84.3 (3.0)
10 yr	95.8 (3.0)	90.9 (4.3)	88.8 (3.7)	90.5 (4.1)
20 yr	100.1 (3.8)	97.2 (5.5)	94.2 (4.7)	96.3 (5.1)
50 yr	105.8 (4.8)	105.3 (7.0)	101.1 (6.0)	103.9 (6.5)

Average and Standard Deviations of Sample Data

	Annual	Winter	Spring	Summer
Average	85.7	76.41	76.38	76.83
SD	7.8	11.13	9.54	10.45
Delta	6.0	8.68	7.44	8.15
Lambda	82.2	71.41	72.08	72.12

FILE NO. 3066001 STATION: SLAVE LAKE
Period of Record: 1972 - 1988 (15 years data)

Maximum Wind Speed	Annual	Winter	Spring	Summer
	140 km/hr	140 km/hr	100 km/hr	106 km/hr

Directional Frequency (%) of Maximum Winds (15 Years)

Dir	Annual	Winter	Spring	Summer
N	0	0	0	7
NE	0	0	0	0
E	0	0	0	0
SE	0	0	0	0
S	0	0	0	0
SW	0	0	0	0
W	80	73	80	73
NW	20	27	20	20

Return Periods

	Return Period (years)			
Wind Speed	Annual	Winter	Spring	Summer
50 km/hr	1.0	1.0	1.0	1.0
70 km/hr	1.0	1.0	1.0	1.0
90 km/hr	1.4	1.7	7.1	3.3
110 km/hr	5.8	6.2	140.7	37.7
130 km/hr	35.7	27.6	-999.0	492.0

	Wind Speed (km/hr)			
Return Prd	Annual (sd)	Winter (sd)	Spring (sd)	Summer (sd)
2 yr	96.5 (3.2)	92.6 (3.9)	80.1 (2.0)	84.8 (2.4)
5 yr	108.4 (5.4)	107.0 (6.5)	87.5 (3.3)	93.6 (4.0)
10 yr	116.2 (7.3)	116.6 (8.8)	92.4 (4.5)	99.4 (5.4)
20 yr	123.8 (9.2)	125.8 (11.2)	97.1 (5.7)	105.0 (6.8)
50 yr	133.6 (11.7)	137.7 (14.2)	103.2 (7.3)	112.2 (8.6)

Average and Standard Deviations of Sample Data

	Annual	Winter	Spring	Summer
Average	98.7	95.27	81.47	86.47
SD	13.5	16.37	8.38	9.93
Delta	10.5	12.77	6.54	7.75
Lambda	92.6	87.90	77.69	82.00

FILE NO. 3072920 STATION: GRANDE PRAIRIE
Period of Record: 1955 - 1988 (34 years data)

	Annual	Winter	Spring	Summer
Maximum Wind Speed	122 km/hr	121 km/hr	122 km/hr	120 km/hr

Directional Frequency (%) of Maximum Winds (34 Years)

Dir	Annual	Winter	Spring	Summer
N	3	0	3	3
NE	0	0	0	0
E	0	0	3	0
SE	0	0	0	0
S	0	0	0	0
SW	6	0	6	6
W	91	91	85	88
NW	0	9	3	3

Return Periods

	Return Period (years)			
Wind Speed	Annual	Winter	Spring	Summer
50 km/hr	1.0	1.0	1.0	1.0
70 km/hr	1.0	1.0	1.0	1.0
90 km/hr	1.1	2.2	2.5	1.9
110 km/hr	5.8	14.3	20.7	11.8
130 km/hr	64.0	115.8	204.0	96.8

	Wind Speed (km/hr)			
Return Prd	Annual (sd)	Winter (sd)	Spring (sd)	Summer (sd)
2 yr	99.5 (1.6)	88.7 (1.9)	87.2 (1.7)	90.9 (1.9)
5 yr	108.7 (2.7)	99.4 (3.2)	97.0 (2.9)	101.4 (3.2)
10 yr	114.7 (3.7)	106.5 (4.3)	103.5 (4.0)	108.4 (4.3)
20 yr	120.5 (4.7)	113.3 (5.5)	109.7 (5.0)	115.1 (5.4)
50 yr	128.0 (6.0)	122.0 (7.0)	117.8 (6.4)	123.8 (6.9)

Average and Standard Deviations of Sample Data

	Annual	Winter	Spring	Summer
Average	101.2	90.71	89.00	92.82
SD	10.3	12.08	11.10	11.95
Delta	8.1	9.42	8.65	9.32
Lambda	96.6	85.27	84.01	87.45

FILE NO. 3081680 STATION: COLD LAKE
Period of Record: 1956 - 1988 (33 years data)

Maximum Wind Speed	Annual	Winter	Spring	Summer
	121 km/hr	119 km/hr	108 km/hr	121 km/hr

Directional Frequency (%) of Maximum Winds (33 Years)

Dir	Annual	Winter	Spring	Summer
N	6	9	3	6
NE	0	0	0	0
E	3	3	0	3
SE	0	0	3	0
S	15	0	9	6
SW	0	0	3	0
W	55	67	55	52
NW	21	21	27	33

Return Periods

	Return Period (years)			
Wind Speed	Annual	Winter	Spring	Summer
50 km/hr	1.0	1.0	1.0	1.0
70 km/hr	1.0	1.3	1.2	1.1
90 km/hr	1.6	3.5	4.6	2.5
110 km/hr	7.2	13.3	31.0	12.5
130 km/hr	44.7	55.2	228.4	73.1

	Wind Speed (km/hr)			
Return Prd	Annual (sd)	Winter (sd)	Spring (sd)	Summer (sd)
2 yr	93.8 (2.2)	80.0 (2.8)	79.7 (2.0)	86.4 (2.3)
5 yr	105.8 (3.6)	95.6 (4.7)	91.0 (3.4)	99.0 (3.8)
10 yr	113.7 (4.9)	105.9 (6.4)	98.4 (4.6)	107.4 (5.2)
20 yr	121.3 (6.2)	115.8 (8.1)	105.6 (5.9)	115.4 (6.6)
50 yr	131.2 (8.0)	128.6 (10.3)	114.8 (7.5)	125.7 (8.4)

Average and Standard Deviations of Sample Data

	Annual	Winter	Spring	Summer
Average	96.0	82.94	81.79	88.73
SD	13.6	17.63	12.74	14.28
Delta	10.6	13.74	9.94	11.13
Lambda	89.9	75.01	76.05	82.30

FILE NO. 3012205 STATION: EDMONTON INTERNATIONAL
Period of Record: 1961 - 1988 (28 years data)

	Annual	Winter	Spring	Summer
Maximum Wind Speed	146 km/hr	126 km/hr	113 km/hr	146 km/hr

Directional Frequency (%) of Maximum Winds (28 Years)

Dir	Annual	Winter	Spring	Summer
N	11	14	7	7
NE	0	0	0	0
E	0	0	0	0
SE	0	0	0	0
S	0	0	0	4
SW	0	0	7	0
W	54	25	57	54
NW	36	61	29	36

Return Periods

	Return Period (years)			
Wind Speed	Annual	Winter	Spring	Summer
50 km/hr	1.0	1.0	1.0	1.0
70 km/hr	1.0	1.0	1.0	1.1
90 km/hr	1.2	2.1	2.1	2.0
110 km/hr	3.9	16.4	15.0	6.4
130 km/hr	19.7	166.8	134.5	24.8

	Wind Speed (km/hr)			
Return Prd	Annual (sd)	Winter (sd)	Spring (sd)	Summer (sd)
2 yr	100.5 (2.5)	89.6 (1.9)	89.2 (2.0)	90.1 (3.1)
5 yr	113.4 (4.3)	99.2 (3.2)	99.4 (3.4)	106.1 (5.3)
10 yr	122.0 (5.8)	105.6 (4.3)	106.2 (4.6)	116.7 (7.2)
20 yr	130.2 (7.3)	111.8 (5.4)	112.6 (5.8)	126.9 (9.0)
50 yr	140.8 (9.3)	119.7 (6.9)	121.0 (7.4)	140.0 (11.5)

Average and Standard Deviations of Sample Data

	Annual	Winter	Spring	Summer
Average	102.9	91.39	91.11	93.04
SD	14.6	10.91	11.54	18.13
Delta	11.4	8.51	9.00	14.14
Lambda	96.3	86.48	85.91	84.88

FILE NO. 3012210 STATION: EDMONTON NAMAO
Period of Record: 1956 - 1988 (33 years data)

Maximum Wind Speed	Annual	Winter	Spring	Summer
	138 km/hr	126 km/hr	134 km/hr	138 km/hr

Directional Frequency (%) of Maximum Winds (33 Years)

Dir	Annual	Winter	Spring	Summer
N	15	33	9	12
NE	0	0	0	0
E	0	0	0	0
SE	0	0	0	0
S	3	0	3	0
SW	3	0	3	3
W	45	33	52	52
NW	33	33	33	33

Return Periods

	Return Period (years)			
Wind Speed	Annual	Winter	Spring	Summer
50 km/hr	1.0	1.0	1.0	1.0
70 km/hr	1.0	1.1	1.1	1.0
90 km/hr	1.3	2.1	2.4	1.8
110 km/hr	3.4	7.8	9.9	5.1
130 km/hr	12.1	33.8	47.3	17.9

	Wind Speed (km/hr)			
Return Prd	Annual (sd)	Winter (sd)	Spring (sd)	Summer (sd)
2 yr	100.4 (2.9)	88.8 (2.7)	86.7 (2.5)	92.6 (3.1)
5 yr	116.5 (4.9)	103.7 (4.5)	100.8 (4.3)	109.6 (5.2)
10 yr	127.2 (6.6)	113.5 (6.1)	110.2 (5.8)	120.9 (7.0)
20 yr	137.5 (8.4)	123.0 (7.7)	119.1 (7.3)	131.7 (8.8)
50 yr	150.7 (10.7)	135.2 (9.9)	130.7 (9.4)	145.7 (11.3)

Average and Standard Deviations of Sample Data

	Annual	Winter	Spring	Summer
Average	103.4	91.58	89.36	95.76
SD	18.3	16.83	15.95	19.27
Delta	14.3	13.12	12.43	15.02
Lambda	95.1	84.00	82.19	87.09

FILE NO. 3031093 STATION: CALGARY INTERNATIONAL
Period of Record: 1955 - 1988 (34 years data)

	Annual	Winter	Spring	Summer
Maximum Wind Speed	127 km/hr	127 km/hr	127 km/hr	122 km/hr

Directional Frequency (%) of Maximum Winds (34 Years)

Dir	Annual	Winter	Spring	Summer
N	41	35	38	38
NE	0	0	0	0
E	0	0	0	0
SE	0	0	0	3
S	3	0	12	0
SW	3	0	3	0
W	38	59	29	44
NW	15	6	18	15

Return Periods

Return Period (years)

Wind Speed	Annual	Winter	Spring	Summer
50 km/hr	1.0	1.0	1.0	1.0
70 km/hr	1.0	1.0	1.0	1.0
90 km/hr	1.0	1.1	1.2	1.3
110 km/hr	2.4	4.3	8.0	8.5
130 km/hr	33.1	36.6	93.2	96.0

Wind Speed (km/hr)

Return Prd	Annual (sd)	Winter (sd)	Spring (sd)	Summer (sd)
2 yr	108.1 (1.4)	101.6 (1.8)	96.9 (1.6)	96.2 (1.6)
5 yr	116.1 (2.4)	111.6 (3.0)	105.9 (2.7)	105.3 (2.7)
10 yr	121.3 (3.2)	118.2 (4.0)	111.9 (3.7)	111.4 (3.7)
20 yr	126.4 (4.1)	124.6 (5.1)	117.6 (4.6)	117.2 (4.7)
50 yr	132.9 (5.2)	132.8 (6.5)	125.0 (5.9)	124.7 (6.0)

Average and Standard Deviations of Sample Data

	Annual	Winter	Spring	Summer
Average	109.6	103.47	98.56	97.88
SD	9.0	11.31	10.20	10.34
Delta	7.0	8.82	7.96	8.07
Lambda	105.6	98.38	93.97	93.23

FILE NO. 3034480 STATION: MEDICINE HAT
Period of Record: 1960 - 1988 (29 years data)

	Annual	Winter	Spring	Summer
Maximum Wind Speed	148 km/hr	145 km/hr	148 km/hr	132 km/hr

Directional Frequency (%) of Maximum Winds (29 Years)

Dir	Annual	Winter	Spring	Summer
N	7	10	10	31
NE	0	0	0	0
E	10	0	3	7
SE	3	0	0	3
S	0	10	3	0
SW	21	21	7	17
W	45	55	59	28
NW	14	3	17	14

Return Periods

	Return Period (years)			
Wind Speed	Annual	Winter	Spring	Summer
50 km/hr	1.0	1.0	1.0	1.0
70 km/hr	1.0	1.0	1.0	1.0
90 km/hr	1.1	1.7	1.7	1.4
110 km/hr	2.6	5.8	6.8	4.3
130 km/hr	11.0	26.6	33.9	17.8

	Wind Speed (km/hr)			
Return Prd	Annual (sd)	Winter (sd)	Spring (sd)	Summer (sd)
2 yr	105.9 (2.6)	93.6 (2.8)	92.5 (2.6)	97.3 (2.9)
5 yr	119.7 (4.5)	107.8 (4.6)	106.0 (4.4)	112.2 (4.9)
10 yr	128.7 (6.0)	117.3 (6.3)	115.0 (5.9)	122.1 (6.6)
20 yr	137.5 (7.6)	126.3 (7.9)	123.6 (7.5)	131.6 (8.3)
50 yr	148.8 (9.7)	138.1 (10.1)	134.7 (9.6)	143.9 (10.6)

Average and Standard Deviations of Sample Data

	Annual	Winter	Spring	Summer
Average	108.5	96.21	95.03	100.07
SD	15.5	16.15	15.30	16.90
Delta	12.1	12.60	11.93	13.18
Lambda	101.5	88.94	88.15	92.46

FILE NO. 3033880 STATION: LETHBRIDGE
Period of Record: 1955 - 1988 (34 years data)

	Annual	Winter	Spring	Summer
Maximum Wind Speed	171 km/hr	171 km/hr	148 km/hr	153 km/hr

Directional Frequency (%) of Maximum Winds (34 Years)

Dir	Annual	Winter	Spring	Summer
N	3	0	9	0
NE	0	0	0	0
E	0	0	0	0
SE	0	0	0	0
S	0	0	3	0
SW	3	6	3	9
W	94	94	85	91
NW	0	0	0	0

Return Periods

	Return Period (years)			
Wind Speed	Annual	Winter	Spring	Summer
50 km/hr	1.0	1.0	1.0	1.0
70 km/hr	1.0	1.0	1.0	1.0
90 km/hr	1.0	1.0	1.1	1.0
110 km/hr	1.1	1.2	2.4	2.3
130 km/hr	2.7	3.2	9.0	12.5

	Wind Speed (km/hr)			
Return Prd	Annual (sd)	Winter (sd)	Spring (sd)	Summer (sd)
2 yr	125.8 (2.2)	122.5 (2.4)	107.1 (2.6)	108.3 (2.1)
5 yr	138.3 (3.7)	136.3 (4.1)	121.7 (4.4)	119.9 (3.5)
10 yr	146.6 (5.1)	145.4 (5.6)	131.4 (5.9)	127.6 (4.7)
20 yr	154.5 (6.4)	154.1 (7.0)	140.7 (7.5)	135.0 (5.9)
50 yr	164.7 (8.2)	165.4 (9.0)	152.7 (9.6)	144.5 (7.6)

Average and Standard Deviations of Sample Data

	Annual	Winter	Spring	Summer
Average	128.1	125.09	109.82	110.44
SD	14.1	15.55	16.55	13.15
Delta	11.0	12.12	12.91	10.25
Lambda	121.8	118.09	102.37	104.52