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Quantitative Studies of Driving Rain Exposure on A Vertical Building Facade in An Urban Area

Dan Zhu

A Thesis

in

The Centre

for

Building Studies

Presented in Partial Fulfilment of The Requirements
for The Degree of Master of Applied Science at
Concordia University
Montreal, Quebec, Canada

October 1994

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Abstract

Quantitative Studies of Driving Rain Exposure on A Vertical Building Facade in An Urban Area

Dan Zhu

A computation methodology is developed to derive quantitatively the driving rain exposure of vertical building facades. This methodology is helpful in determining long term and extreme exposure conditions by analyzing local climatological data. This methodology can be used to derive numerical values of rain precipitation, impact intensity, impact frequency and impact duration on a vertical surface of a building. These results provide a more realistic picture of the exposure to driving rain as compared to the one provided by the existing Driving Rain Index which is non-quantitative in nature.

The quantitative driving rain exposure for 15 major Canadian cities is derived by using this methodology and by making use of the climatological data recorded at local meteorological stations. These are presented in the form of rose diagrams. These diagrams provide useful information to Canadian building engineers and architects so that they may develop appropriate design and specifications for building envelopes to withstand the prevailing conditions.

Currently, the driving rain index derived from suburban meteorological record is used as the measure of driving rain exposure throughout the city. In reality, this index is attenuated by various urban topographies. An attenuation coefficient (C_ϕ) is developed in this thesis to arrive at more realistic indices for buildings within the city. The attenuation coefficient can also be used to compute the quantitative driving rain exposure of a building located in an urban area.

To my great parents, without whose encouragement

I could not have completed this work

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List of Symbols

C_{ave}	Average value of different attenuation coefficients (C_{ϕ}) for a specific location
C_{ϕ}	Attenuation coefficient in the direction ϕ
DRI_{m}	Driving rain index at meteorological station (m^2/sec year)
$DRI_{mean(urban)}$	Mean driving rain index for an urban location (m^2/sec year)
$DRI_{\phi(urban)}$	Directional driving rain index for a surface with an orientation ϕ in an urban location (m^2/sec year)
D_{k}	Continuous impact duration of driving rain on a vertical wall during k^{th} occurrence (hr)
$D_{\phi\ Ave\ Max}$	Average maximum impact duration of the driving rain on a vertical wall with an orientation ϕ (hr)
$[D_{\phi\ Max}]_{j}$	Maximum impact duration of driving rain on a vertical wall with an orientation ϕ in a specific month for j_{th} years (hr)
$D_{\phi\ Max}$	Maximum impact duration of driving rain on a vertical wall with an orientation ϕ (hr)
$\overline{H}$	Height of average roof top level (m)
h	Height above average roof top level (m)
h_{t}	Number of hours of driving rain considered (hr)
N	Number of directions considered

n	Number of occurrences of driving rain
$P_{h\theta}$	Driving rain precipitation on a horizontal surface during the time t_θ (mm)
$P_{v\ Total}$	Total amount of driving rain precipitation on a vertical surface (mm)
$P_{v\ Total(urban)}$	Total amount of driving rain precipitation on a vertical surface located at urban area (mm)
$P_{\theta\ Total}$	Total amount of driving rain precipitation on a vertical wall with an orientation ϕ (mm)
R_h	Rainfall on a horizontal surface (mm/hr)
R_i	Hourly rainfall on a horizontal surface during a specific hour i (mm/hr)
R_m	Rate of rainfall during wind at the meteorological station (mm/hr)
R_v	Rainfall on a vertical surface (mm/hr)
$R_{v\ ave}$	Average intensity of driving rain on a vertical surface (mm/hr)
$R_{v\ Ave\ (urban)}$	Average intensity of rain on a vertical surface in an urban area due to wind from the direction of θ (mm/hr)
$R_{v\ Max}$	Maximum intensity of driving rain on a vertical surface (mm/hr)
$R_{\phi\ Ave}$	Average driving rain intensity on a vertical wall with an

	orientation ϕ (mm/hr)
$\mathbf{R_{\phi \text{ Ave Max}}}$	Average maximum intensity of driving rain on a vertical wall with an orientation ϕ (mm/hr)
$\mathbf{R_{\phi \text{ Max}}}$	Maximum intensity of driving rain on a vertical wall with an orientation ϕ (mm/hr)
$\mathbf{t_i}$	Total time of driving striking on a vertical wall ϕ (hr)
$\mathbf{t_{ke}}$	Ending times of the kth time occurred driving rain (hr)
$\mathbf{t_{ks}}$	Starting times of the kth time occurred driving rain (hr)
$\mathbf{T_\theta}$	Impact frequency of driving rain on a vertical surface with an orientation ϕ (hr)
$\mathbf{t_\theta}$	Number of hours of simultaneous rain and wind from the direction of θ (hr)
$\mathbf{U_m}$	Wind speed recorded at a meteorological station (m/sec)
$\mathbf{U_{(z)}}$	Wind speed at an effective height z (m/sec)
$\mathbf{u_*}$	Shear velocity of the flow (m/sec)
V	Wind speed (m/sec)
$\mathbf{V_{a\,\theta}}$	Attenuated wind speed in the direction θ (m/sec)
$\mathbf{V_i}$	Hourly mean wind speed during a specific hour i (m/sec)
$\mathbf{V_m}$	Wind speed during rain at the meteorological station (m/sec)
$\mathbf{V_{m\theta}}$	Wind speed in direction θ during the rain at the meteorological station (m/sec)

V_θ	Wind speed in the direction of θ (m/sec)
Y	Number of years
z	Effective height (m)
z_d	Zero plane displacement (m)
z_g	Height above ground (m)
z_o	Roughness length (m)
θ_i	Direction of the hourly mean wind speed during a specific hour i (degree)
θ	Wind direction (angle from normal to the wall) (degree)

Chapter 1: Introduction

1.1 Phenomenon of Driving Rain

Wind driving rain is one of the most common phenomena in nature. It is the rain carried along by wind and it strikes vertical building surfaces at an angle. The rain drops of different sizes (different diameters) tend to fall vertically with certain velocities due to gravity. The resultant action leads the drops to strike the vertical surfaces of a building. In fact, most of the rain in nature is associated with wind. An absolutely calm weather during the rain is rare. For example, by analysing meteorological data recorded at three stations in the region of Montréal, Canada, from 1976 to 1989, it was observed that the total rainfall and the rainfall accompanied by wind are approximately the same [Fig 1.1]. Also, based on a statistical information provided by Wu [1], it is observed that, no wind condition (calm) prevails in this region only 5% of total time [table 1.1].

1.2 Problems Experienced Due to Driving Rain

The elements of the building envelope, like walls and roof, are usually exposed to driving rain. One of the functional requirements of these two elements is to prevent the penetration of driving rain. Another aspect of driving rain is related to changes in appearance of exposed surfaces. Of these two aspects, rain penetration is usually regarded as more critical. However changes in surface appearance typically imply changes in either the physical or chemical nature of the materials concerned, i.e. decay and deterioration.

The driving rain may be considered as one of the most important causes of failures in the building envelope components. The problem arises in two main ways. Firstly, the driving rain forces water into pores of porous materials such as brick, mortar and concrete and make them wet or even saturated. Dampness on the inner surfaces may result from this water in the material. Due to a higher thermal conductivity of damp materials, the heat losses through these materials are increased. In a cold climatic region, rainwater entrapped in pores and cracks of porous materials causes detrimental results such as spalling due to freeze-thaw action.

Also, rainwater may be driven through cracks in the structure, gaps around windows, and so on. Generally gaps down to 0.1mm wide will permit water to be driven through by air pressure [2]. With smaller gaps, capillary forces are the most important, and wind pressure is relatively ineffective. Rainwater coming through openings is more obvious than the gradual accumulation in masonry, so that complaints of rain leakage usually refer to penetration through cracks.

Secondly, the appearance of building facade may undergo visual changes when it interacts with external environmental parameters like long term driving rain exposure, atmospheric pollution, water-soluble salts, ultra-violet radiation, etc. In an urban area, where the atmospheric pollution exists, the rain water over a building facade disperses dirt and pollutants accumulated over a period of time and hence causes an uneven distribution of color in the appearance. This washing action subsequently increases the cost of maintenance for keeping a desirable facade appearance.

However, the degree of changes in visual appearance of the building facade is very much dependant on the degree of local driving rain exposure. Mahmoud A. El-Shimi [3] indicated that "the interaction of weather with facade surfaces usually results in unique patterns of water flow, thereby determining the location and degree of washed and unwashed areas. The differential staining is very much dependant on the quantities of accumulated dirt as well as quantities of rain water moving over facade surfaces. The degree of exposure to driving rain that has a particular orientation, frequency and duration, will substantially affect the resulting weathering patterns".

The problem of exposure of the vertical building envelope components to the driving rain is very acute in Canada. In fact, the problem caused by driving rain on a vertical wall is as severe as that on the roof, or even more than that on roof. According to the survey conducted in 1983 on rain penetration through building envelope, the rain water leakage through wall make up 43% of total leakage cases, while the percentage of the cases through the roof are only 39% [4]. Also, Eppell [4] indicated that "of all the masonry walls documented, 70% exhibited through wall leakage, as compared to 54% of the non-masonry walls".

Problems of driving rain exposure on buildings are more severe in some parts of Canada, especially with respect to some specific locations and orientations. Also, the driving rain exposure varies over the year. Hence, there is a real necessity for a quantitative study of driving rain exposure on a vertical building facade in an urban area. This information is essential for a building envelope design. This is the purpose of this thesis.

Fig. 1.1 Average yearly rainfall in the Montréal region (from April to October)

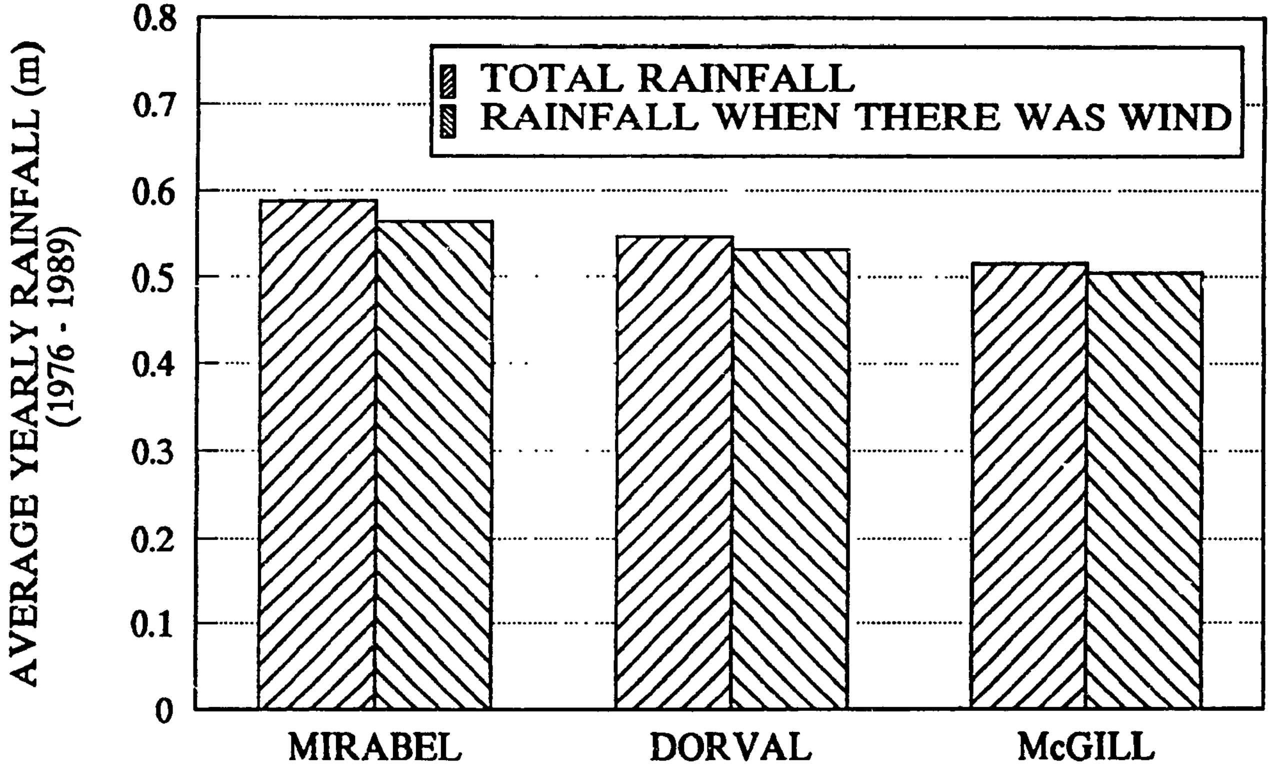


Table 1.1 Number of observations of classified wind speeds in 16 compass directions [Table 6.2.1 of reference 1]

		Wind Speed Class (km/h)									
i	Sector	1-10	11-20	21-30	31-40	41-50	51-60	61-70	71-80	81-90	Total
1	N	6182	3864	934	144	17	1	1	0	0	11143
2	NNE	6934	10296	3618	923	178	31	14	9	0	22003
3	NE	4614	9083	4749	1421	308	83	19	4	0	20281
4	ENE	2363	3362	1142	210	30	5	0	0	0	7112
5	E	3051	2499	398	43	2	0	0	0	0	5993
6	ESE	3386	2511	614	68	2	0	0	0	0	6581
7	SE	4962	4904	1837	359	31	2	0	1	0	12096
8	SSE	5057	6117	2109	438	38	6	0	0	0	13765
9	S	4890	3666	591	71	2	0	0	0	0	9220
10	SSW	5670	6976	1678	281	42	0	0	0	0	14647
11	SW	8634	13640	6937	2196	386	69	24	6	1	31893
12	WSW	9018	14715	9706	3744	816	177	39	9	0	38224
13	W	7732	12265	8249	3172	570	89	18	4	0	32099
14	WNW	4826	6271	3317	986	139	18	3	0	0	15560
15	NW	4528	3732	1233	234	19	3	0	0	0	9749
16	NNW	4538	2427	655	73	1	3	0	0	0	7697
										Calm	13689
							Total for All Directions				271752

Note: Data are derived from hourly records during the period of January 1, 1960 to December 31, 1990 at Dorval Airport, Montréal.

Chapter 2: Review of Literature and Objective of The Study

2.1 Review of Literature

The research on driving rain exposure is not a recent undertaking. Measuring the driving rain by using a rain gauge was initiated during last century. At that time, the aim of the research on driving rain was focused on the design of gauges which would measure accurately the amount of rain falling on the horizontal and sloping ground. Later, in the early part of this century, the U.K. took a big lead in the research on the driving rain exposure on the building surface, since the driving rain condition in that country is very severe. Since the late 70's, researchers and building engineers all over the world have been getting involved in the research of driving rain exposure on the building surface.

Generally, the research to explore the driving rain exposure on a vertical surface or a building facade can be divided into two categories as non-quantitative and quantitative methods. The former is an approach to achieve a relative degree of driving rain, but can not show an exact amount of rain water which strikes on or is collected by a vertical surface. The quantitative method is to explore the real amount of driving rain, in terms of precipitation and intensity, impinging on a building facade. The research work carried out by other researchers is reviewed and presented under these two methods.

2.1.1 Non-Quantitative Methods

Driving Rain Index is the most important non-quantitative approach of measuring the driving rain exposure on a building facade. As cited by Lyberg [5], Hoppestad was the first person to initiate the idea of driving rain index. Hoppestad calculated the amount of driving rain from different directions for many places in Norway. He considered two-hour average wind speed and rainfall data in his study. Also, the rainfall data was drawn from many rainfalls. Hoppestad calculated the average of the product of wind speed (v) and vertical intensity (I). The horizontal intensity I_h was measured simultaneously by a special instrument. Then he calculated what he defined as the driving rain index, K, as c/v_t (c is the constant ie, $c = I_h / vI$, and v_t is the terminal velocity of rain drops). It was found that this driving rain index varied for different meteorological stations, for different wind directions and different times of the year. On the basis of his study, Hoppestad developed a number of driving-rain maps, including directional and total driving rain amounts which would be received by a free-standing gauge.

After Hoppestad's study, similar studies were performed to derive the driving rain map for Sweden, Denmark and Canada [5].

During 1960s, Lacy and Shellard [6] verified that the hourly amount of rain on the horizontal (i.e. normal rainfall on the ground) multiplied by the corresponding component of the wind speed (resolved normal to the surface of the wall and totalled for the day) was proportional to the daily catch of driving rain in gauges mounted directly on a wall.

In view of the fact that the wind speeds were not recorded simultaneously and lacking detailed hourly information for the country as a whole, Lacy et al did not use such an amount of two-hour data as Hoppestad. They suggested a driving rain index on an annual basis, by using annual average rainfall and annual average wind speed data based on certain assumptions. The resultant index is measured in m^2/sec.year.

Based on the observations from climatological stations in all regions of the country, Lacy and Shellard prepared a map of such driving rain indices for the British Isles to measure the relative severity of the driving rain problem in different parts of the country [Fig. 2.1]. Lacy defined as 'Sheltered', those areas where the driving rain index was less than $3m^2$/sec.year; 'moderate' for driving rain index between 3 and $7m^2$/sec.year and 'severe' for over $7m^2$/sec.year [6]. Also, Lacy and Shellard introduced compass roses of driving rain showing the percentage of total driving rain index for eight compass directions in the map of the British Isles.

Driving rain maps were developed for different countries, such as United States of America [7], China [8] and Canada [Fig. 2.2] [9], based on the criteria proposed by Lacy et al. All of these driving rain maps are of small scale in nature and show general distribution of driving rain indices in the respective countries by means of different isopleths. However, these maps can not show the local variations of exposure which must be very significant. An analysis of hourly values of driving-rain index at 23 stations showed that the degree of exposure of buildings varied in different sites mainly due to local topographical effects [10].

Boyd [9] used the annual rainfall and the annual wind speed data in developing the driving rain map of Canada. However, Bobinson and Baker [11] suggested that it would be inappropriate to apply on a continental basis an annual index of exposure derived from an average wind and rainfall values. They encouraged the idea of driving rain index based on monthly or daily values. They used hourly wind speed and rainfall data for a period of 15 years in order to derive the monthly driving rain index for the city of Toronto in Canada. In that study, the monthly driving rain indexes showed the fluctuation of degree of exposure during different seasons and different directions. Robinson et al also indicated that small-scale maps, such as driving rain map of Canada, do not show variations in intensity (increase or decrease in exposure) due to different local features. They suggested that information on driving rain exposure of a particular location can seldom be applied to nearby localities. Boyd [12] also expressed that a better grasp of the driving rain problem could be achieved by computing driving rain indices for each month. He suggested that the computations should be based on the wind speed data for only those days or hours when there was rain, instead of using the mean wind speed for the whole month.

The most recent modification for preparing driving rain index was suggested by Prior [13]. He developed a directional driving rain map for the United Kingdom. Although based on Lacy's method, it has overcome some of the deficiencies of the earlier approaches. By using the hourly measurements of rainfall, wind speed and wind directions, an average annual directional driving rain index and a once in three years spell index have been derived. The former is relevant to weathering and staining of building facades and the latter is useful in assessing the risk of rain penetration through masonry walls. Prior also considered the effect of driving rain not only in the direction normal to the wall but also as a summation over an azimuth sector of 180° with the weighting decreasing as the wind direction departed from the normal to the wall in order to enhance the accuracy of the indexes.

The driving rain map, derived from local driving indices, shows the severity of driving rain exposure on a building facade. However, it is non-quantitative in nature, since it is not able to provide information such as how much amount of rain water or how intense the rain water impacts the building facade. This driving rain map can be used only for comparing exposure at one place with that at another where the exact driving rain information is already known. So, its application in providing exposure information as a design tool is largely limited by its non-quantitative nature.

2.1.2 Quantitative Methods

A quantitative driving rain exposure on a building facade describes the exact amount, the intensity and the duration of rain water acting on the building facades. The initial research in this category was focused on the measurement of driving rain by using rain gauges.

A free-standing rain gauge was the original type of driving rain gauge which was set in an open area with some vertical apertures to collect driving rain water [5]. The earliest free-standing rain gauges designed to measure the inclination of the falling rain drops were set up in Britain as early as 1870 [14]. Later, Lacy [14] mentioned that, a first free-standing gauge designed to provide data on the amount of rain which could be expected to fall on the walls of buildings was made at the Building Research Station, Garston, U.K. in 1936 by Beckett. Also, the measurements by using free-standing rain gauge have been performed in many countries [14].

Lyberg [5] mentioned that Holmgren was the first one to design a driving rain gauge to be installed on the wall of a building. Later, experiments were performed by Lacy by using this type of rain gauge. Lacy measured the driving rain at several places in Great Britain and on different types of buildings. Among them, the most significant one was made in 1956 in Glasgow region [14]. The driving rain gauges were mounted on two flats which are located in the town and in the suburban area respectively. It was found that the amount of driving rain exposure on facades in suburban location might be much greater than that in the town. Also, it was found by Lacy [14] that the gauge on the building usually collected less rain than the free standing gauge, perhaps due to the "curtaining" effect of the wind described by Khlusov. Lacy [14] cited that Khlusov measured wind speeds over the surface of a building of 25m high and suggested that rising current of air close to the face of a building gives some measure of protection from precipitation.

Lyberg mentioned that Künzel, Frank and Schwarz performed measurements on a 15m tall highly exposed building [5]. They found that the amount of driving rain can be more than a factor of ten greater on the top of a facade than a few meters above the ground. Studying wetting of facades subjected to wind driven rain, Couper [15] found that the wetting is strongest near corners and below the roof. This phenomenon was also observed by Meert and Vanackere from their experiments. They performed measurements of driving rain on a facade of a 10m tall laboratory building. Half of the gauges were placed on middle height and half near the top of the facade. The building had a small roof overhang. They found that the catch of driving rain is about a factor of five larger for the top gauges than for the others [5].

The studies mentioned above are of experimental in nature. A mathematical method for computing the quantitative driving rain exposure on a vertical facade has not been explored fully. However, some quantitative studies on driving rain ratio on the vertical surface were carried out.

According to relationship between median rain drop size and the rate of rainfall on the ground developed by Laws and Parsons and relationship between raindrop diameter and terminal velocity found by Best, Lacy [2] developed a relation between the rate of water deposition on vertical walls to that on horizontal surface by an equation

$$R_v = \frac{2}{9} V R_h^{\frac{8}{9}} \tag{2.1}$$

Where R is the rate of rainfall in mm/h, V is the wind speed in m/sec and the suffixes v and h refer to vertical and horizontal surfaces.

In an attempt to evaluate the amount of water that actually strike vertical surfaces, based on the standard experimental quantification method of wind driven rain, Henriques [16] also derived a relation between the driving rain indices and the amount of driving rain on a wall as $1 m^2/s = 90$ to $100 L/m^2$.

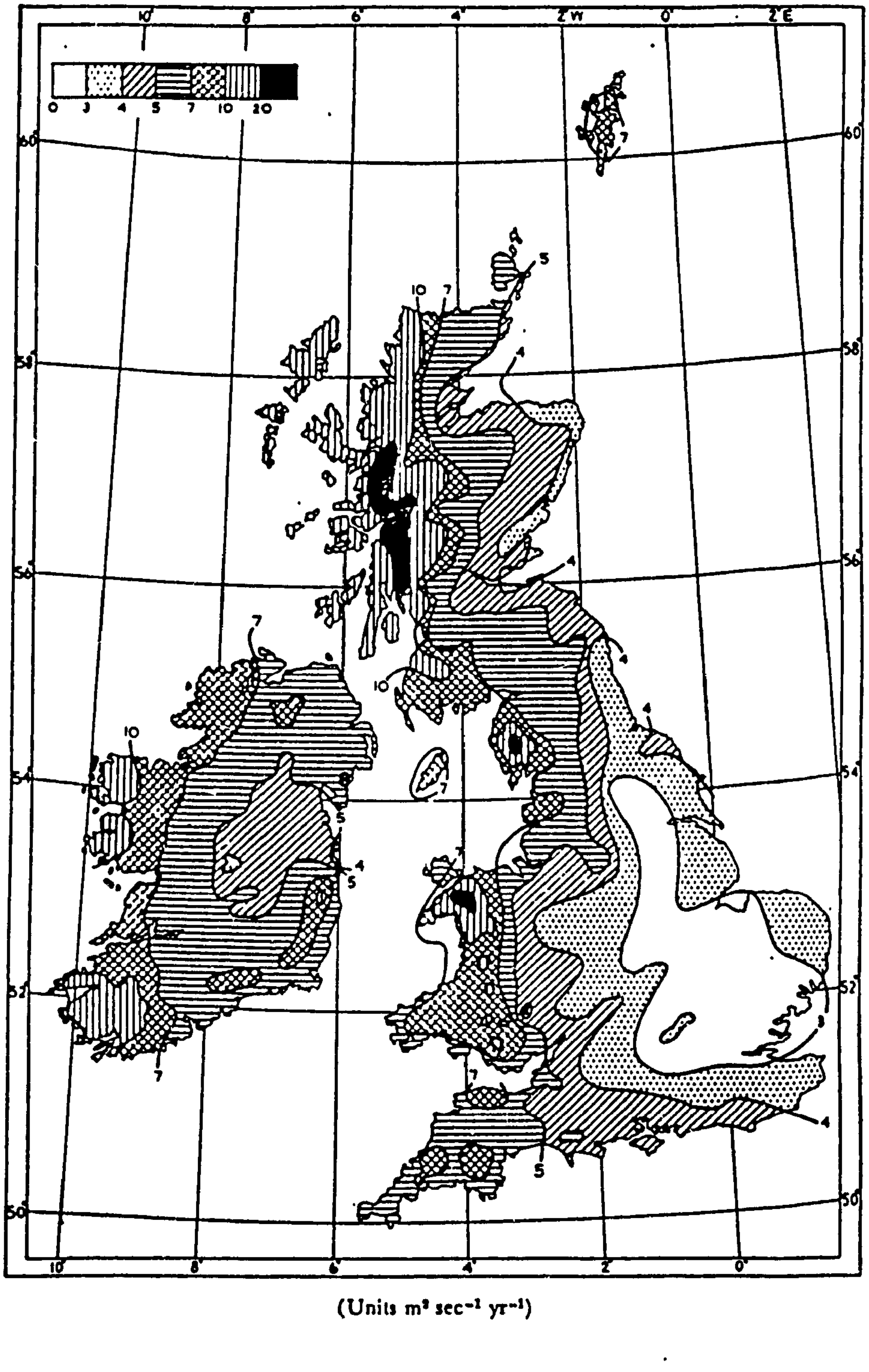
The most recent theoretical quantitative work in this field has been carried out by Choi [17] in 1994. The numerical scheme was used to simulate rain intensity on building surface by using k-ε model to synthesize the effect of wind flow around building, raindrop trajectory and rain drop size distribution. In his study, a building facade was divided into 12 zones. A local effect factor LEF(r) and a overall local effect LIF were developed for each zone according to different wind speed condition and rain drop size distribution. He proposed that the driving rain intensity of certain drop size r impinging onto a zone is therefore equal to the unobstructed rain intensity multiplied by a LEF(r). He concluded that the total driving rain intensity on different zone of the building face can be obtained by multiplying the unobstructed rain intensity by the LIF of the zone. Choi [17] applied the developed model on a rectangular building in Sydney by using the wind and rainfall data from local airport.

2.2 Scope and Objective

It has been observed from the review of the literature that there are very few direct quantitative methods (three of them were mentioned in section 2.1) to represent the exact exposure condition on a vertical surface. In the existing quantitative methodologies, only the intensity of driving rain on a building surface was considered while the other important parameters on a vertical wall such as rain precipitation, rain drop impact frequency and impact duration on a vertical wall have not been considered. Also, the quantitative methods have never been applied to explore the driving rain exposure for a building in Canada. The driving rain map is the only source of information on driving rain exposure variation across the Country. The driving rain map of Canada, which was developed in 1964, is non-quantitative in nature. This map, having annual driving rain index as a unit of measurement, has not matched the requirements of building envelope design. It was also observed that the effect of local topography condition has never been considered in any quantitative or non-quantitative methods, even though it influences local driving rain exposure.

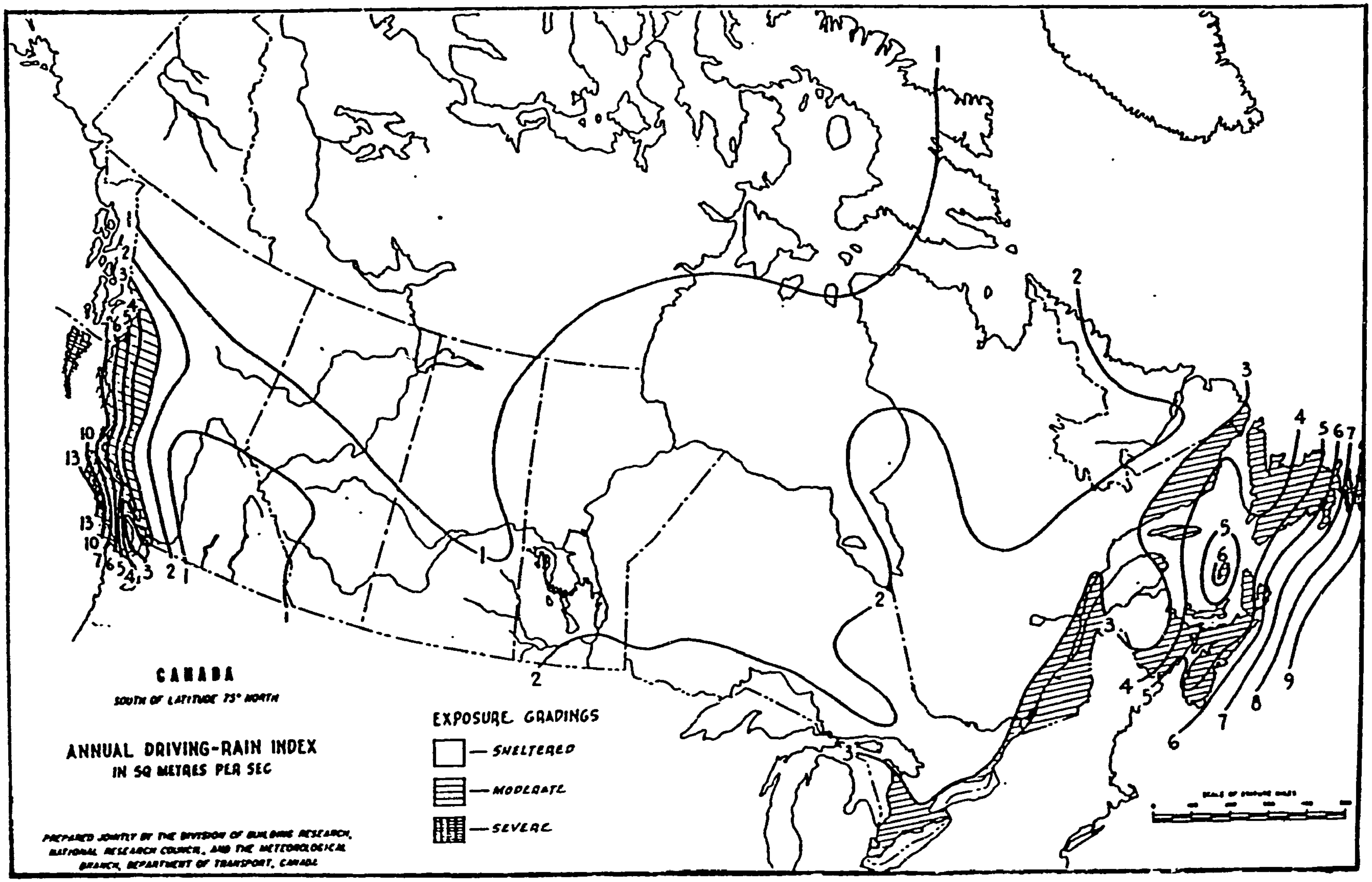
This study is aimed at four aspects including, (1) the development of a method to derive the quantitative driving exposure for the building facade based on the relationships proposed by Lacy and Henriques, (2) the application of the developed methodology for the Montréal region as a case study, (3) the development of quantitative driving rain exposure on building facades for 15 important Canadian Cities, as a tool for design of the building envelope, and (4) the development of methodology to amend the quantitative results of driving rain exposure based on different topographic conditions, and verification of the methodology in a case study.

Fig. 2.1 Driving rain map of British Isles [5]



(Units $m^2 sec^{-1} yr^{-1}$)

Fig. 2.2 Driving rain map of Canada [8]



Chapter 3: Quantitative Studies of Driving Rain Exposure on A Vertical Surface

3.1 Methodology

The procedures developed by Lacy [2], Henriques [16] and Choi [17] described in section 2.1 could be applied to explore the quantitative driving rain exposure on building facades. In this study, the basic relationships developed by Lacy and Henriques are utilised due to some advantages over the numerical method of Choi. The advantages include

(1) Local meterological data recorded (wind speed, wind direction and rain precipitation) could be directly applied in the computation.

(2) The results achieved by using the relationships represent a general average exposure condition and general extreme condition of a specific region. Whereas the numerical method provides driving rain exposure for a specific building configuration at a particular location. Thus the results obtained by using the relationships in reference [2] and [16] provide guidelines to architects and building designers in designing the building envelope.

(3) The computation involved using these relationships is not complex. However,

computation for a building with a complex geometry or with a non uniform surroundings may be difficult if the numerical approach was used.

Based on the theoretical formulation developed for driving rain intensity by Lacy [2, 14] and the empirical relationship developed for amount of driving rain by Henriques [16], two methods have been developed to quantify the intensity and precipitation.

3.1.1 Method I

As mentioned earlier, equation (2.1) shows the relationship between the rainfall rate on the horizontal and vertical surfaces. However, given that the impingement of driving rain on a vertical facade is not exclusively from a direction normal to the wall, but over an azimuth sector of 180°, the driving rain intensity on a vertical facade can be represented by

$$R_v = \frac{2}{9} \left(\frac{P_{h\theta}}{t_\theta}\right)^{\frac{8}{9}} V_\theta \cos\theta \tag{3.1}$$

where R_v (mm/hr) is the rate of rainfall or intensity of rain on a vertical surface due to wind from the direction of θ (angle from normal to the wall), V_θ (m/sec) is the wind speed in the direction of θ, $P_{h\theta}$ (mm) is the precipitation on a horizontal surface during the time t_θ when there is wind from the direction of θ and t_θ is the number of hours of simultaneous rain and wind from the direction of θ.

Thus, the average rate or intensity of driving rain on a vertical surface (mm/hr) is given as,

$$R_{v\,Avg} = \frac{\frac{2}{9}\sum_{\theta=-90}^{+90^\circ}\left(\frac{P_{h\theta}}{t_\theta}\right)^{\frac{8}{9}} V_\theta \cos\theta}{N} \tag{3.2}$$

where N is the number of directions considered in a period of time.

The maximum intensity of the driving rain on a vertical surface (mm/hr) is given by

$$R_{v\,Max} = MAX\,\{\frac{2}{9}\left(\frac{P_{h\theta}}{t_\theta}\right)^{\frac{8}{9}} V_\theta \cos\theta\,\} \quad where\ \theta = -90\ to\ +90^\circ \tag{3.3}$$

The total amount of driving rain precipitation on a vertical surface can also be given (based on the similar assumptions on which the intensity of driving rain on a vertical facade has been derived in equations (3.1) and (3.2)) as

$$P_{v\,Total} = \frac{2}{9}\sum_{\theta=-90}^{+90^\circ}\left(\frac{P_{h\theta}}{t_\theta}\right)^{\frac{8}{9}} V_\theta \cos\theta\ t_\theta \tag{3.4}$$

where $P_{v\ Total}$ (mm) is the total amount of driving rain precipitation on a vertical surface.

3.1.2 Method II

From the empirical relationship of driving rain index and the amount of driving rain on a wall as reported by Henriques (1 m^2/s = 90 to 100 L/m^2) [16], the total amount of driving rain on a vertical surface is computed as

$$P_{v\ Total} = 100 \sum_{\theta=-90}^{+90^{\circ}} P_{h\theta}\ V_{\theta} \cos\theta \qquad (3.5)$$

Since, the driving rain intensity can be expressed as precipitation per unit time, average driving rain intensity on the vertical surface is given as

$$R_{v\ Ave} = 100 \frac{\sum_{\theta=-90}^{+90^{\circ}} P_{h\theta}\ V_{\theta} \cos\theta}{\sum_{\theta=-90}^{+90^{\circ}} t_{\theta}} \qquad (3.6)$$

3.1.3 Assumptions

Whatever assumptions made by Lacy & Henriques in their basic relationships, are valid and the same for the developed methods I and II respectively

Lacy [2] indicated that the basic relationship (Eq. 2.1) developed is under the assumption that there is no deflection of the wind or the raindrops around the objective building. It is also assumed by Lacy that the rain behaves as if all the drops were of the median size D_{50} (median raindrop diameter) appropriate to the intensity. Also, the methods described in sections 3.1.1 and 3.1.2 assumed that the results obtained by using the quantitative parameters show uniform distribution of driving rain at any portion of a vertical wall, unlike the observation made by Couper [15] shows that top edges and the corners of a building facade collect more rain water than the rest of the facade. In addition, the degree of exposure of a vertical surface obtained by using the quantitative parameters will be the most severe one as the quantitative parameters are derived with an assumption that there exists no deflection of the wind or raindrop around the surface. The experimental relation developed by Henriques is derived from the results obtained by using freestanding vertical pluviometer and 2 wall mounted gauges. Since it converts a non-quantitative driving rain index to a quantitative intensity, it is also assumed that the location of mounted gauges on wall have no relation with the amount of rain that gauges collected.

Although these assumptions may result in some inaccuracy, i.e. the results obtained by the methods described in sections 3.1.1 and 3.1.2 may not match exactly with the realistic situation, it can provide the information of average and extreme rain exposure for buildings in a whole region. Like other existing information such as snow load, wind load, temperature and humidity, it is accurate enough to use in the design of buildings.

3.2 Case Study

The quantitative driving rain exposure on a building facade in the Montréal region is computed by using the methods described in section 3.1. For this purpose, two climatological stations, namely, (i) McGill (located in downtown Montréal) and (ii)

Dorval (An International Airport at a distance of approximately 15km from downtown Montréal (Fig 3.1)) were chosen to represent the urban and semi-urban situations of the Montréal region. Fig 3.2 shows the lay out and configuration of the McGill climatological station, which is surrounded by multistorey buildings. Hourly rain precipitation and hourly mean wind speed data recorded at these two climatological stations were obtained from Ministère de l'Environnement, Gouvernement du Québec and Atmospheric Environment Service, Environment Canada respectively. The details of the climatological data are given in Table 3.1.

Table 3.1 Description of McGill and Dorval station

S.No	CLIMATOLOGICAL STATION	DETAILS OF CLIMATOLOGICAL DATA
1	McGill (Downtown Montréal) (Longitude:73° 35'W) (Latitude:45° 30'N)	Hourly rainfall and hourly directional mean wind speed data from 1st Jan'67 to 1st April'90.
2	Dorval (Montréal Airport) (Longitude:73° 45'W) (Latitude:45° 28'N)	Hourly rainfall and hourly directional mean wind speed data from 1st May'60 to 31st Dec'90.

Fig 3.1 Position of different meteorological stations in the Montréal region [23]

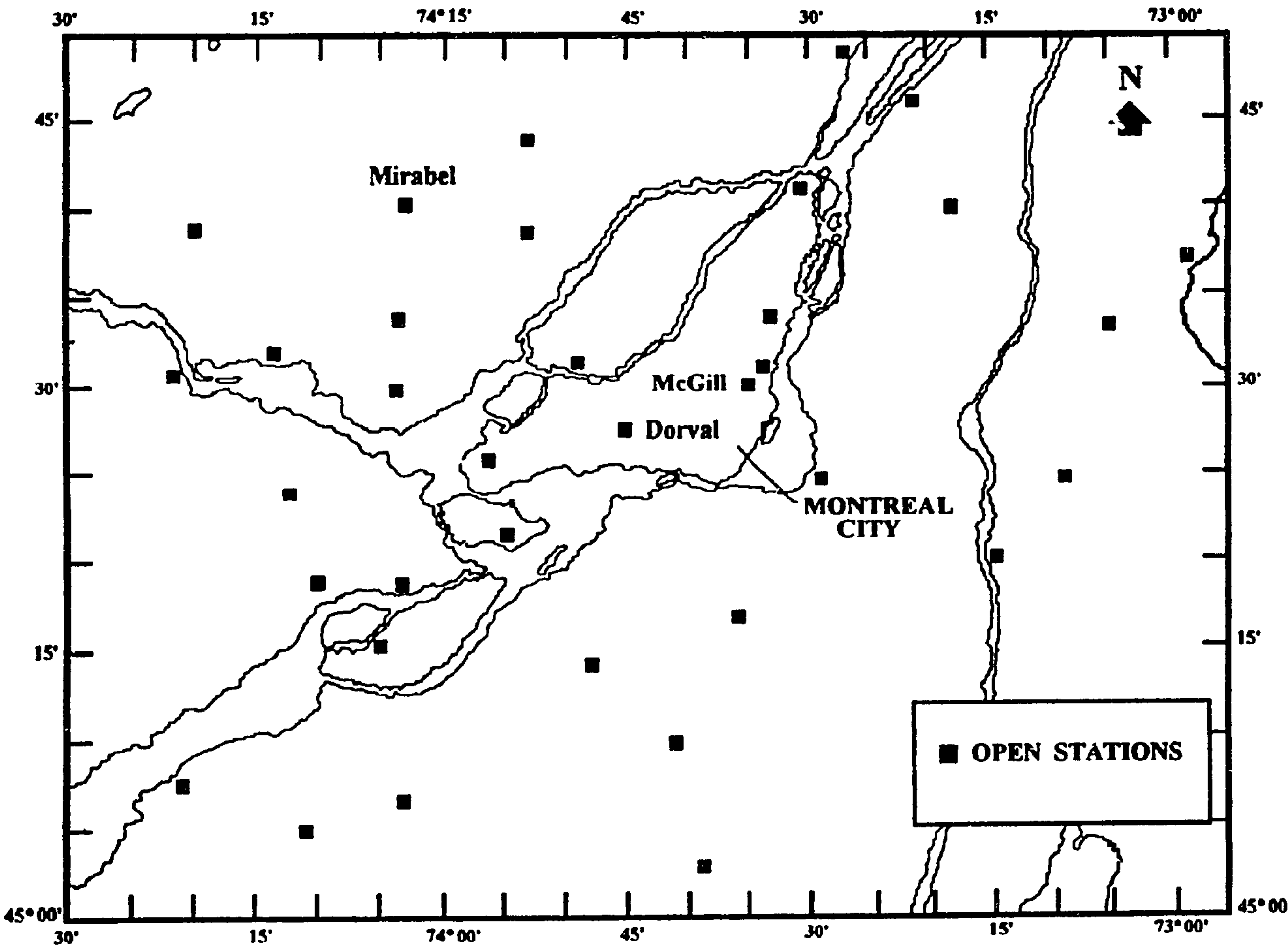
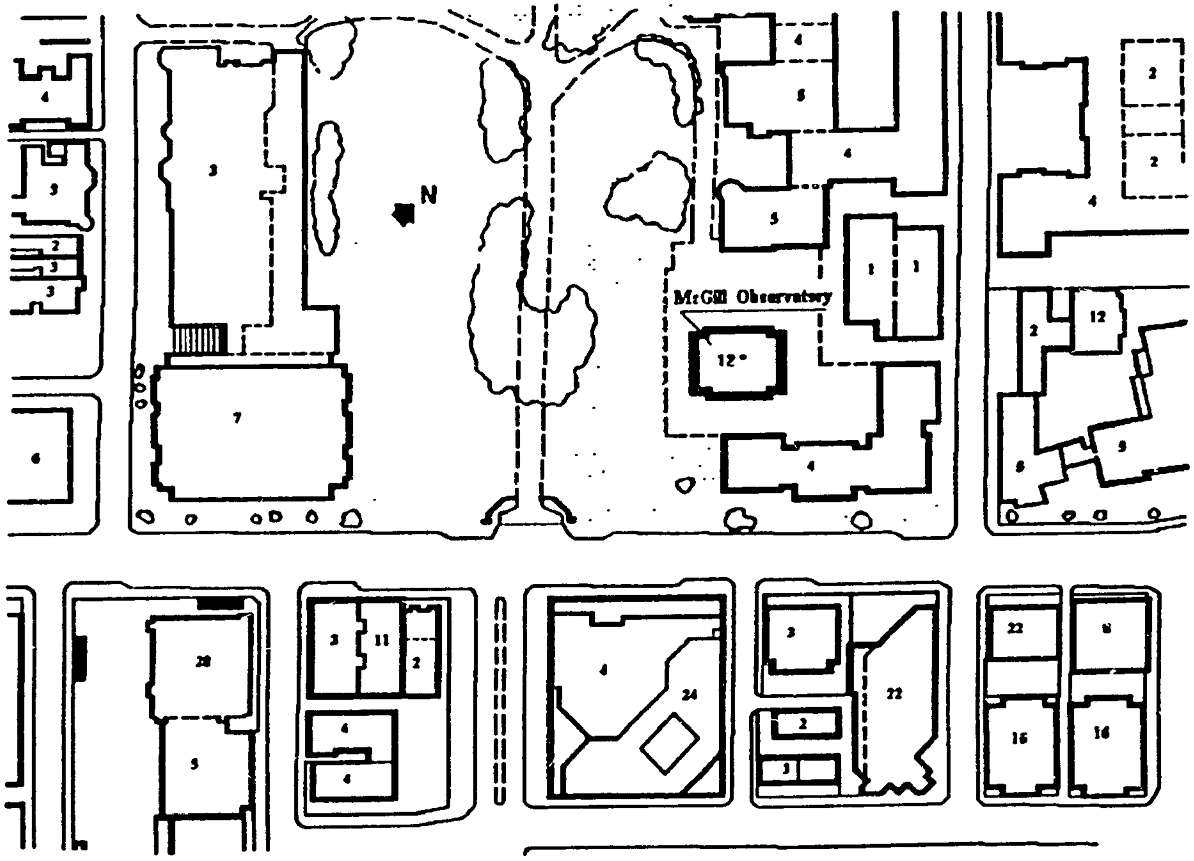


Fig. 3.2 Surrounding layout of the McGill meteorological station



* The number on the building block denotes the number of floors

3.2.1 Assumptions

In the calculation of both methods, it has been assumed that (i) any vertical building facade (placed along any one of the 8 directions) is subjected to rain from three directions which cover a sector of 45° each and hence a total of 135° (Fig. 3.3) and (ii) the driving rain from two sectors of 22.5° each, adjacent to the wall, will have a small influence on the surface and hence this driving rain has not been considered in the computation.

3.2.2 Data Analysis

The data in both climatological stations is with respect to 8 directions, namely, N, NE, E, SE, S, SW, W and NW (ie., 0° to 315°). Initially, the whole data has been processed in order to find out (i) the simultaneous occurrence of rain and wind (ii) the mean wind speed during rain in a particular month for each direction (iii) the mean rain precipitation on the horizontal surface in a particular month for each direction and (iv) the monthly frequency of driving rain. This exercise has been carried out for both stations. By making use of the two methods described earlier, (i) the monthly values of intensity and precipitations of driving rain and (ii) the yearly value of driving rain precipitation have been calculated.

3.2.3 Results and Disussion

The driving rain precipitation on the horizontal surface and the mean wind speed during rain for the McGill and the Dorval stations are shown in figures. 3.4 to 3.7. From these figures, it is clear that, in the Montréal region the driving rain has seasonal variations. The precipitation during summer is relatively high compared to that of in winter (which is low). However, the mean wind speed during winter is much higher than that occurring in other seasons. It has also been observed from figures 3.8 and 3.9 that, irrespective of any season, the driving rain reflects certain directional characteristics. In the downtown Montréal region, over 55% of the time the driving rain occurs from northeast and southwest directions. Whereas, in the Dorval station, the frequency of the driving rain from the directions northeast, southeast and south is higher than the frequency of the driving rain from the remaining directions. The difference in directional characteristics at the downtown Montréal station may be due to local topographical features.

Figures 3.10 and 3.11 show the calculated driving rain precipitation on vertical surfaces using both methods for both the downtown Montréal and the Dorval stations respectively. From Fig. 3.10, vertical surfaces facing southwest or northeast in downtown Montréal collect more rain water than any other vertical facade in any direction. Whereas, from Fig. 3.11, it has been observed that, in a semi-urban area, larger precipitation occurs on the facade facing a sector from northeast to south direction.

However, figures 3.12 and 3.13 reveal that the maximum driving rain intensity on vertical facades does not occur in the same direction as of that of the maximum precipitation. At both stations, the facades facing towards northwest experience severe rainfall intensity, though the total precipitation in this direction is relatively low. These results reflect that, although storms from northwest are very severe, their occurrence is low.

The exposure pattern obtained from the method 1 compare favourably with the patterns obtained from the method 2 (Figures. 3.10 to 3.13). The magnitudes of the pattern obtained by using method 1 are approximately double than those obtained by using method 2. This observation is similar to the one cited by Couper [15] in Australia. The differences could be due to the limitations involved in the methods.

(a) The theoretical relationships in method I are based on the assumption that there exists no deflection of the wind or raindrop [2]. However, in reality the trajectory of the rain drops may curve.

(b) The accuracy of the experimental results used in method 2 is a function of the experimental methodology adopted and weather conditions during the experimental stage. For example, (i) the amount of rain collected in the wall-mounted rain gauge depends on the location of the rain gauge [14] and (ii) in a unit time, a high intensity rain with a short duration can have the same driving rain index value as a low intensity rain with a long duration when the mean wind speed is the same. However, the raindrop size distribution for these two kinds of driving rain patterns is different, since the intensity is not the same [2]. Hence, the terminal velocity of the raindrop and the raindrop deflection pattern are not the same and would cause different experimental results.

Fig. 3.3 The multiple directions of driving rain acting on a building facade with a north orientation are resolved in to three main directions: NW, N and NE

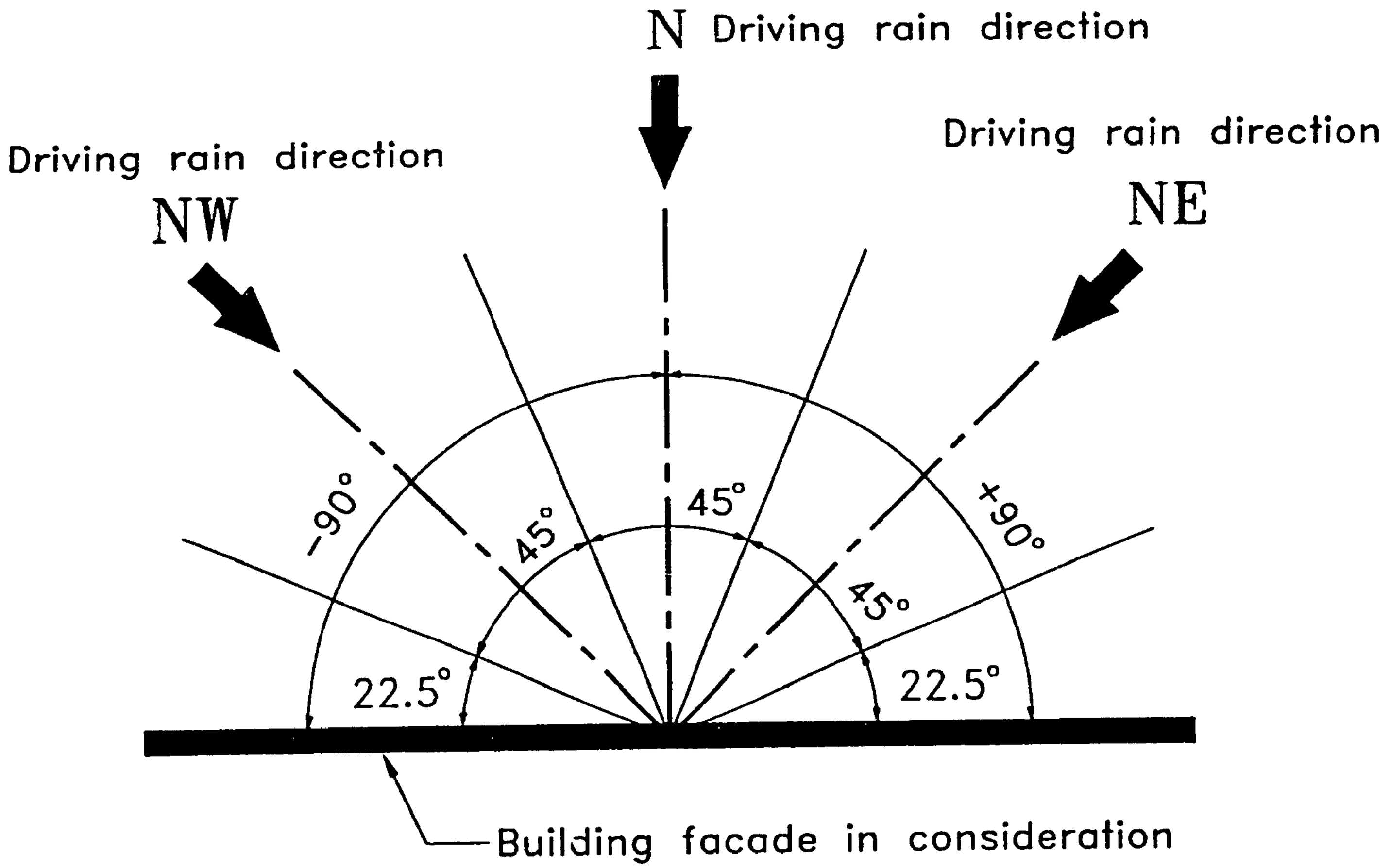


Fig. 3.4 Driving Rain precipitation on horizontal surface (mm) - McGill station

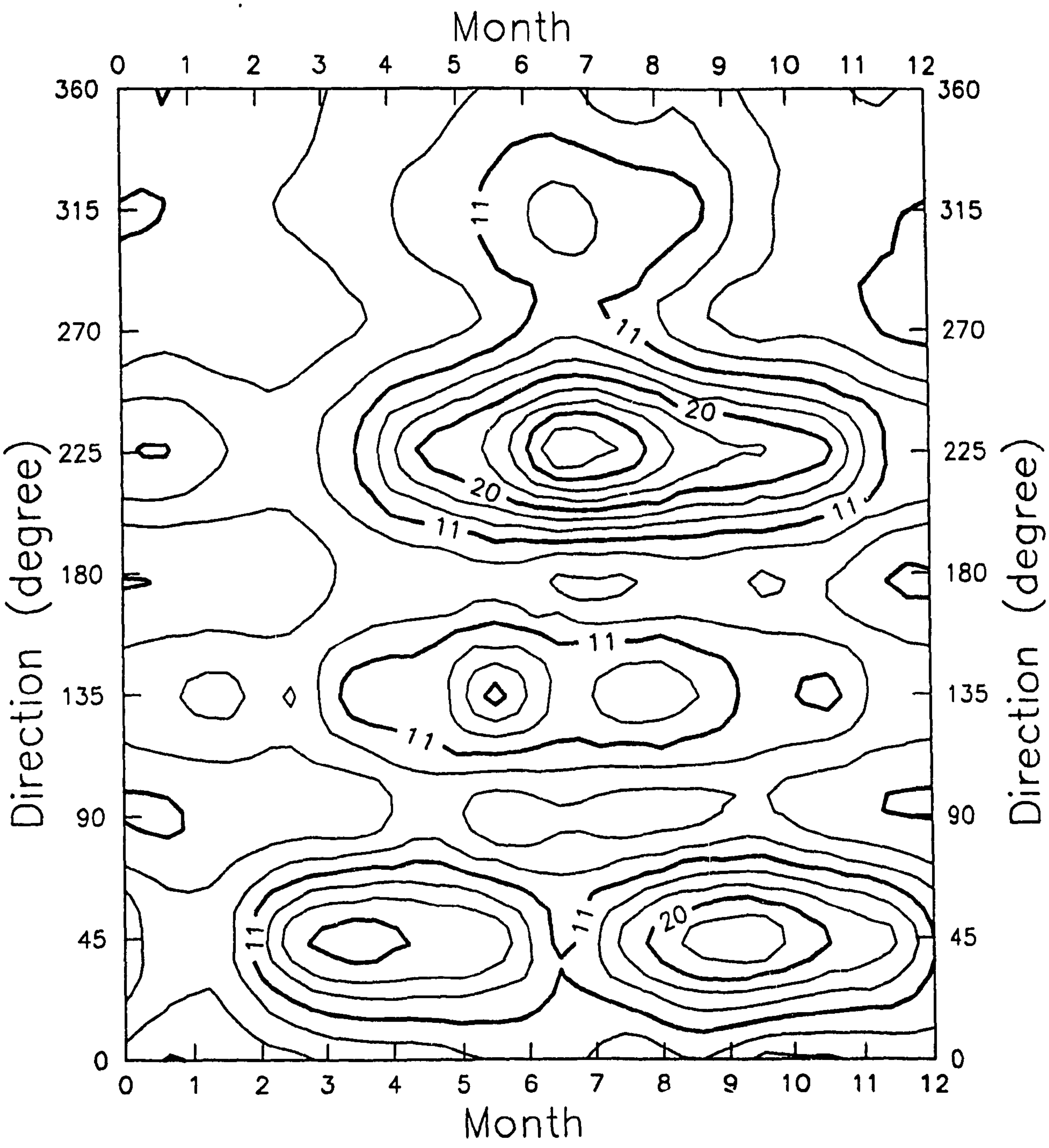


Fig. 3.5 Mean wind speed during rain (m/sec) - McGill station

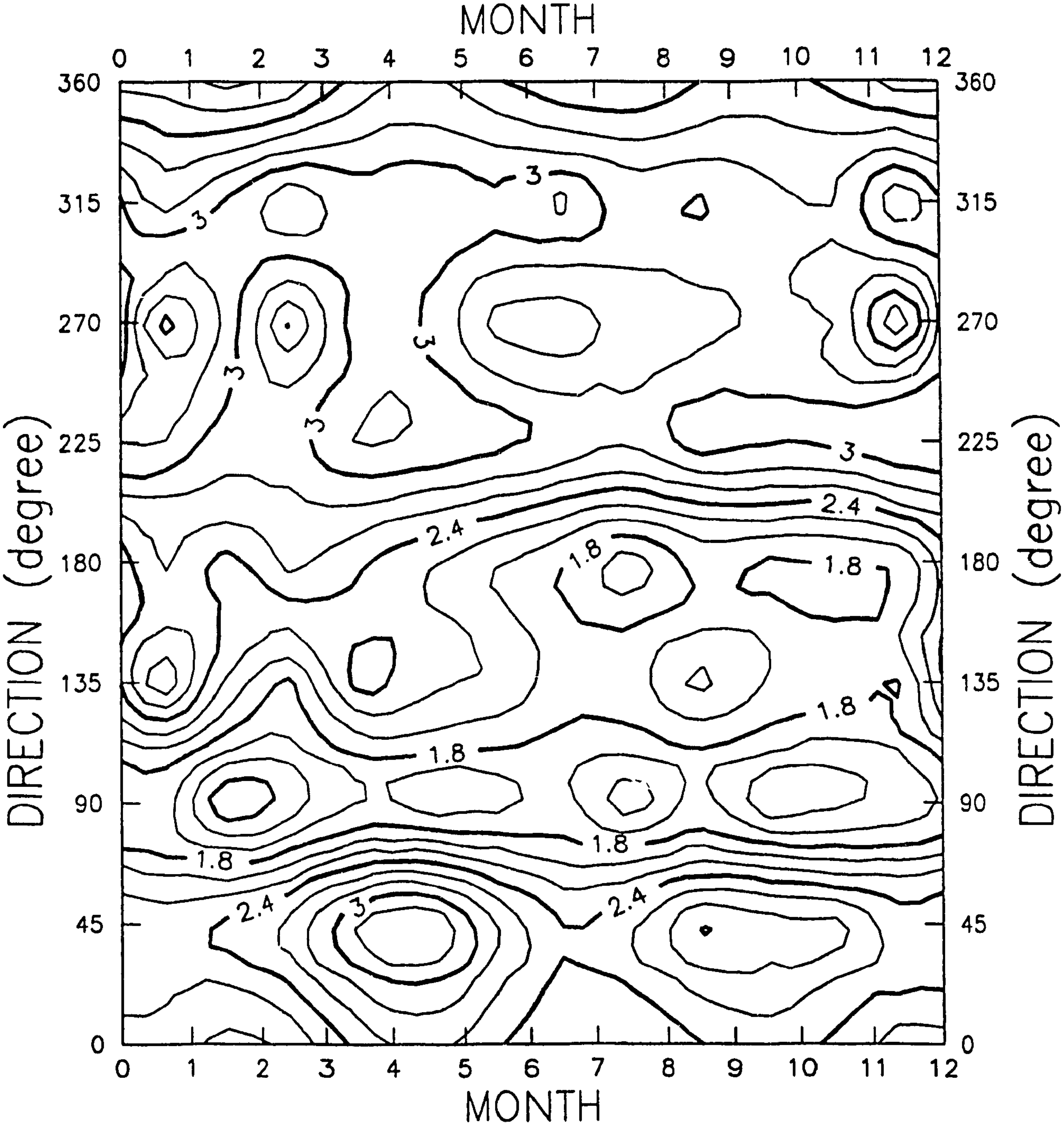


Fig. 3.6 Driving rain precipitation on horizontal surface (mm) - Dorval station

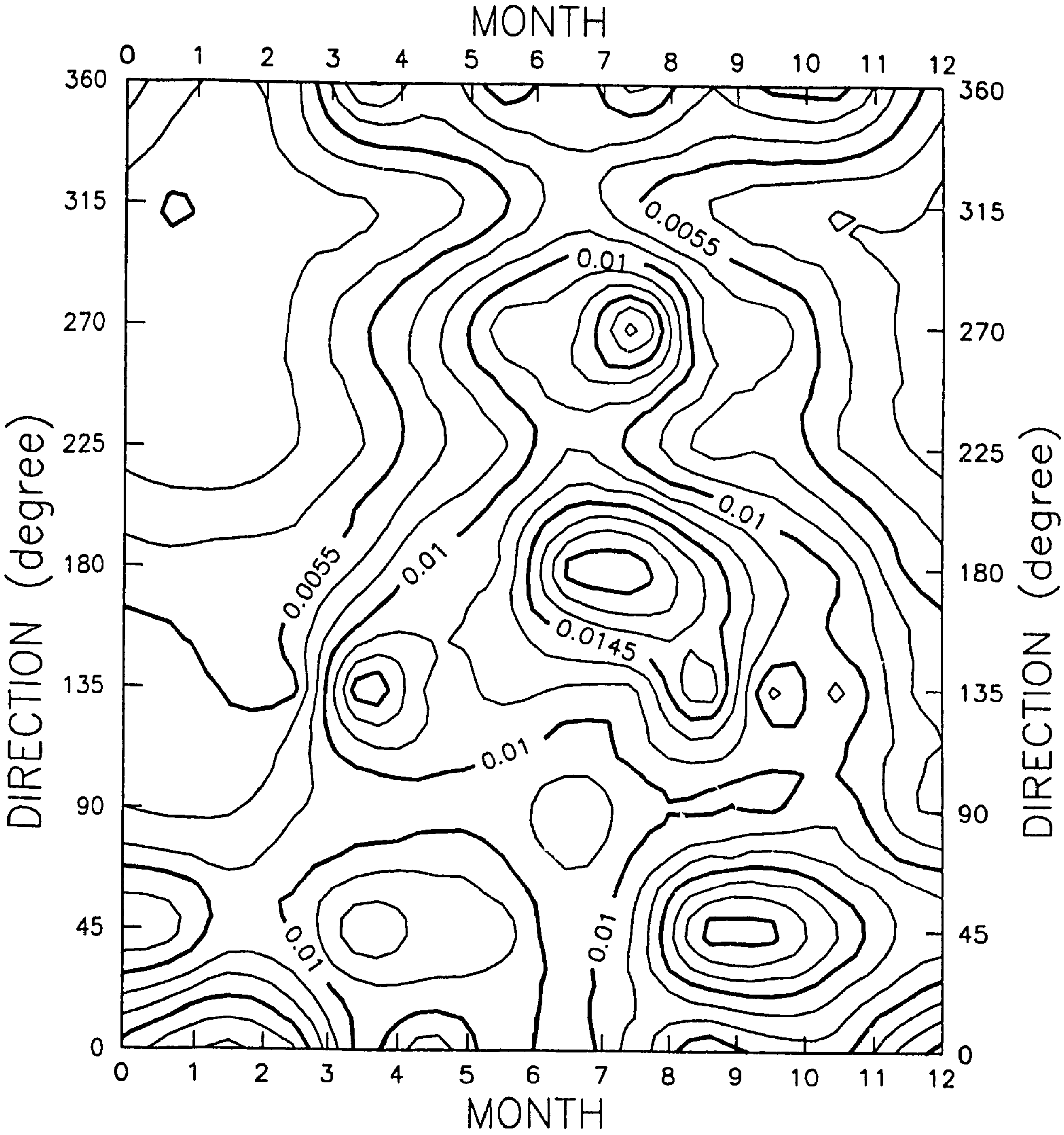


Fig. 3.7 Mean wind speed during rain (m/sec) - Dorval station

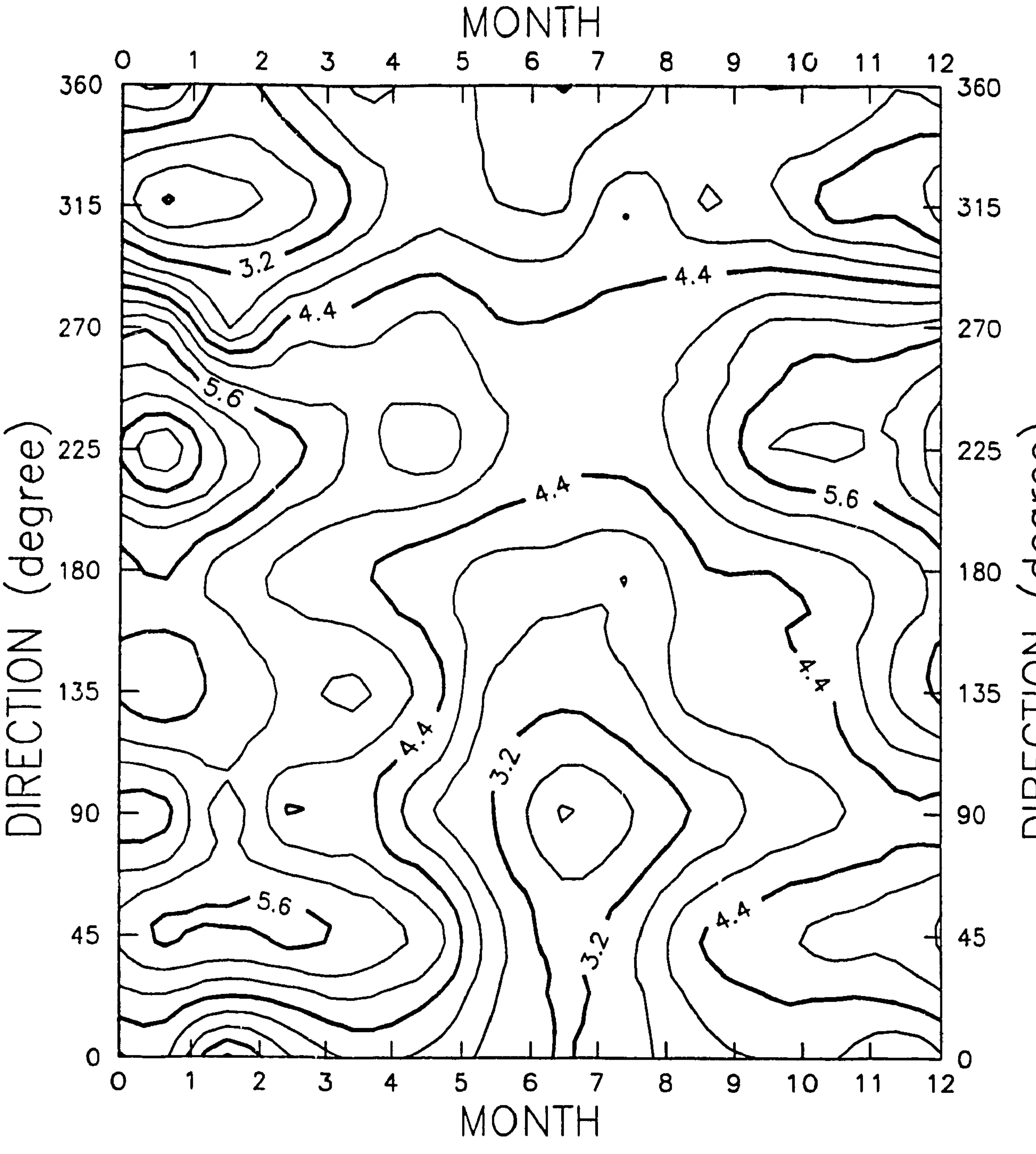


Fig. 3.8 Driving rain frequency (hr) - McGill station

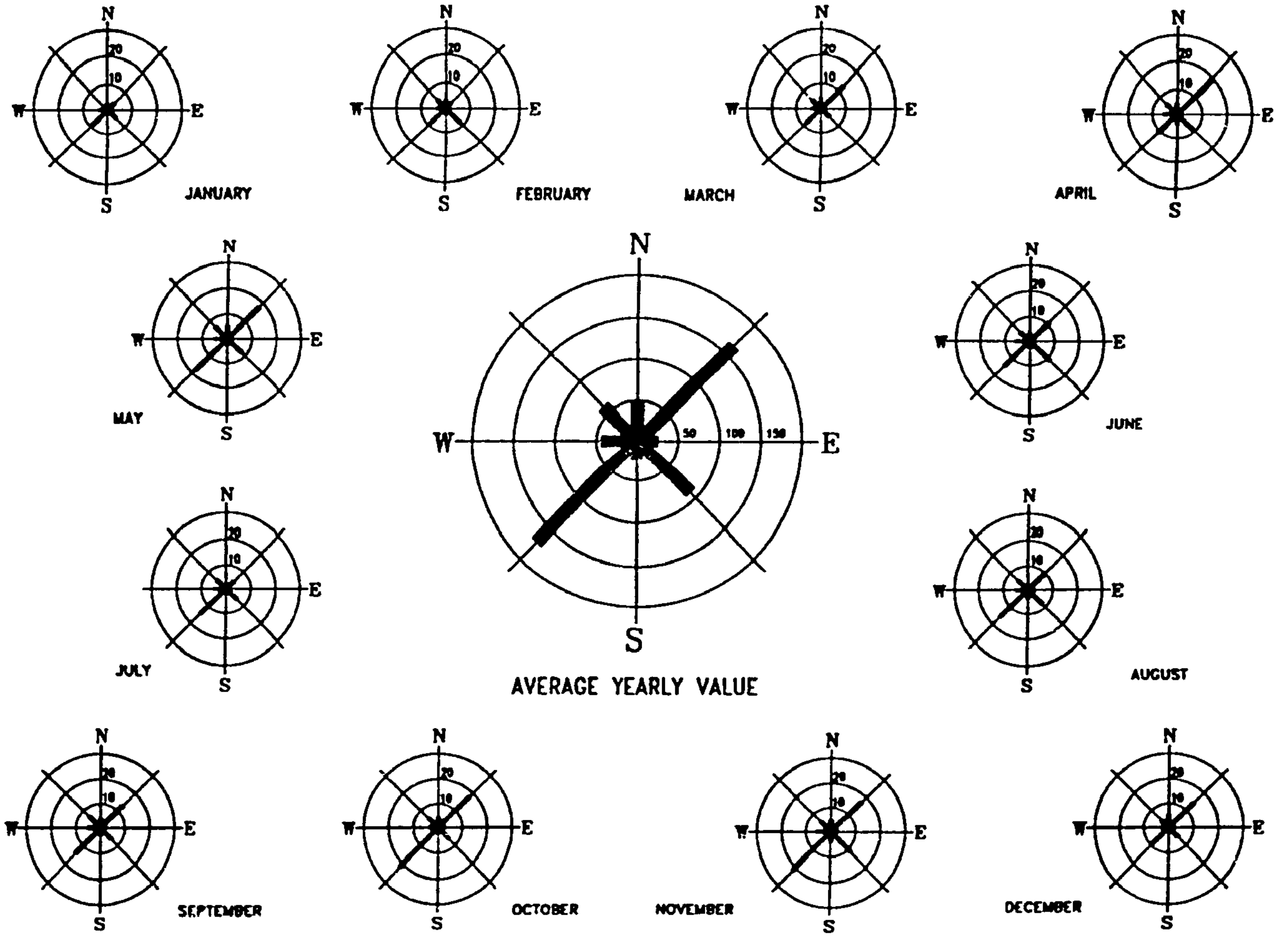


Fig. 3.9 Driving rain frequency (hr) - Dorval station

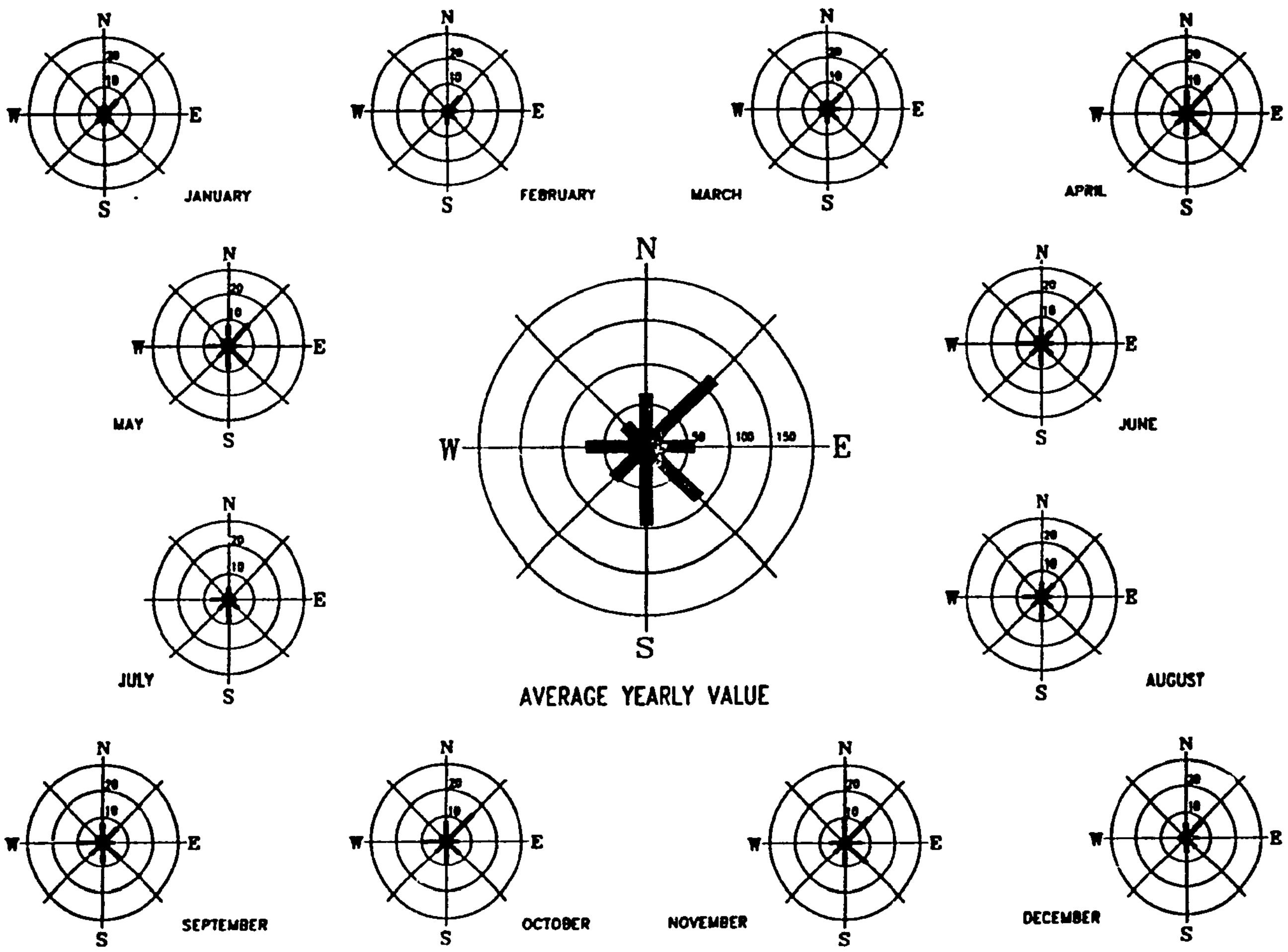


Fig. 3.10 Driving rain precipitation on a vertical surface (mm) - McGill staion

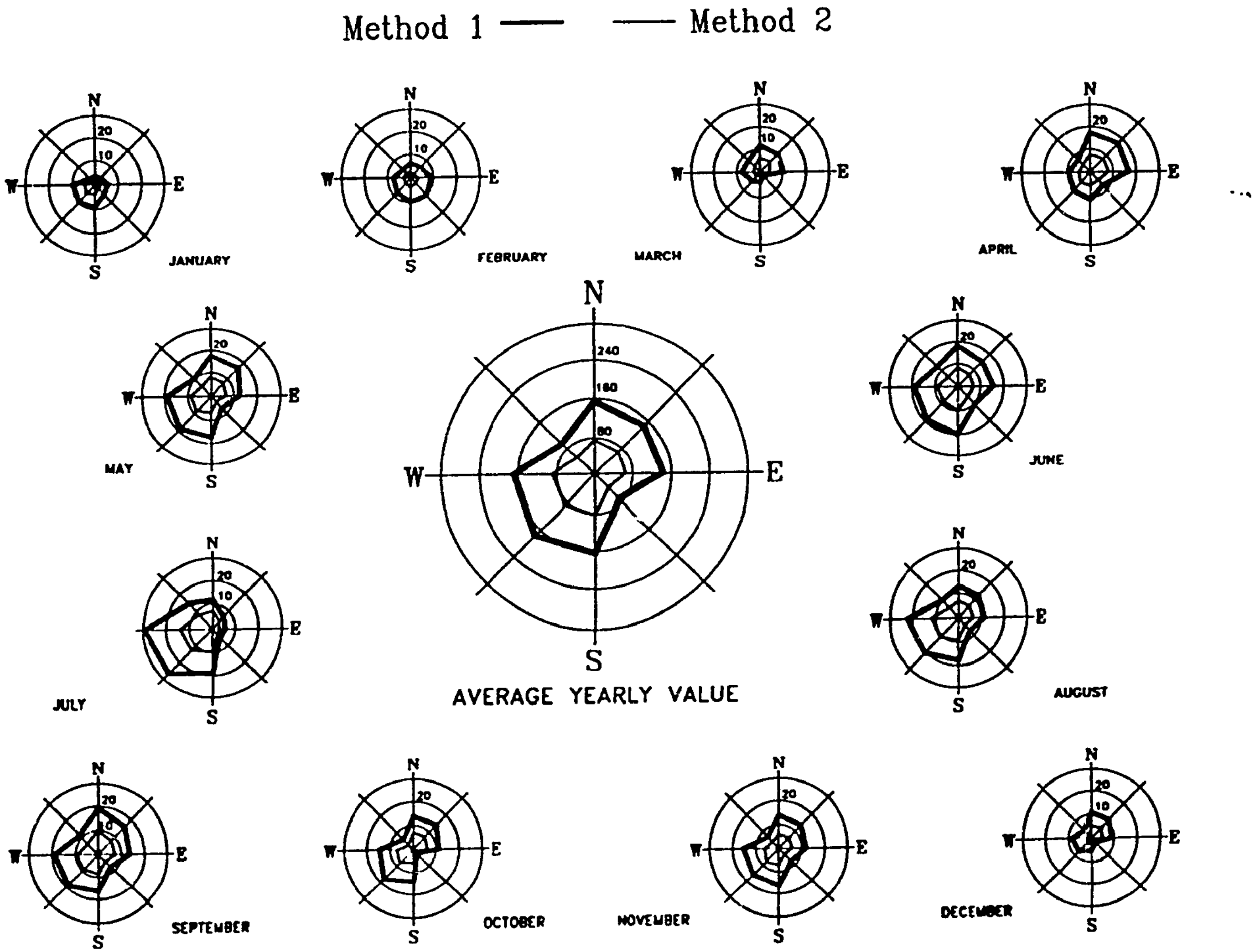


Fig. 3.11 Driving rain precipitation on a vertical surface (mm) - Dorval station

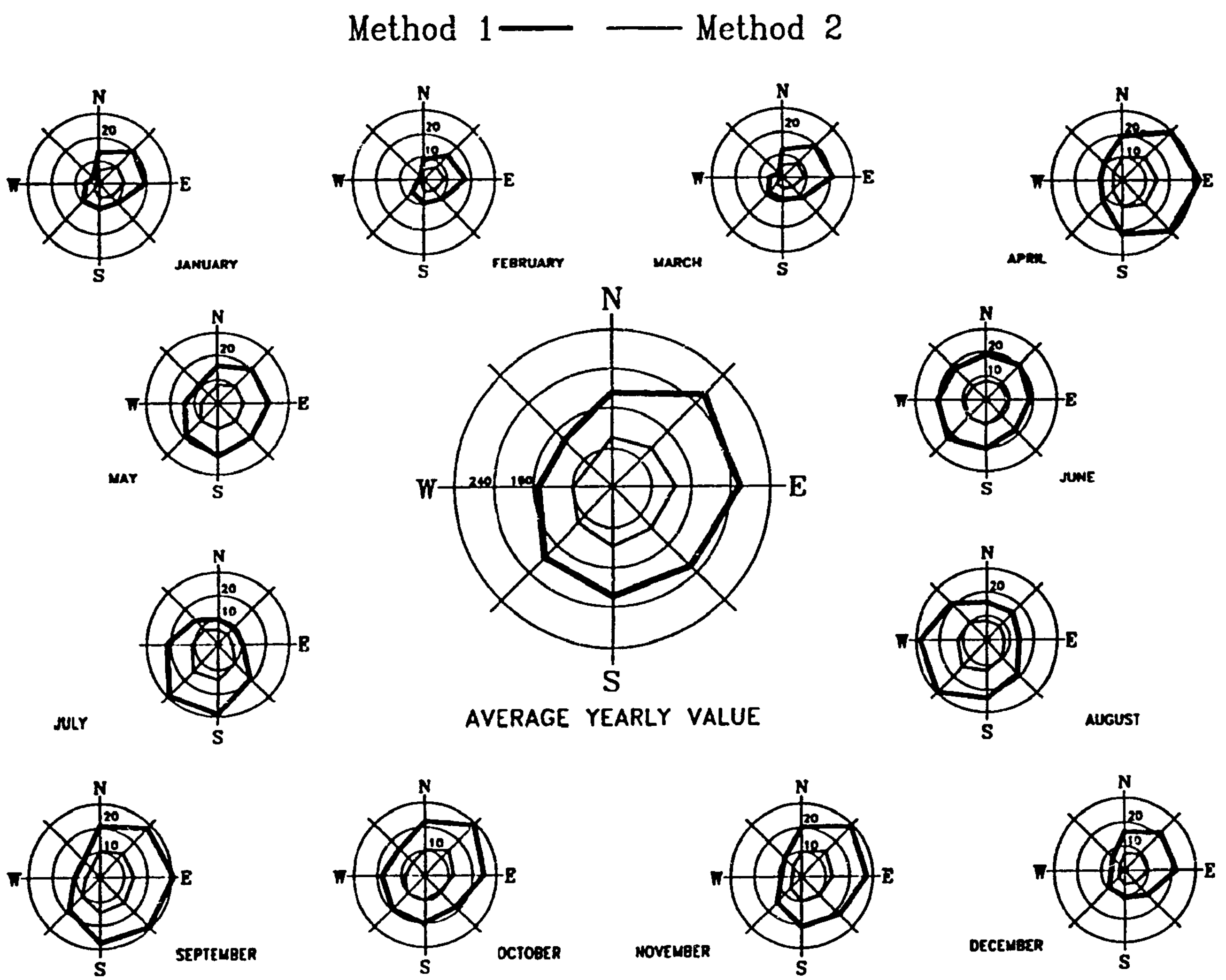
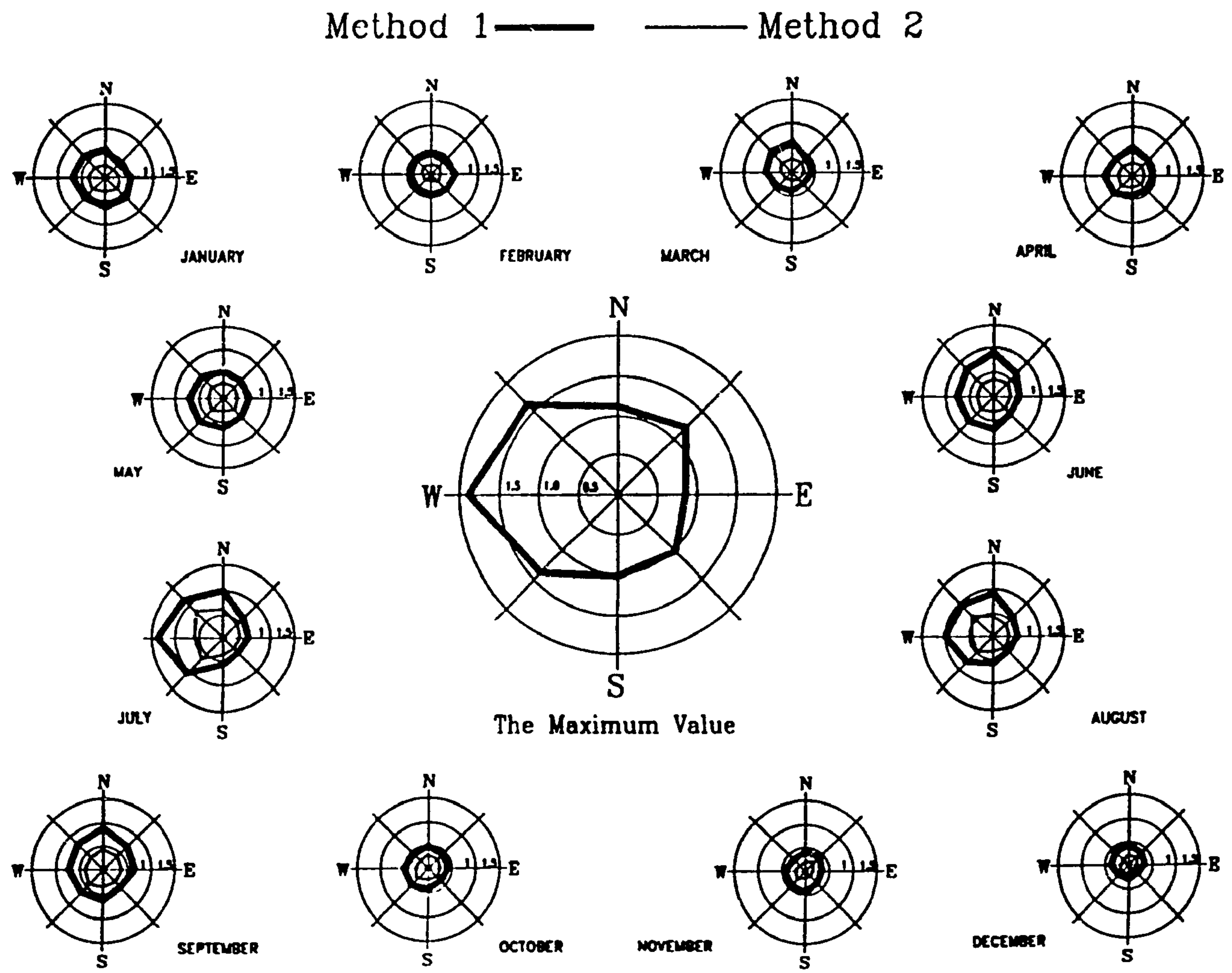


Fig. 3.12 Average driving rain intensity on vertical surface (mm/hr) - McGill station



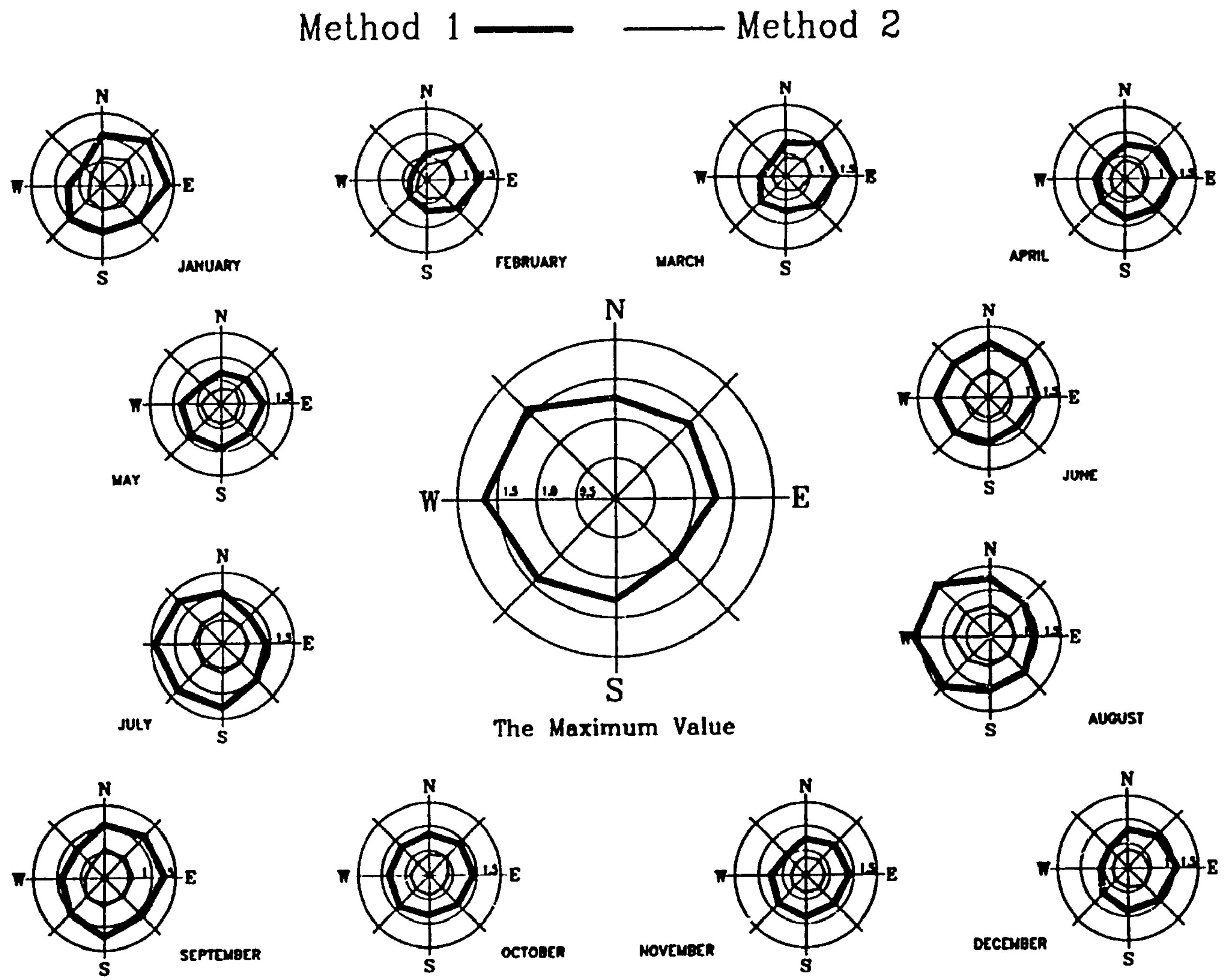
JANUARY FEBRUARY MARCH APRIL

MAY The Maximum Value JUNE

JULY AUGUST

SEPTEMBER OCTOBER NOVEMBER DECEMBER

Fig. 3.13 Average driving rain intensity on vertical surface (mm/hr) - Dorval station



3.3 Improvement in The Computation Methodology

The method I mentioned in section 3.1.1 can achieve the quantitative results of driving rain exposure on a vertical wall by computing the local wind and rainfall data. However, this method has some shortcomings. Firstly, this method is not able to consider all the direction of driving rain striking the vertical facade (Fig. 3.3 shows that the driving rain from two sectors of 22.5° is ignored in computation). Secondly, the total precipitation $P_{p\theta}$ and total raining time t_θ are derived from meteorlogical data. At present, the hourly weather data, like hourly wind speed, wind direction and rain fall are available in most of the meteorological stations. The quantitative results could be more realistic by incorporating this hourly data and all directions of driving rain. Thus, the method I can be improved to derive four quantitative parameters of driving rain exposure on a vertical wall, namely, precipitation, impact frequency, intensity and impact duration.

3.3.1 Precipitation of Driving Rain on A Vertical Surface

The total amount of driving rain precipitation on the vertical surface can be obtained by using hourly meteorological data through hourly integration. It can be given as

$$P_{\phi\ Total} = \frac{2}{9}\sum_{i=1}^{h_t} R_i^{\frac{8}{9}}\ V_i\ Cos\theta_i \quad where \quad -90^\circ \le \theta \le +90^\circ \qquad (3.7)$$

where $P_{\phi\ Total}$ (mm) is the total amount of driving rain precipitation on a vertical wall with an orientation ϕ (Fig. 3.14), R_i(mm) is the hourly rainfall on a horizontal surface during a specific hour i, V_i (m/sec) is the hourly mean wind speed during a specific hour i, θ_i is the direction of the hourly mean wind speed normal to the vertical wall with an orientation ϕ during a specific hour i and h_t is the number of hours of driving rain considered during a specific period of time (day, week, month or year).

3.3.2 Impact Frequency of Driving Rain on A Vertical Surface

The impact frequency of driving rain on a vertical wall indicates the total time (in hours) of driving rain that impinges on a vertical facade with an orientation ϕ during a specific period of time (day, week, month or year). It can be given as

$$T_\phi = \sum_{i=1}^{h_t} t_i \tag{3.8}$$

where T_ϕ(hr) is the impact frequency of driving rain, t_i is the total time of driving rain impinging on a vertical wall with an orientation ϕ during a specific hour i.

3.3.3 Intensity of Driving Rain on A Vertical Surface

By using both precipitation and wetting frequency of driving rain on a vertical wall as mentioned in equations (3.7) and (3.8), the average driving rain intensity on a vertical wall with an orientation ϕ can be given as

$$R_{\phi\ Ave} = \frac{P_{\phi\ Total}}{T_\phi} \tag{3.9}$$

where $R_{\phi\ Ave}$(mm/hr) is the average driving rain intensity on a vertical wall with an orientation ϕ, $P_{\phi\ Total}$(mm) is the total amount of driving rain precipitation on a vertical wall with an orientation ϕ [eq.(3.7)], T_ϕ(hr) is the impact frequency of driving rain on a vertical wall with an orientation ϕ [eq.(3.8)].

The maximum intensity (mm/hr) of the driving rain on a vertical surface is given by

$$R_{\phi\ Max} = MAX\ \{\frac{2}{9} R_i^{\frac{8}{9}}\ V_i \cos\theta_i\ \}\ \ where\ \ \begin{array}{ccccc} 1 & \leq & i & \leq & h_t \\ -90^\circ & \leq & \theta & \leq & +90^\circ \end{array}\ \ and \qquad (3.10)$$

where $R_{\phi\ Max}$(mm/hr) is the maximum intensity of driving rain on a vertical wall with an orientation ϕ, R_i(mm) is the hourly rainfall on a horizontal surface during a specific hour i, V_i (m/sec) is the hourly mean wind speed during a specific hour i, θ_i is the direction of the hourly mean wind normal to the vertical wall with an orientation ϕ during a specific hour i and h is the number of hours of driving rain considered during a specific period of time (day, week, month or year).

Finally, average maximum intensity of the driving rain on a vertical wall with an orientation ϕ is given by

$$R_{\phi\ Ave.Max} = \frac{1}{Y} \sum_{j=1}^{Y} \{\ R_{\phi\ Max}\ \}_j \qquad (3.11)$$

where $R_{\phi\ Max}$(mm/hr) is the maximum intensity of driving rain on a vertical wall observed for a specific month during a year and Y is the number of years.

The average driving rain intensity could be considered suitable for assessing long term performance of the building envelope. The maximum intensity is an extreme value and the mean maximum intensity is a mean peak value. These two values could be considered from a perspective of short term performance. The mean maximum intensity could serve as a guideline in the design of building enclosure.

3.3.4 Impact Duration of Driving Rain on A Vertical Surface

The impact duration of driving rain on a vertical wall indicates the time in hours during which a vertical surface is continuously impacted by the driving rain. In other words, it is a continuous duration between the moment a vertical surface starts receiving driving rain and the moment no driving rain could be received on the vertical surface. The two types of impact durations of driving rain considered are (i) Maximum impact duration and (ii) Mean maximum impact duration.

The maximum impact duration (hr) of the driving rain on a vertical wall is given by

$$\begin{aligned} D_{\phi\,Max} &= MAX\,\{\,D_k\,\} \quad \text{where } 1 \le k \le n \ \text{ and} \\ & \qquad\qquad\qquad D_k = t_s - t_e \end{aligned} \tag{3.12}$$

where $D_{\phi\,Max}$(hr) is the maximum impact duration of driving rain on a vertical wall with an orientation ϕ, D_k(hr) is the continuous impact duration of driving rain on a vertical wall during k^{th} occurrence, n is the number of occurrences of driving rain during a specific period of time (day, week, month or year) and t_{ks} and t_{ke} are the starting and ending times of the k^{th} time occurred driving rain.

The average maximum impact duration (hr) of the driving rain on a vertical wall with an orientation ϕ, ($D_{\phi\ Ave.Max}$) is given by

$$D_{\phi\ Ave.Max} = \frac{1}{Y}\sum_{j=1}^{Y} \{D_{\phi\ Max}\}_j \tag{3.13}$$

where $[D_{\phi\ Max}]_j$ (hr) is the maximum impact duration of driving rain on a vertical wall with an orientation ϕ in a specific month for jth year, Y is the number of years.

The results of the impact duration are considered with respect to the month in which the driving rain ended whenever the driving rain is continuous over a few days in two different months (i.e., starting at the end of one month and ending at the start of next month).

3.4 Derivation of Driving Rain Exposure for Various Canadian Cities

The improved computation method as described in section 3.3 has been applied to quantify the driving rain exposure on a vertical wall of a building located at various Canadian cities. For this purpose, the climatological data of respective cities are used. The quantification of driving rain exposure is expressed in terms of (i) precipitation (ii) impact frequency (iii) intensity and (iv) impact duration. The various Canadian cities considered in this study are Calgary, Edmonton, Fredericton, Halifax, Montreal, Ottawa, Quebec City, Regina, Saskatoon, St. John's, Toronto, Vancouver, Victoria, Winnipeg and Yellowknife. Hourly rain precipitation and hourly mean wind speed data recorded at the climatological stations mentioned above were obtained from Atmospheric Environment Service, Environment Canada. The climatological data of each city included in this study was recorded at respective local meteorological station. Generally these meteorological stations are located at airports or on the outskirts of city, These stations are equipped with recording facilities for hourly wind speed, wind direction and rainfall at any point of time. Generally the topography of these climatological stations (airports or on outskirts of the city) is almost uniform. The effect of topography on the direction and speed of wind will be minimal at these stations. Thus the derived results from the meteorological data recorded at airport or outskirts of a city represent the uniform driving rain environment for each city. The details of climatological data are given in Table 3.2.

From the climatological data recorded at various cities, it is assumed that the wind and rainfall are continuous during an hour when the rainfall and mean wind speed are recorded. Also the data used in this study reflect the climatic conditions of an open area. However a building located in an urban area may not have the same degree of driving rain exposure compared to that of a building located in an open area. Generally the degree of exposure to driving rain in the urban area is lower due to mainly the attenuation of the wind speed by the topography. It may be assumed that the quantitative parameters (precipitation, impact frequency, intensity and impact duration) derived from the climatological data recorded at open area would represent the driving rain exposure of that specific region (as the most severe condition).

3.4.1 Results

The average monthly precipitation [eq.(3.7)], the monthly impact frequency [eq.(3.8)], the maximum and mean maximum intensities [eq.(3.10) and (3.11)] and the maximum and mean maximum impact durations [eq.(3.12) and (3.13)] of driving rain on a vertical wall for various cities are computed. The results for each city are listed in Appendix II as fig. A1 to fig. A60. These results will be useful to analyze the facts contributing to the deterioration on building envelopes.

Figures A1 to A15 show the average monthly driving rain precipitation and summation value on a vertical wall in each direction for 15 cities. Figures A16 to A30 show the average monthly impact frequency of driving rain and the summation value of the impact frequency on a vertical wall in each direction for 15 cities. Figures A31 to A45 show the values of maximum intensity and mean maximum intensity of driving rain and the maximum values of both from the available monthly values for each direction. Figures A46 to A60 show the maximum and mean maximum impact durations of driving rain and the maximum values of both from the available monthly values for each direction.

3.4.2 Discussion

The quantitative results of driving rain show that the driving rain exposure varies greatly from city to city. This kind of information is also provided by the driving rain map of Canada (Fig. 2.2). However, the quantitative results provided some extra information on driving rain exposure.

Driving rain map of Canada shows that the driving rain exposure in west and east coast regions of Canada is severe than that observed in inland region. The coastal cities like Vancouver, Victoria, Halifax and St.John's have higher values of driving rain index compared to the driving rain index values of other cities in the map. But the quantitative results of driving rain show that the coastal cities are not necessarily be under the influence of severe exposure. In other words, those coastal cities with a high value of driving rain index will have higher values of annual precipitation (rainfall on a vertical surface) and total impact frequency derived from quantitative results, but not necessarily higher intensity and impact duration values. Although walls of buildings located in coastal cities may collect more rainfall and have a longer impact frequency, it does not mean that the buildings in coastal cities get exposed to severe and longer storms compared to those in inland and vice versa. For example, Vancouver has a larger total rainfall but mild rain intensity where as Regina has a strong intensity and lesser rainfall.

The quantitative driving rain exposure results also provide information on exposure variation in different directions. The quantitative results also remind the building designer that each facade of a building may have different driving rain exposure characteristics. For example, one facade may have large precipitation and low intensity and the other may have low precipitation and high intensity of driving rain.

The seasonal variation of driving rain exposure over a year can also be seen from the quantitative results. Generally, the driving rain exposure during winter is smaller than the driving rain exposure in summer. But in some coastal cities, the driving rain precipitation on a vertical surface during winter may be larger than the driving rain precipitation in summer (for eg., Halifax, Victoria, Vancouver). The seasonal variation of driving rain exposure supplemented with the variation of other weather factors like radiation, temperature and wind pressure (already explored by the researchers) could be helpful in determining the performance of the material used in the building facade.

The driving rain index shown in driving rain map of Canada can be used for comparing the driving rain exposure among different places. But the exact local driving rain exposure needed for a designer can not be obtained from the driving rain map of Canada. Whereas the quantitative driving rain results are useful in comparing the driving rain exposure among different places as well as in obtaining the exact local driving rain exposure needed for a building designer. The quantitative results also give an indication for researchers about the conditions to which wall specimens should be subjected in a driving rain test apparatus. For example, one side of a wall specimen is continuously impacted by water at an intensity of 138 L/m^2 in a standard test of water leakage of masonry wall (ASTM E514). The intensity of 138 L/m^2 may not be suitable for any location in Canada as the maximum intensity occurred in Canadian cities is not uniform. Instead of 138 L/m^2, a realistic and appropriate value can be used for a specific location obtained from quantitative results. Similarly the max impact duration may be used as duration of test unlike 4 hours.

Also, the driving rain intensity and impact duration on a vertical surface can be directly used for examining the behaviour of the building envelope material. These quantitative driving rain values along with other climatic factors provide researchers to simulate entire local weather conditions in order to study the performance of materials.

Fig. 3.14 Representation of the building facade orientation and the direction of wind

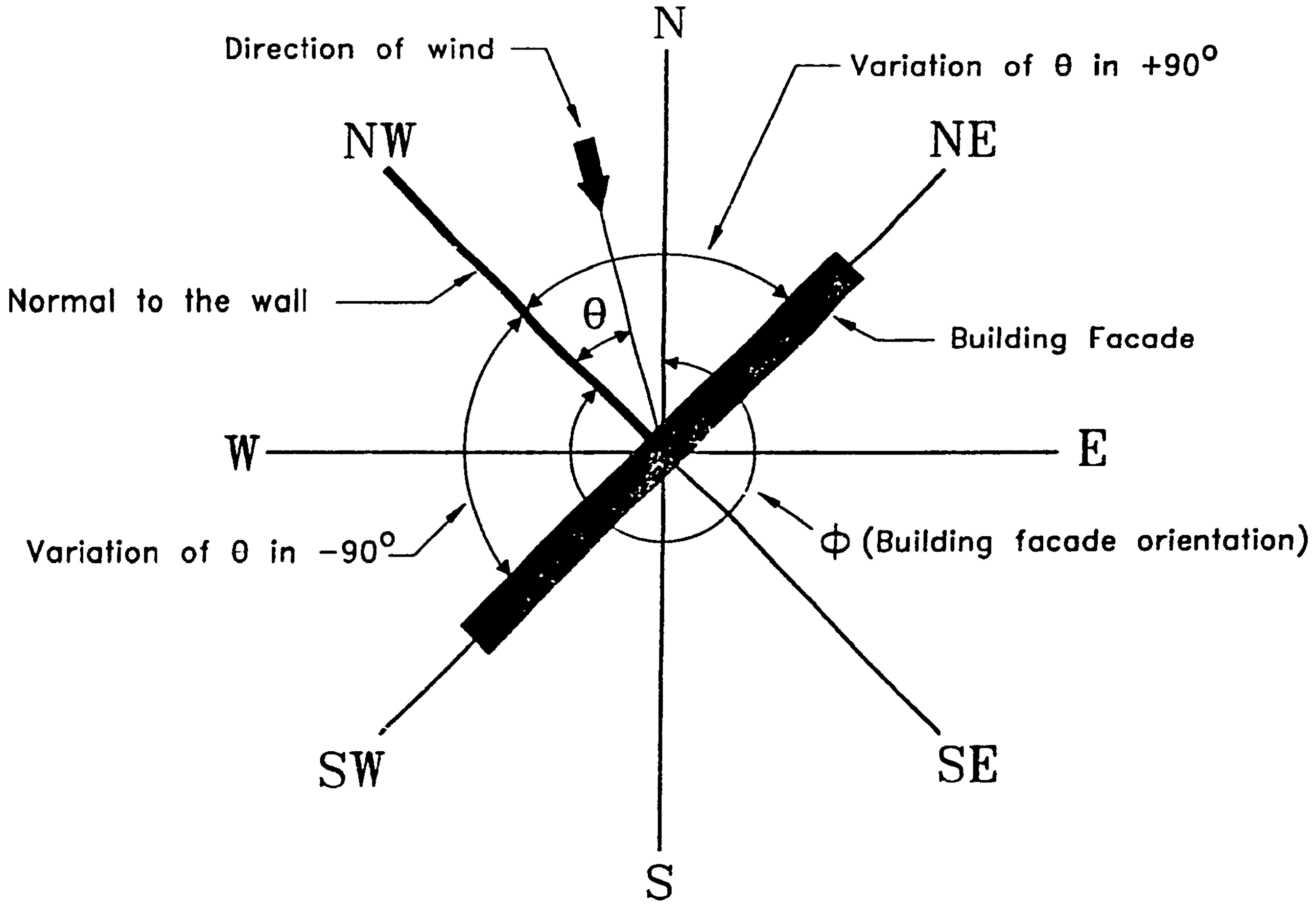


Table 3.2 Details of climatological data of various Canadian cities

CITY	STATION NAME	STATION NUMBER	LATITUDE	LONGITUDE	DURATION OF DATA
Calgary	Calgary International Airport	3031093	51°07'	114°01'	60.05.01-60.10.31
Edmonton	Edmonton Municipal Airport	3012208	53°34'	113°31'	60.04.01-90.10.31
Fredericton	Fredericton Airport	8101500	45°52'	66°32'	84.06.01-90.12.31
Halifax	Halifax International Airport	8202250	44°53'	63°31'	77.03.01-88.07.31
Montreal	Dorval International Airport	7025250	45°28'	73°45'	60.05.01-90.12.31
Ottawa	Ottawa International Airport	6106000	45°19'	75°40'	67.07.01-90.12.31
Quebec City	Quebec City Airport	7016294	46°48'	71°23'	61.05.01-90.10.31
Regina	Regina Airport	4016560	50°26'	104°40'	60,04,01-90,10,31
Saskatoon	Saskatoon Airport	4057120	52°10'	106°41'	60,04,01-90,10,31
St. John's	St. John's Airport	8403506	47°37'	52°44'	61.06.01-90.02.28
Toronto	Toronto Downsview Airport	6158443	43°45'	79°29'	64,03,01-82,06,30
Vancouver	Vancouver International Airport	1108447	49°11'	123°10'	60.04.01-90.12.31
Victoria	Victoria International Airport	1018620	48°39'	123°26'	64.08.01-90.12.31
Winnipeg	Winnipeg International Airport	5023222	49°54'	97°14'	60.04.01-90.11.30
Yellowknife	Yellowknife Airport	2204100	62°28'	114°27'	62.08.01-90.10.31

3.5 Potential Applications of The Study in Exploring Wetting Pattern on A Building Facade

The wetting pattern on the building facade caused by the driving rain is usually complex and far from uniform. It is mainly decided by two factors. The first factor is the driving rain drop trajectory around the building envelope. This parameter is variable and uncontrollable. The second factor is associated with facade geometry and its materials. These parameters are controllable. In other words, the wetting pattern is caused by direct impact of rain drops and then the run off of the rain water on the building surface, because the character of facade geometry and material are the most important elements to determine the feature of surface run off on the building.

The driving rain drop trajectory is a function of

(i) direction of driving rain
(ii) incident angle of falling of rain drops on a vertical surface
(iii) precipitation and intensity of rain water on the facade
(iv) rain water impact duration on the facade
(v) prevailing wind conditions
(vi) range of rain water droplet size and
(vii) kinetic energy of rain droplet.

All these variables contribute to a wetting pattern on the facade while there is a driving rain. But the wetting pattern caused always varies from time to time, since these variables are different from one storm to another. However a general wetting pattern was suggested by Couper according to the observation work [15]. During a typical rainstorm, the top area and the corner of the windward face will be wetted in the case of both high rise and low rise building (fig. 3.15). Generally, in low rise buildings, wetting is comparatively uniform due to the wind flow patterns which usually permit a more steady rain field than that on tall buildings. In tall buildings wetting of facades is highly dependent on the wind condition in the surrounding environment and it is effect on the accompanied rain field.

The facade geometry and materials determine the surface runoff and hence produces the final wetting pattern as storm continues. It includes

(i) continuous precipitation and duration of the rain,
(ii) geometrical configuration of the facades,
(iii) surface texture and irregularities of the facade,
(iv) porosity and size of the capillaries of the surface material, and
(v) air pressure difference across the enclosure.

It is difficult to assess the effect of surface run off to the wetting pattern of the facade. However, there are some general type of wetting patterns observed [3]. They are

(i) The corner of vertical projections or recessions that block and collect water run off moving diagonally across an adjacent planar surface will be highly wetted, since they are the continuous vertical channels of the run off. Masonry and building panel joints, expansion and construction joints, columns or pilasters, mullions and frames of windows, and decorative nibs or recesses can all be included in this category.

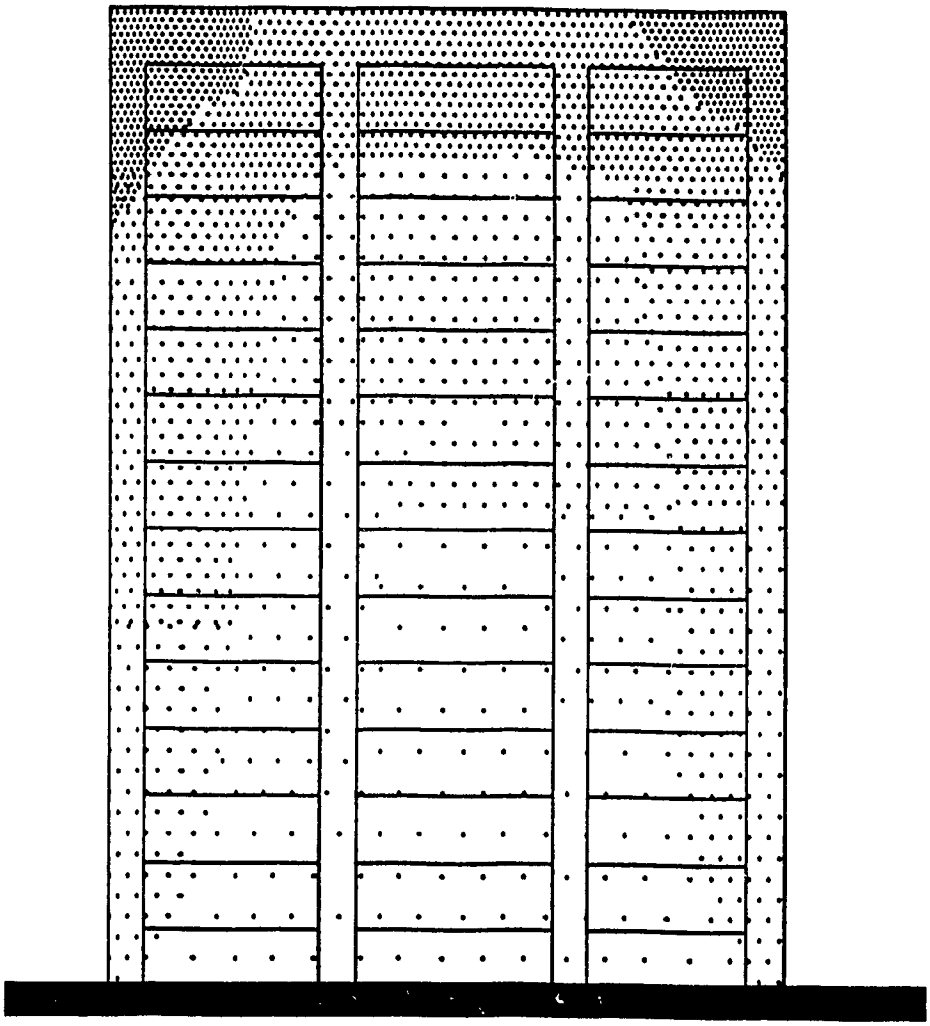
(ii) The elements under the horizontal planes or sloping surface which allow water to flow on or down may have a high risk of over wetted. Exposed structural frame members, Window frames and sills and their junctions with glassing, coping flush with walls below, cantilevered slabs for balconies, and projected parts of walls forming soffits fall within this category.

(iii) The other area that have high risk of wetting is in the discontinuities of planes and channels on the facade. The run off is terminated and changes the nature there, such as edge of soffit, base of a mullion, lowest edge of a drip detail.

So far, the research work on the wetting pattern on the building facade is based on the site observations. No theoretical or experimental method was found in the literature to explore the relationship between the wetting pattern and the factors influence it. Due to the difficulties of a theoretical approach that has to consider air flow pattern around objective building and the influence of surrounding buildings (which are extreme complicated and unclear), the experimental approach may the best way under current situation. A wind tunnel with rain simulation is suggested to apply for this purpose. By this methodology, a building with any type of geometrical configurations could be tested in the tunnel in order to find the wetting pattern on the facade. This methodology helps in exploring a specific configuration of a building which may have a high risk of wetting under a certain condition of driving rain.

Among the factors influencing the wetting pattern, the amount of rain water collected by the facade and the time that rain acts on the facade are important. The quantitative results of driving rain exposure on the building facade provide such information. By using this information it is possible to design an experimental approach for exploring wetting pattern. The quantitative results in terms of precipitation, impact intensity, impact frequency and impact duration on the facade can be easily simulated in experiments.

Fig. 3.15 Typical wetting pattern on the face of a multi-storey building subjected to driving rain [15]



Chapter 4: Derivation of Driving Rain Exposure For An Urban Area

4.1 Introduction

At present, many researchers and building engineers find the degree of exposure of a building envelope to driving rain with the help of driving rain index (DRI) maps. But, the DRI map does not represent variations in exposure of driving rain due to local topographic and geographical features. Lacy showed that the amount of driving rain recorded at the same time for two buildings in Glasgow region (UK) was different [14]. These two buildings were surrounded by different topographic and geographical features. The case study described in section 3.2 of Chapter 3 also revealed that quantitative driving rain exposure in the downtown of Montréal is different from that in the suburban region.

Generally meteorological stations located at airports or on the outskirts of the city (suburban region) record the hourly wind speed and the rainfall data. But, to prepare the DRI or quantitative driving rain exposure results for an urban area, the local long term data of wind speed and rainfall are relevant. However, a meteorological station is seldom located at the centre of the city. So, in order to derive the driving rain exposure in the urban area, it is necessary to modify the results derived from the data recorded at the suburban meteorological station.

Atmospheric scientists attributed the difference between the amount of rain fall in an urban area and that of the surrounding rural area to urbanisation [18]. As cited by Hall [19], Changnon and Landsberg illustrated the order of magnitude of the long term changes in climate that may be produced by towns and cities. They demonstrated the variations in the individual climatic elements (e.g., precipitation) and brought out the contrast between urban and rural areas with reference to specific sites. As an example, from the studies in Europe and North America, Landsberg illustrated that the precipitation produced by cities is 5-15% more than that in surrounding rural areas. Huff and Changnon [20] studied the precipitation modification in eight American urban areas of varying size, type and climate. Out of the eight cities, six showed strong evidence of urban effects on precipitation. The evidence was weak or non-existent at the other two cities. They concluded from their study that urban precipitation enhancement is a function of city size, industrial complexity and urban thermal effects. Powe [21] mentioned that in Montréal, heavier precipitation over the city near Mount Royal is due to thermal effects and topography. However, in the Montréal region, the total rainfall and the rainfall during wind (from April to October) at the McGill station (located in downtown Montréal) is approximately equal to that at Dorval and Mirabel stations (located at distance of 14 and 40 km away from downtown Montréal) (Figs. 3.1 and 1.1).

To derive the driving rain exposure in the urban area by modifying the data recorded at the suburban meteorological station, it is assumed that the total rainfall and the rainfall during wind in both the urban area and the suburban meteorological station are approximately the same. With this assumption, the urban DRI is developed by simply modifying the suburban wind data. This method is verified for the Montréal region.

4.2 Methodology

4.2.1 Derivation of Wind Speed

By using Logarithmic Law [22], the wind speed at a certain height from ground for a certain geographic terrain can be obtained as

$$U_{(z)} = \frac{1}{k} u_* \ln\frac{z}{z_o} \tag{4.1}$$

where

$$z = z_g - z_d \tag{4.2}$$

$$z_d = \overline{H} - \frac{z_o}{k} \tag{4.3}$$

and from the Similarity Model [22],

$$\frac{u_{*1}}{u_{*2}} = (\frac{z_{o1}}{z_{o2}})^{0.0706} \tag{4.4}$$

where k is Von Kárman's constant (≈0.4), $U_{(z)}$ is the mean wind speed at an effective height z, u_* is the shear velocity of the flow, z_o is the roughness length, z_g is the height above ground, z_d is the zero plane displacement, $\bar{H}$ is the average or general roof-top level (Fig. 4.1), z_{o1} and z_{o2} are the roughness lengths for the two terrains and u_{*1} and u_{*2} are the friction velocities for the two terrains.

Generally, the wind speed at meteorological stations is measured at a height of 10m from the ground in an open area. However, in the derivation of DRI for an urban area, the value of wind speed measured at a height of 10m above ground is considered as inappropriate for the following reasons:

(i) In the central business locality of a large city, the zero plane displacement (z_d) is normally near the average roof-top of the buildings and not at the ground level.

(ii) The location of 10m height from ground is likely to be in a turbulent area below the zero plane displacement.

For a building facade with a given orientation ϕ (Fig. 3.14), a relationship between the wind speed in an urban area at a height of ($\bar{H}$+h) and the wind speed recorded at a meteorological station at 10m height is derived as:

$$U_{(\bar{H}+h)} = C_{\phi}\, U_m \tag{4.5}$$

where $U_{(\bar{H}+b)}$ is the wind speed in an urban area at a height of ($\bar{H}$+h), U_m is the wind speed recorded at a meteorological station, h is the height above average or general roof-top level of the building and C_ϕ is an attenuation coefficient in the direction ϕ. This coefficient varies according to topography and the value of ($\overline{H}$+h). Three values, 5, 10 and 15m above the general roof-top level, were selected to identify the appropriate height at which the wind speed would be equivalent to the wind speed recorded at the meteorological station. Different values of C_ϕ are given in table 4.1 and the calculations involved in deriving those values are given in the Appendix I. The coefficient C_ϕ represents the wind speed attenuation in a certain direction at any time. Hence attenuation of wind speed during rain may be represented by the same coefficient C_ϕ.

4.2.2 DRI for An Urban Location

The mean DRI for an urban location can be derived from the data recorded at the meteorological station as

$$DRI_{mean(urban)} = C_{ave} \, V_m \, R_m \tag{4.6}$$

where V_m is the wind speed during rain at the meteorological station (m/sec), R_m is the rate of rainfall during wind at the meteorological station (mm/hr) and C_{ave} is the average value of different attenuation coefficients (C_ϕ) for a specific location, i.e.,

$$C_{ave} = \frac{\sum_{\phi=0}^{360^\circ} C_\phi}{N} \tag{4.7}$$

Based on the directional DRI developed by Prior [13], a directional DRI for an urban location can be obtained by using the following mathematical model.

$$DRI_{\phi(urban)} = \sum_{\theta=-90}^{+90^{\circ}} R_m \, V_{a\,\theta} \, COS\theta \tag{4.8}$$

where $V_{a\,\theta} = C_\theta \, V_{m\theta}$, $V_{a\,\theta}$ is the attenuated wind speed in the direction θ, C_θ is the attenuation coefficient in the direction of θ, $V_{m\theta}$(m/sec) is the wind speed in direction θ during the rain at the meteorological station, R_m (mm/hr) is the rate of rainfall at the meteorological station during the time when there is wind in the direction θ, θ is the angle between the wind direction and the normal to the wall concerned and $DRI_{\phi\ (urban)}$ is the directional driving rain index for a building facade with a orientation ϕ in an urban location (Fig. 3.14).

For computational simplicity, equation (4.8) can be approximated as:

$$DRI_{\phi(urban)} = C_\phi \sum_{\theta=-90}^{+90^{\circ}} R_m \, V_{m\theta} \, COS\theta \tag{4.9}$$

or

$$DRI_{\phi(urban)} = C_\phi \, DRI_m \tag{4.10}$$

where DRI_m is the driving rain index computed from the data recorded at the meteorological station.

4.2.3 Quantitative Driving Rain Exposure for Urban Location

The quantitative driving rain models developed in Chapter 3 (Equations 3.2 and 3.4) could be made more realistic by incorporating the value of directional attenuation coefficients. On this basis, the average intensity of the driving rain on a vertical surface in an urban area may be calculated as:

$$R_{v\,Ave\,(urban)} = \frac{\frac{2}{9}\sum_{\theta=-90}^{+90^\circ} C_\theta V_{m\theta}\left(\frac{P_{h\theta}}{t_\theta}\right)^{\frac{8}{9}} \cos\theta}{N} \tag{3.11}$$

Also, the total amount of driving rain precipitation on a vertical surface in an urban area may be calculated as:

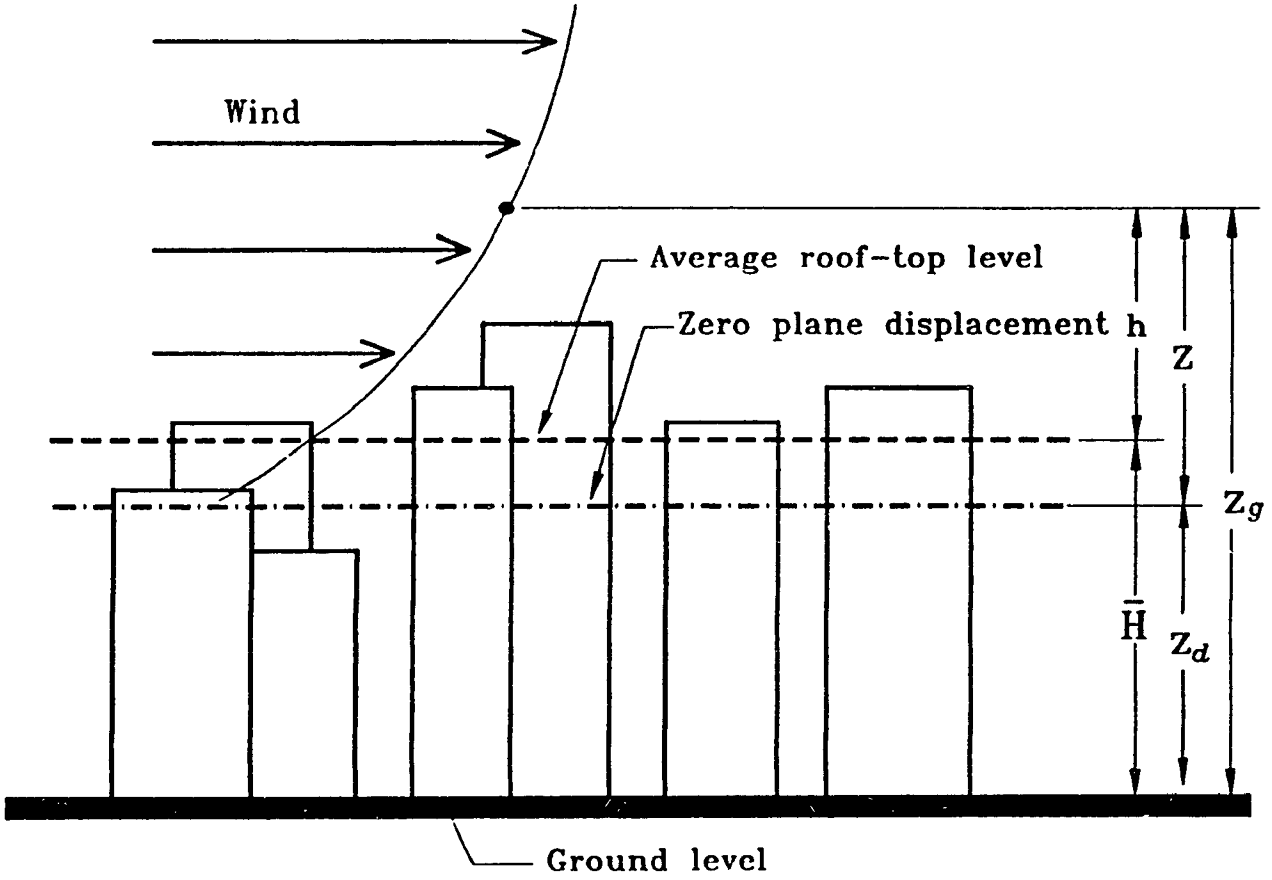
$$P_{v\,Total(urban)} = \frac{2}{9}\sum_{\theta=-90}^{+90^\circ} C_\theta V_{m\theta}\left(\frac{P_{h\theta}}{t_\theta}\right)^{\frac{8}{9}} \cos\theta\; t_\theta \tag{4.12}$$

where $R_{v\ Ave\ (urban)}$ (mm/hr) is the average intensity of rain on a vertical surface in an urban area due to wind from the direction of θ (angle from normal to the wall), $P_{v\ Total\ (urban)}$ (mm) is the total amount of driving rain precipitation on a vertical surface, C_θ is the attenuation coefficient in the direction of θ, $V_{m\theta}$ (m/sec) is the wind speed in the direction of θ during rain at the meteorological station, $P_{h\theta}$ (mm) is the precipitation on a horizontal surface due to wind from the direction of θ, t_θ is the number of hours of simultaneous rain and wind from the direction of θ and N is the number of directions considered in a period of time.

Table 4.1 Values of C_θ for various topographical categories

LOCATION	TOPOGRAPHICAL CATEGORIES		
	LARGELY URBANIZED AREA centre of large city, high rise building district $z_o = 2.5$ m	MODERATELY URBANIZED AREA centre of small town, low building district $z_o = 1$ m	SLIGHTLY URBANIZED AREA outskirts, park in city $z_o = 0.3$ m
$\bar{H} + 5$ m	0.347	0.434	0.587
$\bar{H} + 10$ m	0.432	0.547	0.712
$\bar{H} + 15$ m	0.494	0.620	0.788

Fig. 4.1 Position of zero-plane displacement and average roof-top level in an urban environment



4.3 Case study

There are many meteorological stations in the urban area of the Montréal region (Fig. 3.1). However, the number of stations with both wind speed and rainfall data recorded for a considerable time period are limited. In this study, meteorological stations at McGill and Dorval airport were chosen. The data recorded for a period of 23 years at both the McGill and the Dorval Airport meteorological stations were considered in this study. The McGill station is located in downtown Montréal. The topography of the Dorval station resembles that of an open area.

The McGill meteorological observatory is at the top of the Burnside Hall Building. This building is 12 floors high and is located at the southeast side of the campus (Fig. 3.2). The central business locality is southeast and south of the observatory. The southwest to east sector of the McGill observatory is surrounded by the campus buildings which are lower than the high rise structures in the central business locality. The wind cup is placed at a height of 8m from the roof top.

The surrounding topography of the McGill observatory is not uniform. According to the observation of topographic feature surrounding the Burnside Hall Building and the classification of topography indicated by Simiu and Scanlan [22], the ground roughness of surrounding area of the McGill observatory can be selected. In this study, it is divided into 3 categories as largely, moderately and slightly urbanized areas (Table 4.1). The

North sector of the observatory comprises a group of buildings lower in height than the observatory building and it is considered moderately urbanized with a surface roughness length of 1m. The NE to South sector comprises the main business area of downtown Montréal and is considered largely urbanized with a surface roughness length of 2.5m. Finally the SW to NW sector is covered with grass, plants and scattered trees, and is considered slightly urbanized with a surface roughness length of 0.3m. The average value of all the eight directional C_ϕ for this observatory, for different heights of $\overline{H}$+h is determined by using eq.(4.7). The value of C_ϕ is found to be 0.44, 0.55 and 0.62 for heights of $\overline{H}$+5, $\overline{H}$+10 and $\overline{H}$+15m respectively. The effect of Mount Royal which is the hill located on the northwest side of McGill campus is not considered in this study.

The DRI and the quantitative results derived from meteorological data recorded at the McGill station is used as the actual DRI and quantitative exposure in the central business locality of Montréal. This actual DRI and quantitative results are compared with the DRI and quantitative results derived from the data of the Dorval Airport station by using the mathematical model described in section 4.2 (Eq. 4.6)

4.3.1 Results and Discussion

The meteorological data recorded from January 1967 to December 1989 at both the McGill and the Dorval stations is analyzed. The mean urban DRI is calculated by using equation (4.6). The directional urban DRI is calculated by using equations (4.8) and (4.9). A sample calculation for the mean yearly DRI is shown in Table 4.2. The quantitative DRI in terms of intensity and precipitation is determined by using equations (4.11) and (4.12). Sample calculations for a specific month and the corresponding results are shown in tables 4.3 and 4.4 respectively. The observations are as follows:

(1) The yearly rainfall during wind at these two stations is approximately the same (McGill 0.6358m and Dorval 0.6592m).

(2) The yearly wind speed during rain at the Dorval station is higher than that of the McGill station (Fig.4.2-a & e).

(3) The derived DRI for the McGill station from the actual data measured at the Dorval station is in agreement with the actual DRI of the McGill station (Fig. 4.2-d & e). The derived DRI by using the value of $C_{ave} = 0.62$ for a corresponding height of 15m above the general roof-top level, seems to be the best compared to those obtained by using $C_{ave} = 0.44$ and 0.55 for heights of 5 and 10m above general roof-top level respectively (Fig.4.2). So in the subsequent analysis of the directional DRI, the C_{ϕ} values for a height of $\overline{H}$+15m are used.

(4) Figure 4.3 shows (a) the measured DRI for each of the Dorval and the McGill stations and (b) the derived directional DRI for the McGill station, by using equations (4.8) and (4.9). The derived directional DRI, for the McGill station, using equations (4.8) and (4.9) compare favourably with the corresponding measured values. The differences

could be due to (i) inaccurate surface roughness length values (ii) non-uniformity of surface roughness length in a given sector (iii) unknown turbulence of air flow influence in the vicinity of the observatory and (iv) the influence of specific topographic features. For example, the actual DRI of the SE direction (135°) is lower than the derived DRI value. Probably, it could be due to the obstruction of wind by the two high rise buildings which are much higher and too close to the McGill Observatory building (Fig. 3.2).

(5) Figure 4.4 shows the average yearly driving rain intensity on a vertical surface derived by using equation (4.11). The average intensity on the vertical surface for the McGill station is derived by using the climatic data recorded at the Dorval station and the appropriate attenuation coefficient based on the surrounding topography of the McGill station. The average yearly driving rain precipitation on a vertical surface derived by using equation (4.12) is shown in Fig. 4.5. The precipitation on the vertical surface for the McGill station is derived by using the climatic data recorded at the Dorval station and the appropriate attenuation coefficient based on the surrounding topography of the McGill station. The results in Figs. 4.4 and 4.5 compare favourably with those derived directly from the data recorded at the McGill station.

The difference between the derived DRI and the derived quantitative driving rain exposure for an urban area from the respective actual values can be reduced further by targeting the C_ϕ values to the varying topographic features (Fig. 4.6).

Table 4.2 Sample calculation for the mean yearly DRI

Available data at the Dorval meteorological station:	Hourly wind speed and direction. Hourly rainfall.
Duration of data:	Jan. 1967 to Dec. 1989
Main Process:	Select those hours from the data when wind and rain prevail at the same time.
Average yearly wind speed (m/sec) during rain:	4.763
Average annual rainfall (mm) on the horizontal surface when there was wind:	660.44

RESULT	$C_{avg} = 1$	$C_{avg} = 0.62$
Yearly DRI (m^2/sec)	3.146	1.951

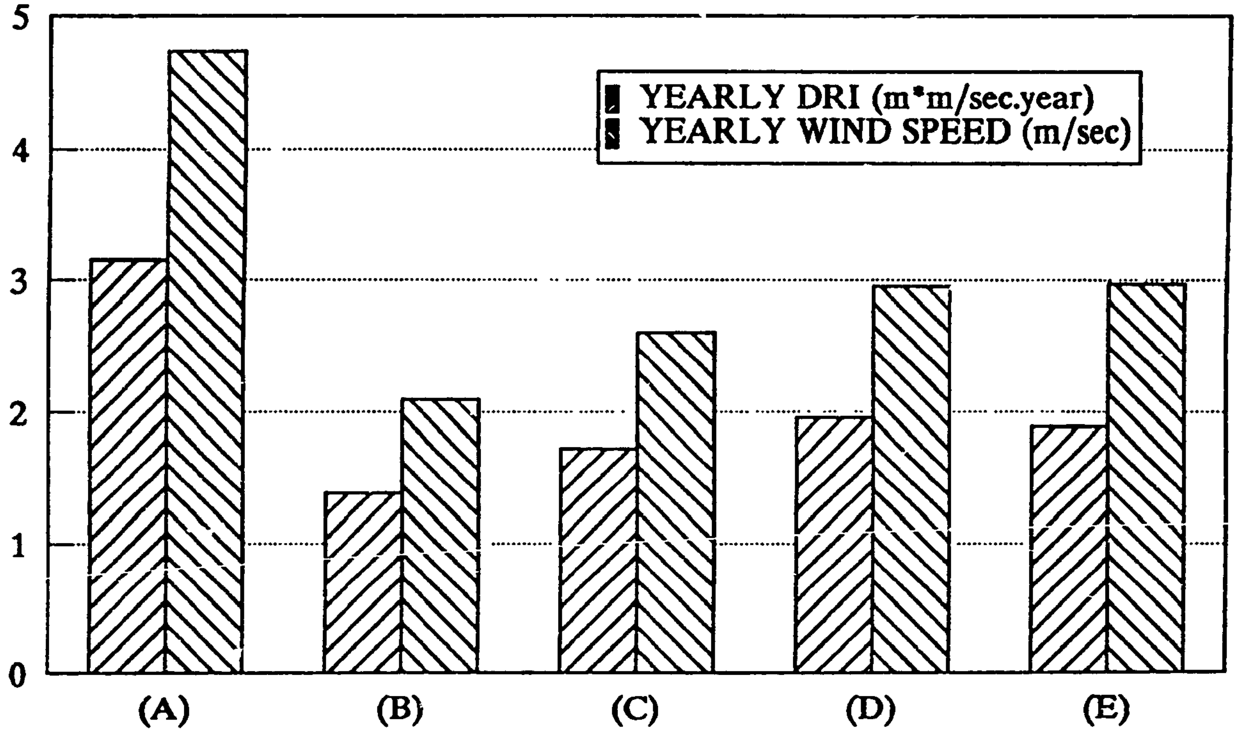
Table 4.3 Sample data for determining the quantitative DRI

Available data at the Dorval meteorological station:	Hourly wind speed and direction. Hourly rainfall.		
Duration of data:	Jan. 1967 to Dec. 1989		
Specific month considered:	JANUARY		
Main Process:	Select those hours from the data when wind and rain prevail at the same time.		
Directions considered:	N	NE	E
Average wind speed (m/sec) during rain:	4.226	5.771	4.031
Average rainfall (mm) on the horizontal surface when there was wind in the direction considered:	3.0	13.0	7.0
Average number of hours of driving rain:	2	7	3

Table 4.4 Results of average intensity and precipitation of driving rain on a vertical building facade

Results for the month of January	Without Attenuation	With Attenuation
Average monthly intensity of driving rain (mm/hr) on a vertical building facade perpendicular to NE (eq. 4.11):	1.387	0.724
Average monthly precipitation of driving rain (mm) on a vertical building facade perpendicular to NE (eq. 4.12):	20.965	10.586

Fig. 4.2 Yearly DRI and wind speed



(A): Actual DRI and wind speed for Dorval station
(B): Derived DRI for McGill station with $C_{ave} = 0.44$
(C): Derived DRI for McGill station with $C_{ave} = 0.55$
(D): Derived DRI for McGill station with $C_{ave} = 0.62$
(E): Actual DRI and wind speed for McGill station

Fig. 4.3 Yearly Directional DRI

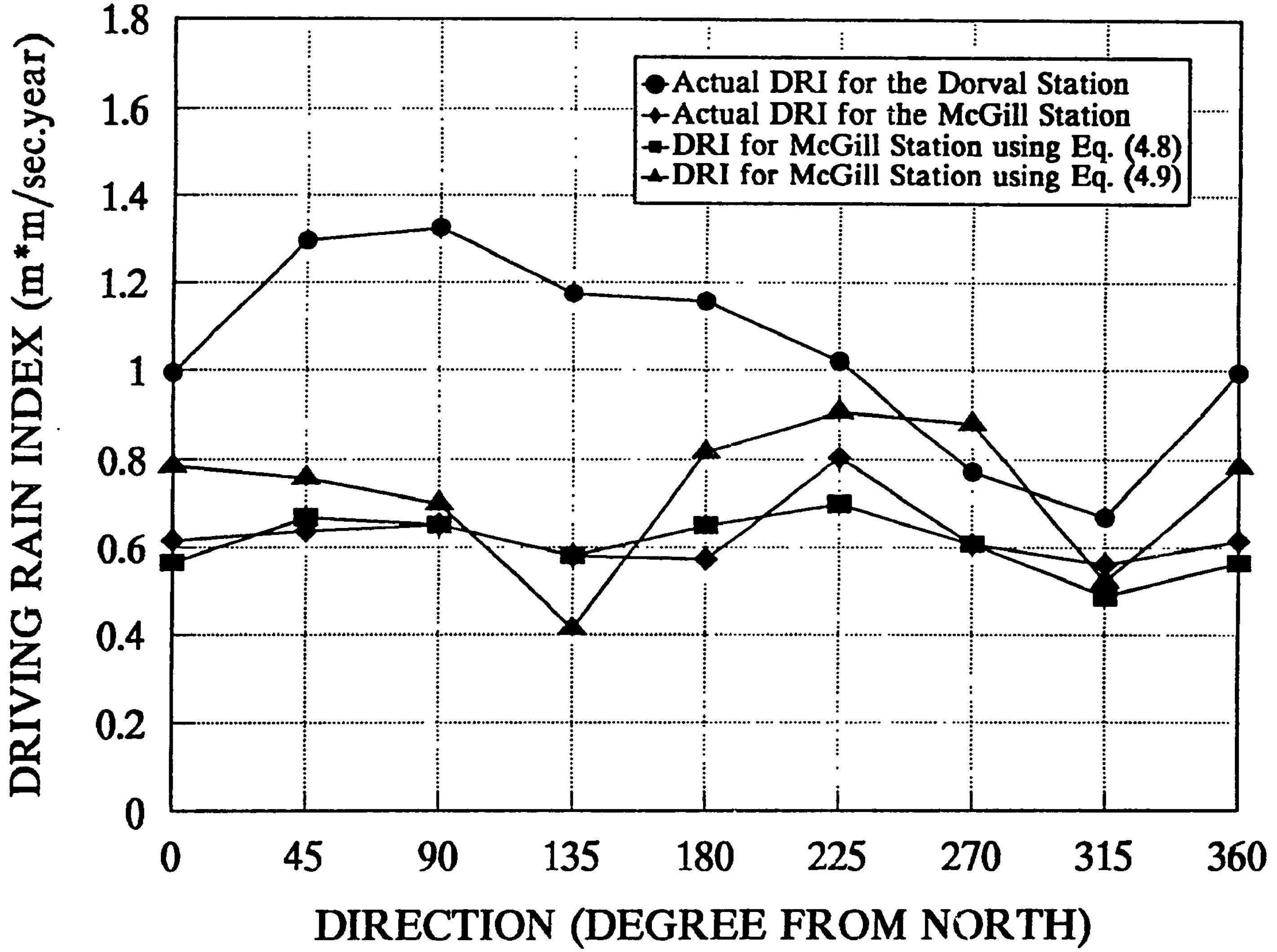


Fig. 4.4 Average yearly driving rain intensity on a vertical building facade

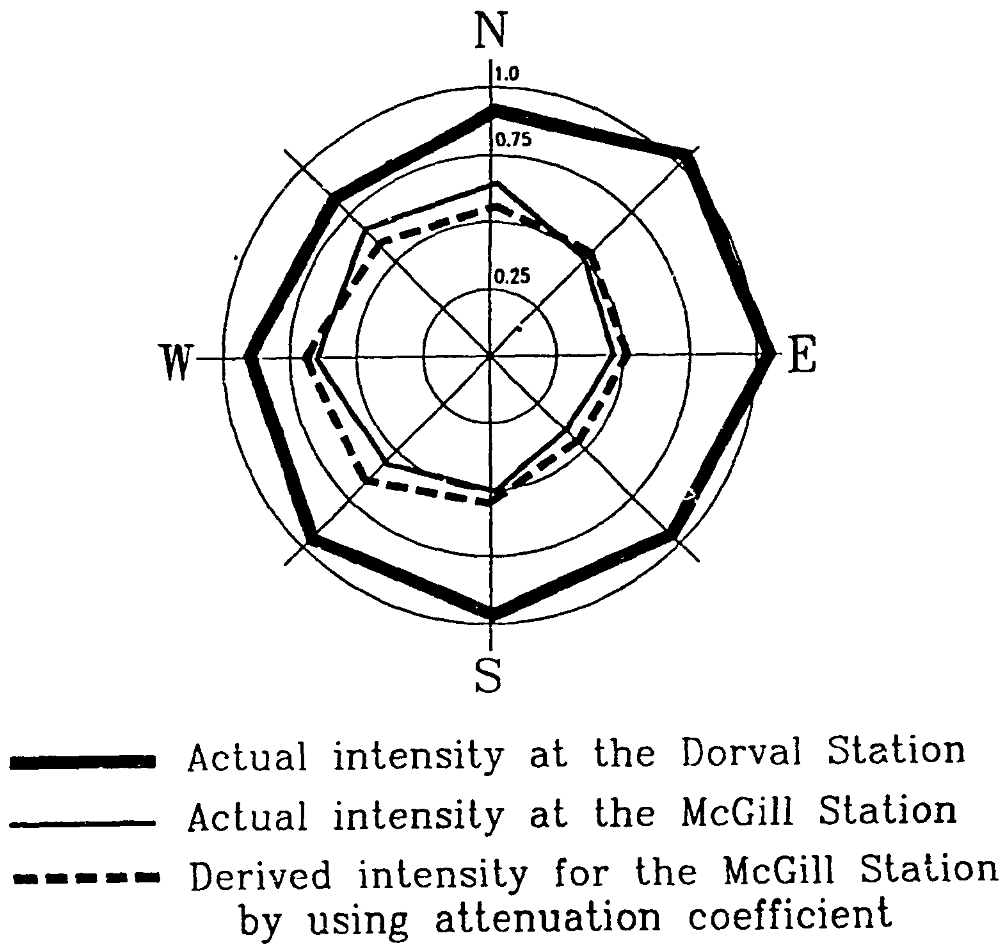


Fig. 4.5 Average yearly driving rain precipitation on a vertical building facade

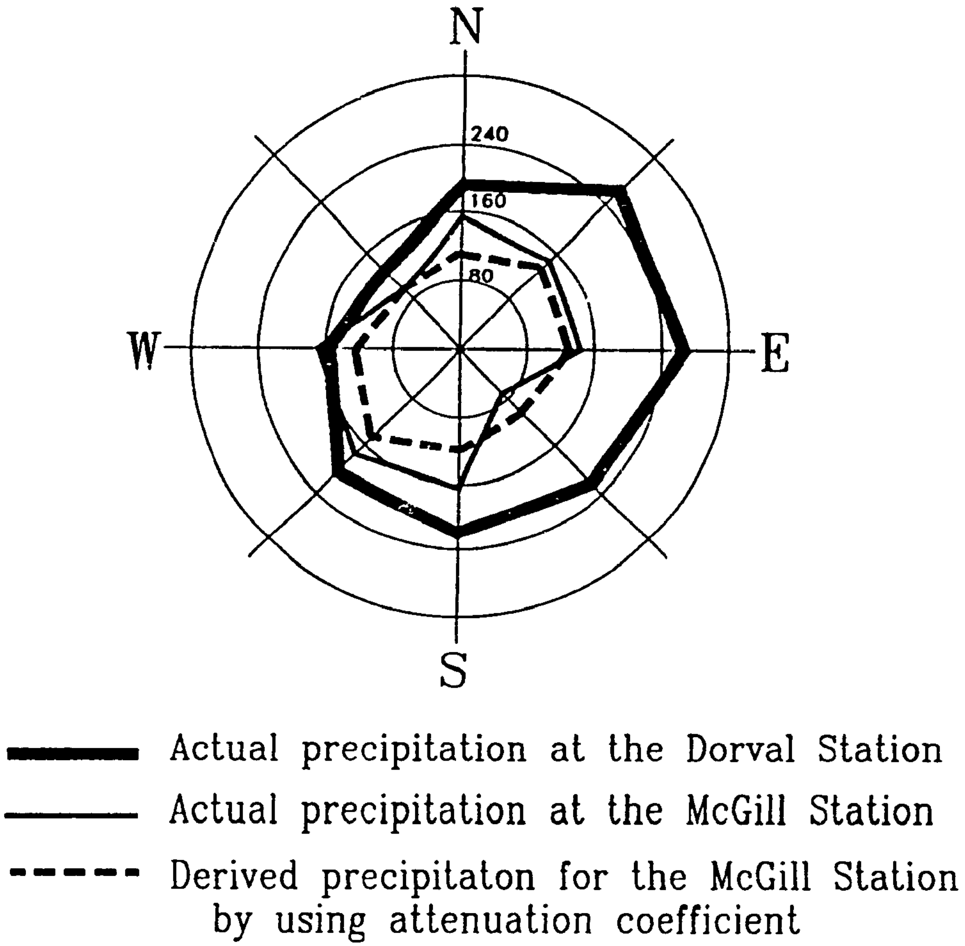
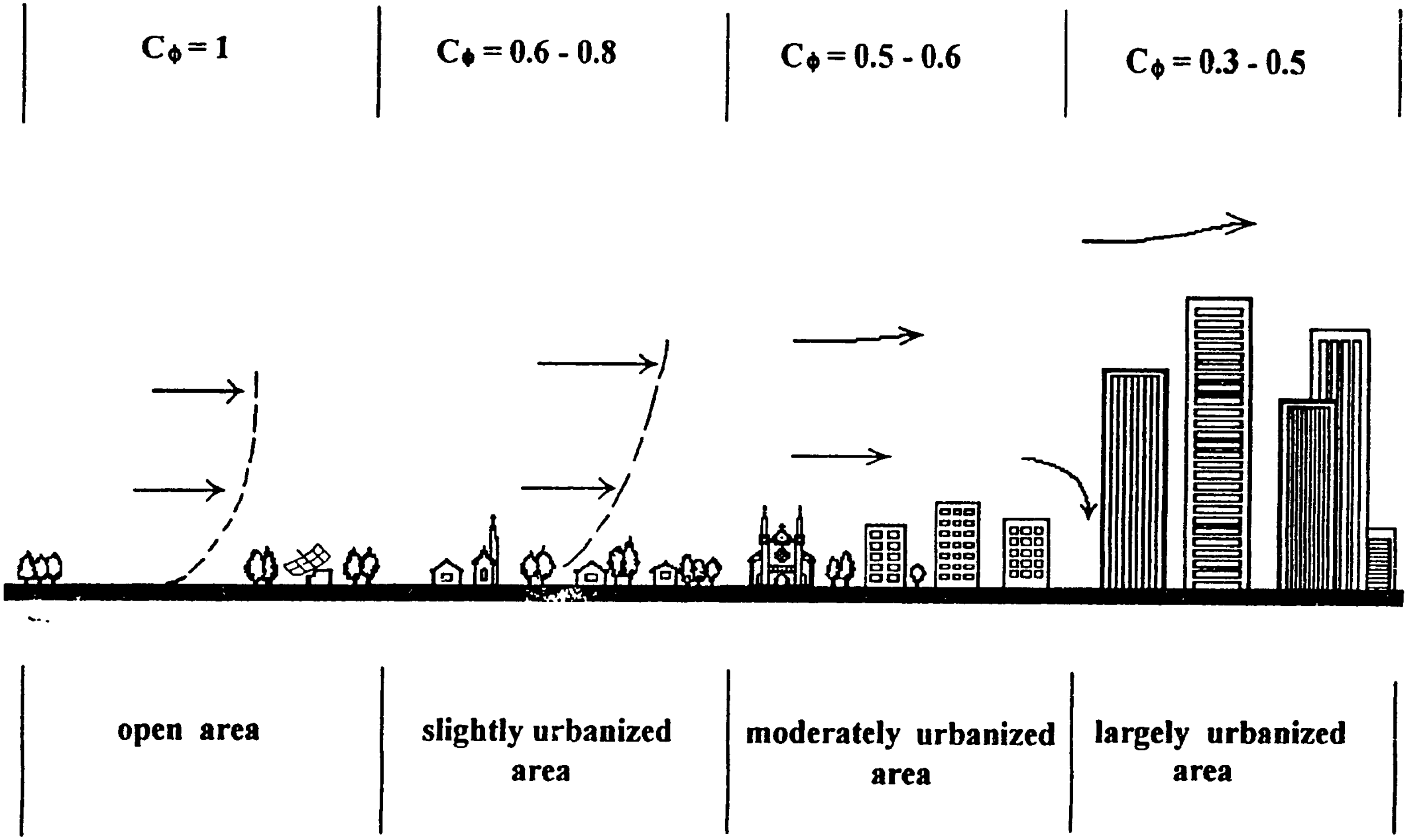


Fig. 4.6 Suggested values of C_ϕ for varying topographic terrains



Chapter 5: Conclusions And Recommendations for Future Work

5.1 Conclusions

Local driving rain exposure on the building facade can be quantified as a tool for building design and maintenance. To achieve the local quantitative driving rain exposure on the building facade, a methodology was developed in this study based on the quantitative relationship developed by Lacy [2]. The quantitative results of driving rain exposure for a specific region are derived by analyzing the local climatological data recorded at that region. These quantitative results represent the general and extreme driving rain exposure condition on the building facade in terms of rain water precipitation, impact intensity, impact frequency and impact duration. Not only the average impact intensity and duration but also the maximum intensity and duration are achieved by this methodology in order to show both long term and short term local driving rain exposure. These quantitative results of driving rain exposure could be used over the existing Driving Rain Index which is non-quantitative in nature.

The quantitative driving rain exposure for 15 important Canadian cities was derived by making use of the climatological data recorded at local meteorological stations. The driving rain parameters, namely, precipitation, intensity, impact frequency and impact duration show that both the degree and characteristics of driving rain exposure vary from city to city. Generally, building facades located in coastal cities suffer a relatively larger precipitation and impact frequency while those located in inland cities may have a larger impact intensity. Since the climatological data used in this application is from the respective local airports, which have almost uniform and plane topographical feature, these quantitative driving rain parameters are useful as a standard local exposure to designers in designing tight building envelope against rain penetration.

Since the local driving rain exposure on a building varies according to the surrounding topographical features, a methodology is developed in this study to establish the local driving rain exposure by amending the standard quantitative results based on the climatological data recorded at the nearby airport. This methodology is verified with a case study for the Montrèal region. The results obtained compare favourably with those derived from the recorded data in the urban area. The degree of exposure to driving rain in the urban area is lower due mainly to the attenuation of the wind speed by the topography. The relationship between the degree of exposure of driving rain in an urban area and that of a suburban climatological station can be represent by the coefficient C_ϕ which reflects the extent of surface roughness of local ground in the direction ϕ. This methodology is useful for preparing DRI and quantitative driving rain exposure for an urban location for which the meteorological data is not available.

5.2 Recommendations for Future Work

The theoretical formulation developed and the results derived in this study could be verified by an experimental observation study on the site. This observational study should include monitoring the amount of driving rain collected in rain gauges mounted on vertical facades of buildings in different regions.

To find the relationship of wetting pattern and the geometry of building facade, it is necessary to test various geometrical configurations of building facades under artificial driving rain condition. This could be achieved by using the derived quantitative driving rain results in a wind tunnel with rain drop simulation.

The impact of driving rain on the durability of building materials could be achieved by tests using the quantitative rain results. Also, design details of building to reduce the wetting area caused by driving rain is suggested as a potential study.

It is necessary to verify the proposed relationship of driving rain exposure between urban area and surrounding suburban area by analyzing more meteorological data from various climatological stations in different topographies at various cities, although the relationship proposed compares favourably with the actual situation in the Montreal region. It is recommended to apply the relationship derived to more cases in other cities. The proposed attenuation coefficient C_ϕ for different topographical features could be verified from a driving rain simulation experiment in a wind tunnel.

In order to achieve a more accurate relationship of driving rain exposure between urban and suburban areas, it is also suggested to find more evidences of rain fall attenuation in the urban area due to the urban effects. The order of variation of rain fall in different geographical environments must be determined before further relationship could be established.

A quantitative driving rain map for Canada can be derived by using this quantitative method to supplement more information over the existing Driving Rain Map of Canada. Nation wide, over 300 meteorological stations record simultaneously the hourly wind speed, wind direction and rainfall data. This record can be used to prepare a map to describe the quantitative driving rain exposure on the facades of a building for most locations in Canada.

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Appendix: I. Deduction of Coefficient C_θ

The relation between wind speed at meterological station (U_m) and wind speed at a certain height in an urban area (U_u) can be represented as

$$U_u = C_\theta U_m \tag{A0}$$

C_θ is the attenuation coefficient.

By using the Logarithmic Law, the wind speed at an effective height z is given as

$$U_{(z)} = \frac{1}{k} u_* \ln\frac{z}{z_o} \tag{A1}$$

where

$$z = z_g - z_d \tag{A2}$$

$$z_d = \bar{H} - \frac{Z_o}{k} \tag{A3}$$

and from Similarity Model [22],

$$\frac{u_{*1}}{u_{*2}} = (\frac{z_{o1}}{z_{o2}})^{0.0706} \tag{A4}$$

where k is Von Karman's constant (≈0.4), $U_{(z)}$ is the wind speed at an effective height z, u_* is the shear velocity of the flow, z_0 is the roughness length, z_g is the height above ground, z_d is a height known as the zero plane displacement, $\overline{H}$ is the general roof-top level, z_{01} and z_{02} are the roughness lengths for the two terrains and u_{*1} and u_{*2} are the friction velocities for two terrains.

Assuming that the height above the ground $z_g = \overline{H}+h$.

By substituting eq.(A3) in eq.(A2),

$$z = z_g - \overline{H} + \frac{z_o}{k}$$

$$i.e., z = \overline{H} + h - \overline{H} + \frac{z_o}{k}$$

$$z = h + \frac{z_o}{k} \tag{A5}$$

By using eq.(A5) with appropriate values of surface roughness length (z_0) for different terrains [22], the effective height for different locations is computed.

For example, for centers of large cities, $z = h + 2.5/0.4$

$$\text{i.e., } z = h + 6.25 \tag{A6a}$$

Similarly,

For densely built-up suburbs, towns $z = h + 2.5$ (A6b)

For sparsely built-up suburbs $z = h + 0.75$ (A6c)

From eq.(A1), the shear velocity of the wind at a height of 10m (usual height at which all the meteorological data is recorded) is calculated as:

$$u_* = \frac{k\ U_{(z)}}{\ln\frac{z}{z_o}}$$

Considering the value of $z_0 = 0.025$m [22],

$$u_* = \frac{0.4\ x\ \underline{Meteorological\ data\ collected\ at\ a\ height\ of}\ 10\ m}{\ln\frac{10}{0.025}}$$

$$i.e., u_* = 0.06676\ U_m \qquad \text{(A7)}$$

where U_m is the wind speed recorded at meteorological station.

By substituting eq.(A7) in eq.(A4), the friction velocity for terrain 2 (i.e., centers of large cities) is given as

$$u_{*2} = \frac{u_{*1}}{\left(\frac{z_{o1}}{z_{o2}}\right)^{0.0706}}$$

$$u_{*2} = \frac{0.06676\ U_m}{(\frac{0.025}{2.5})^{0.0706}}$$

$$u_{*2} = 0.09241\ U_m \tag{A8}$$

The wind speed at an effective height of $\overline{\text{H}}$+h is obtained by substituting the eq.(A7) into eq.(A1) and is given as

$$U_{(\overline{H}+h)} = \frac{1}{0.4}\ 0.09241\ U_m \ln\frac{z}{2.5} \tag{A9}$$

The value of z can be taken from the eqs.(A6a) or (A6b) or (A6c) depending on the type of topographical feature. For example, for an effective height of 15 m above the general roof-top level, in centers of large cities, z = 15+6.25, i.e., 21.25m. Then eq.(A9) becomes

$$U_{(\overline{H}+15)} = 0.4944\ U_m \tag{A10}$$

Hence, the attenuation coefficient Cθ is 0.4944 for this category. Similarly, the values of C_θ for different categories have been calculated and given in table 4.1.

Appendix II: Quantitative Results of Driving Rain Exposure on The Directional Vertical Surfaces for Various Canadian Cities

Figures A1 to A15 show the average monthly driving rain precipitation and summation value on a vertical wall in each direction for 15 cities. Figures A16 to A30 show the average monthly impact frequency of driving rain and the summation value of the impact frequency on a vertical wall in each direction for 15 cities. Figures A31 to A45 show the values of maximum intensity and mean maximum intensity of driving rain and the maximum values of both from the available monthly values for each direction. Figures A46 to A60 show the maximum and mean maximum impact durations of driving rain and the maximum values of both from the available monthly values for each direction.

Fig. A1 Driving rain precipitation on a vertical surface (mm) - Calgary

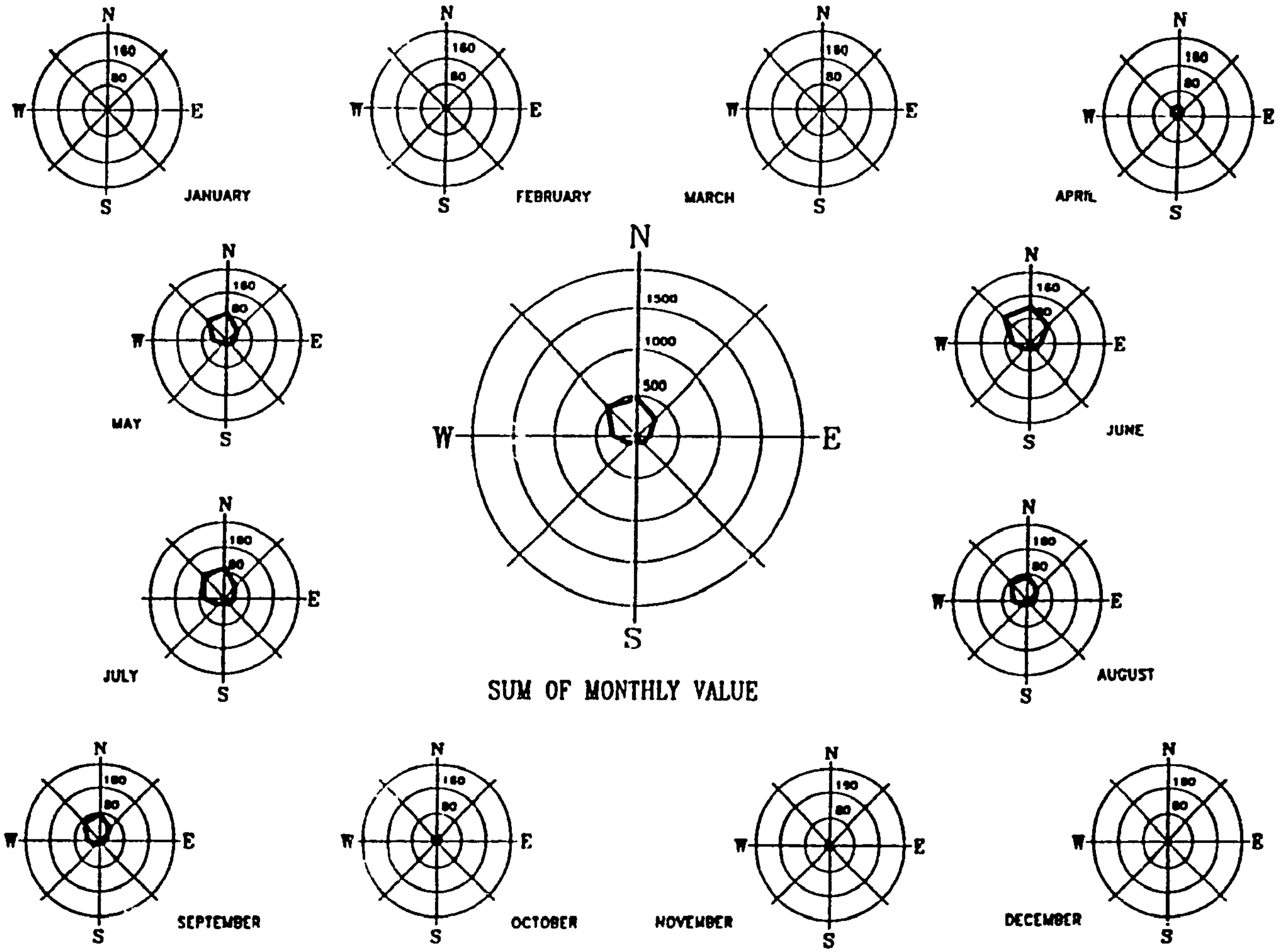


Fig. A2 Driving rain precipitation on a vertical surface (mm) - Edmonton

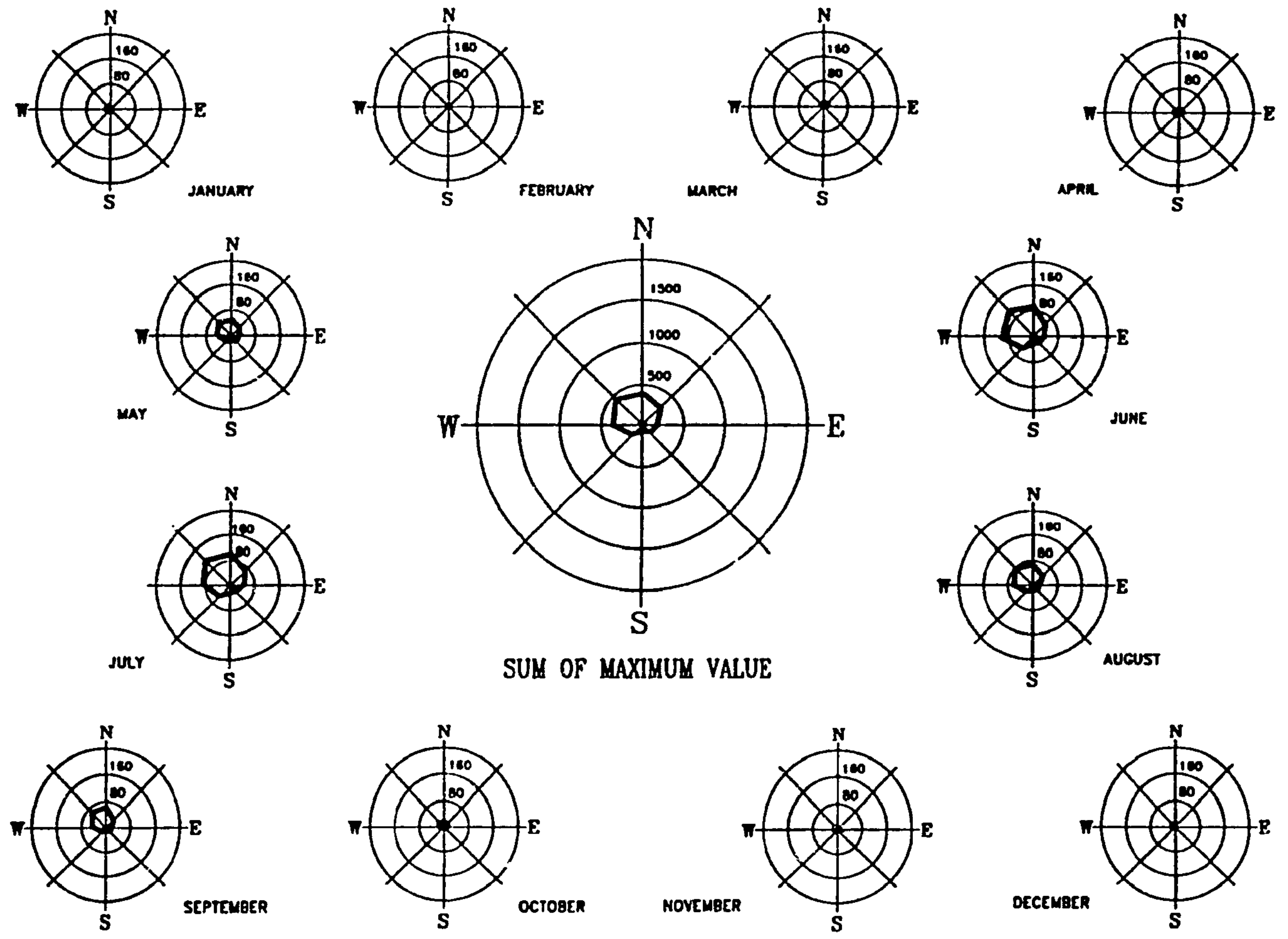


Fig. A3 Driving rain precipitation on a vertical surface (mm) - Fredericton

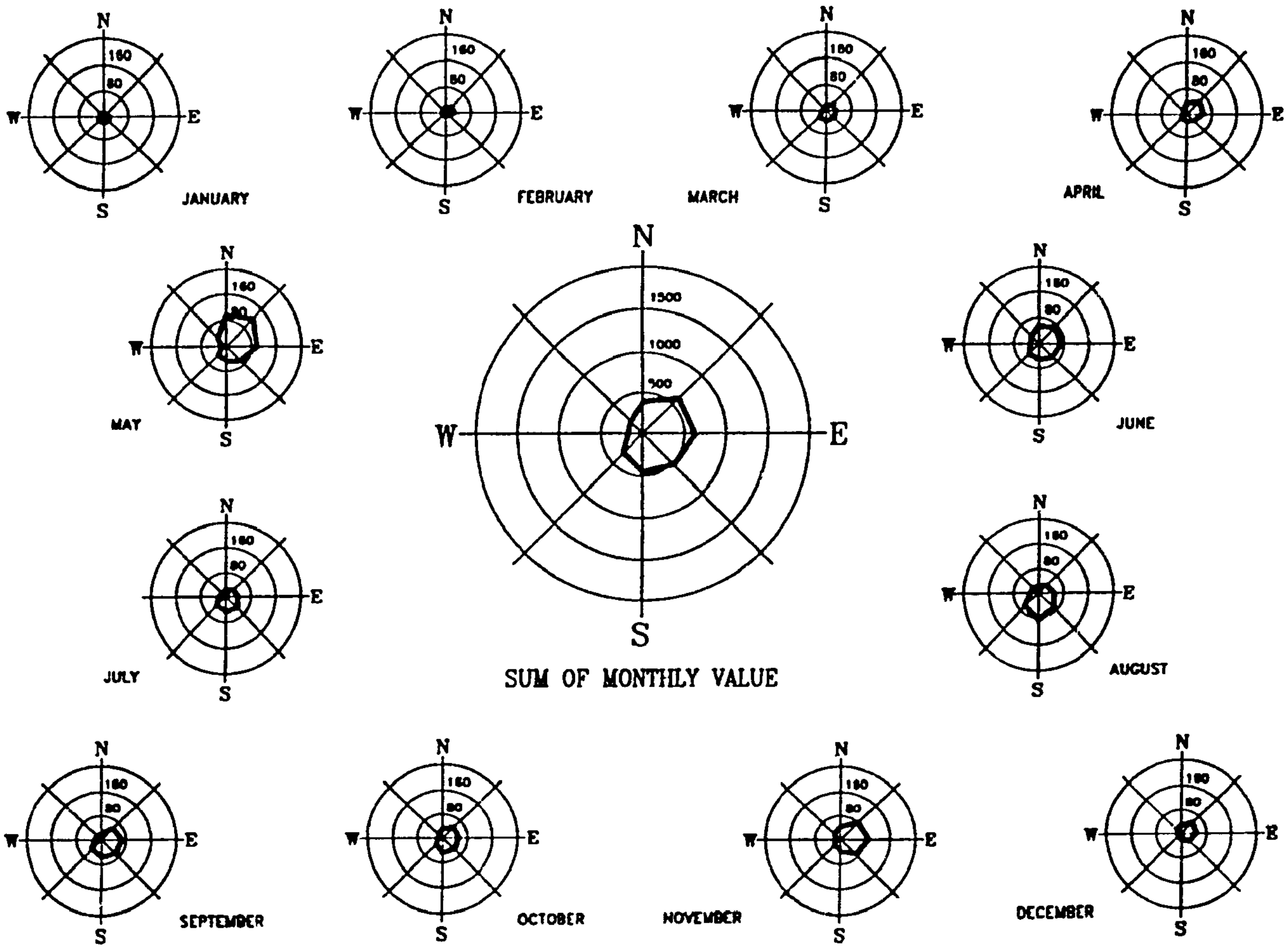


Fig. A4 Driving rain precipitation on a vertical surface (mm) - Halifax

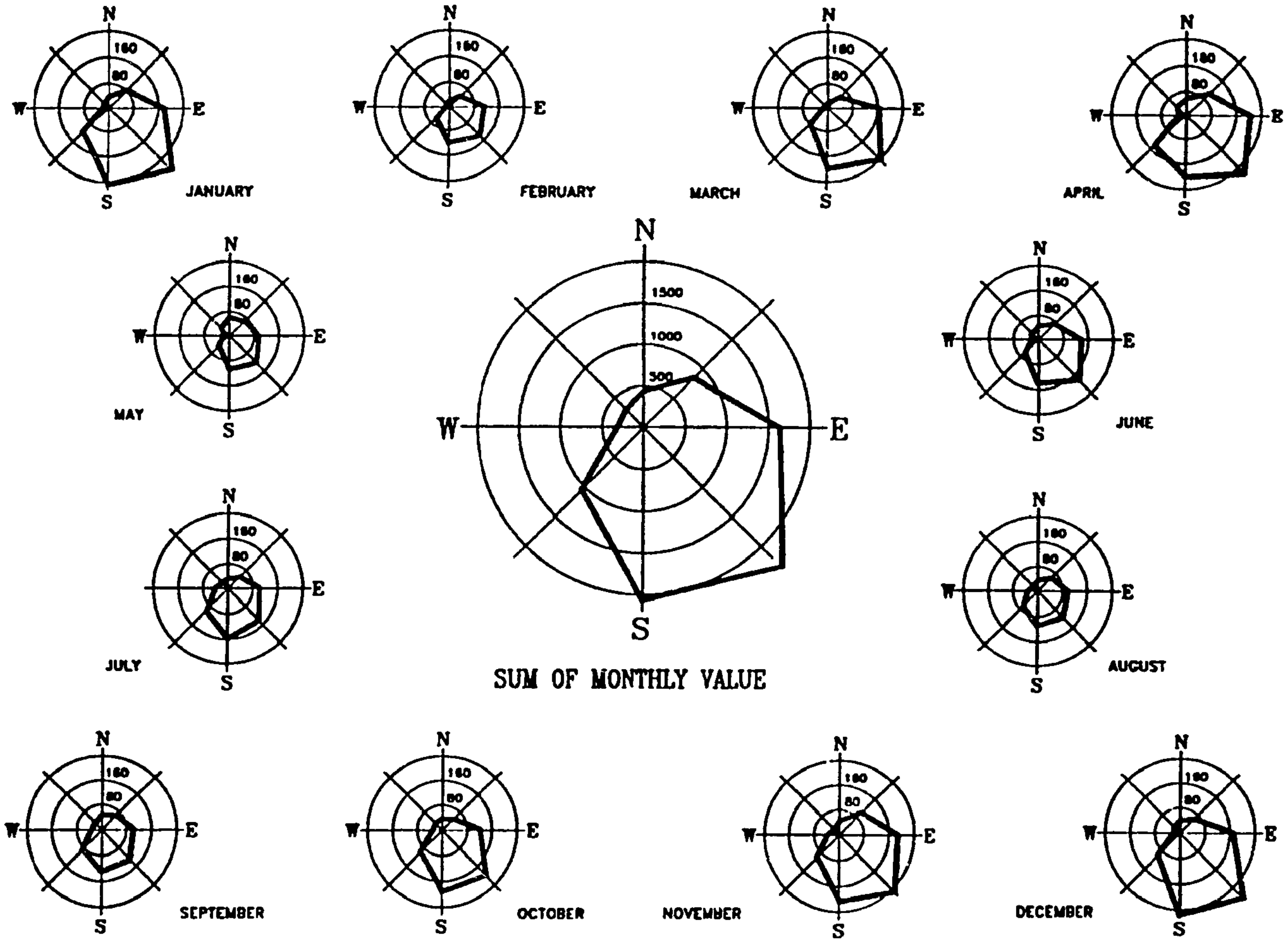


Fig. A5 Driving rain precipitation on a vertical surface (mm) - Montréal

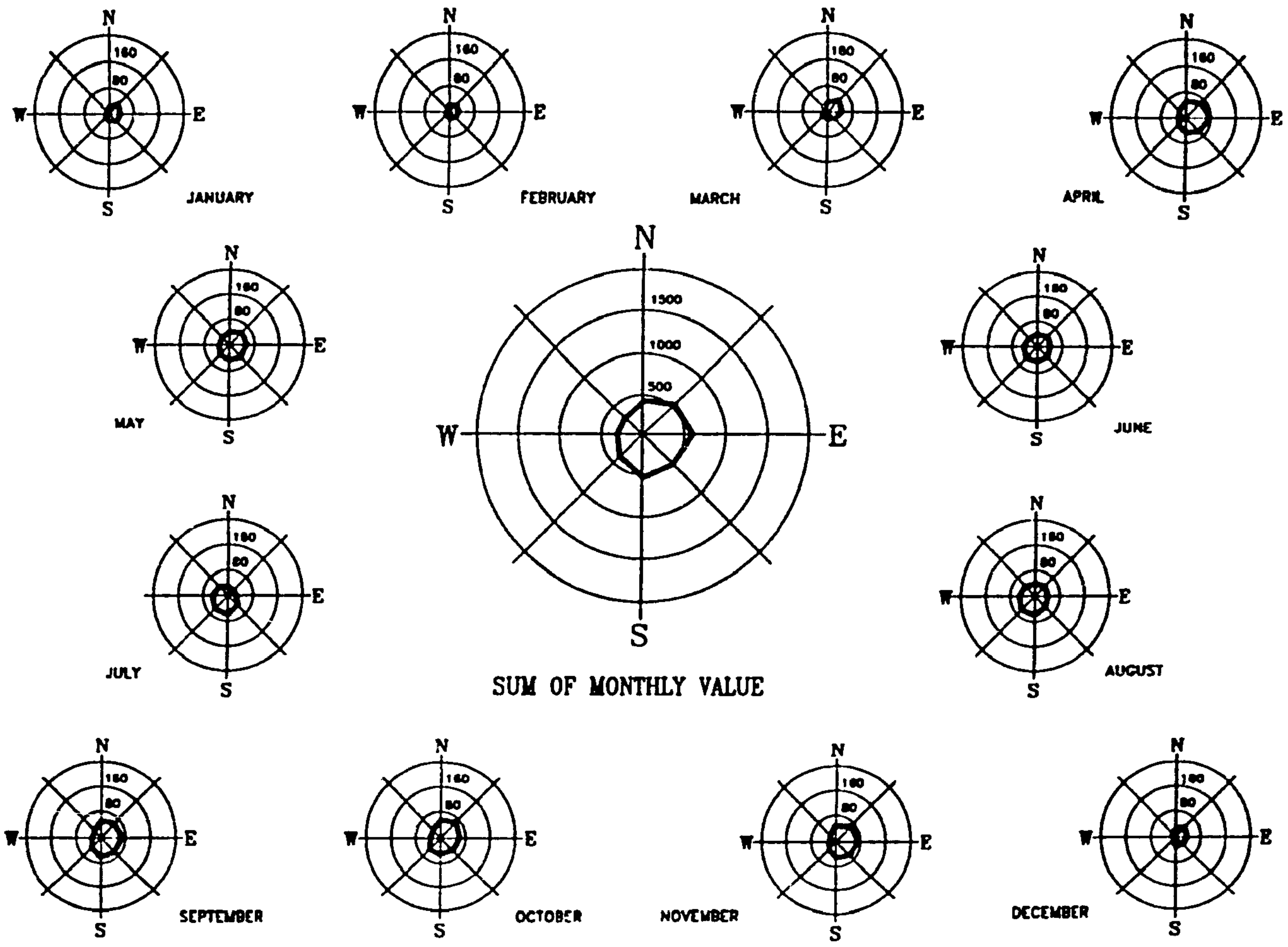


Fig. A6 Driving rain precipitation on a vertical surface (mm) - Ottawa

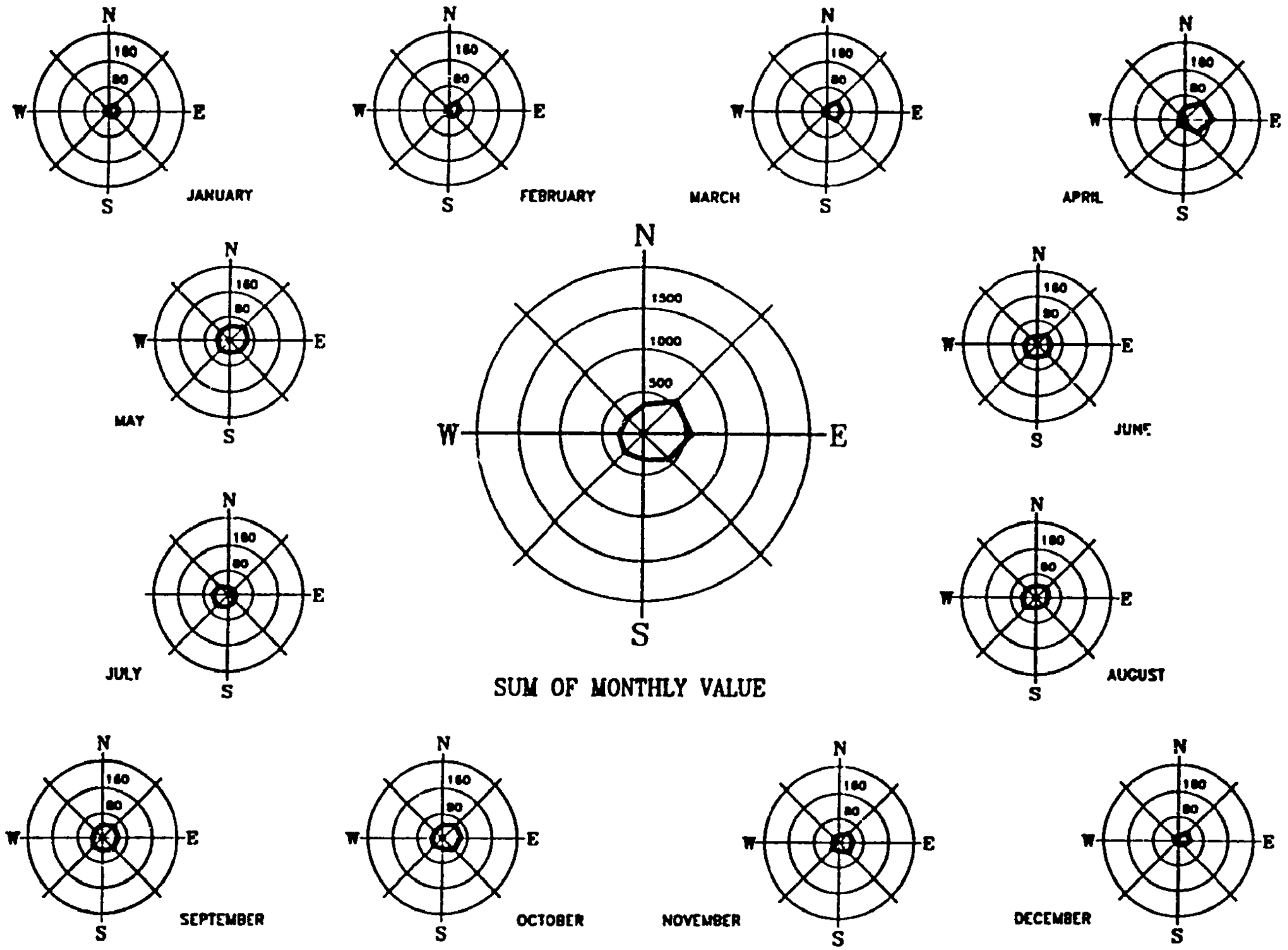


Fig A7 Driving rain precipitation on a vertical surface (mm) - Quebec City

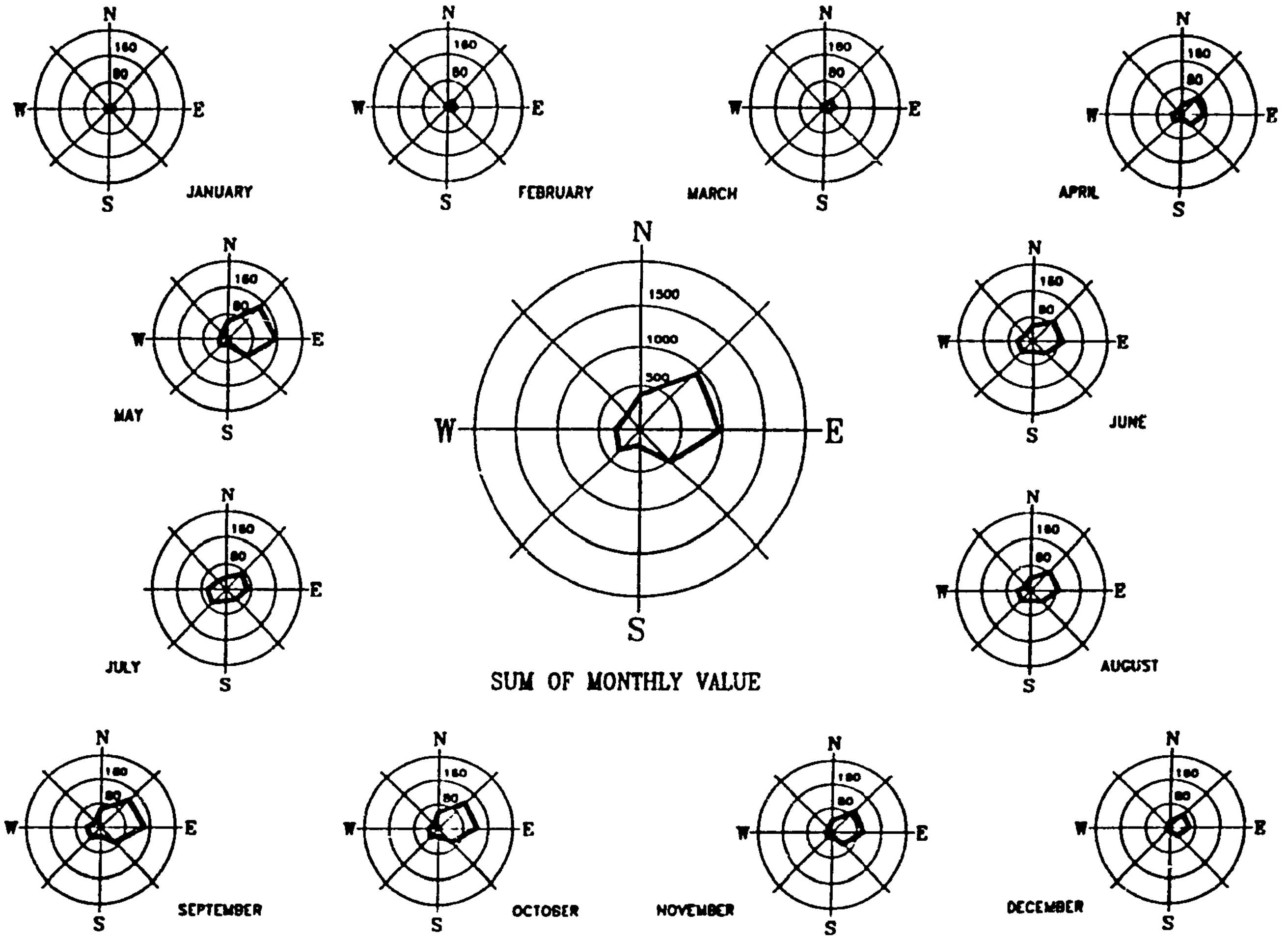


Fig. A8 Driving rain precipitation on a vertical surface (mm) - Regina

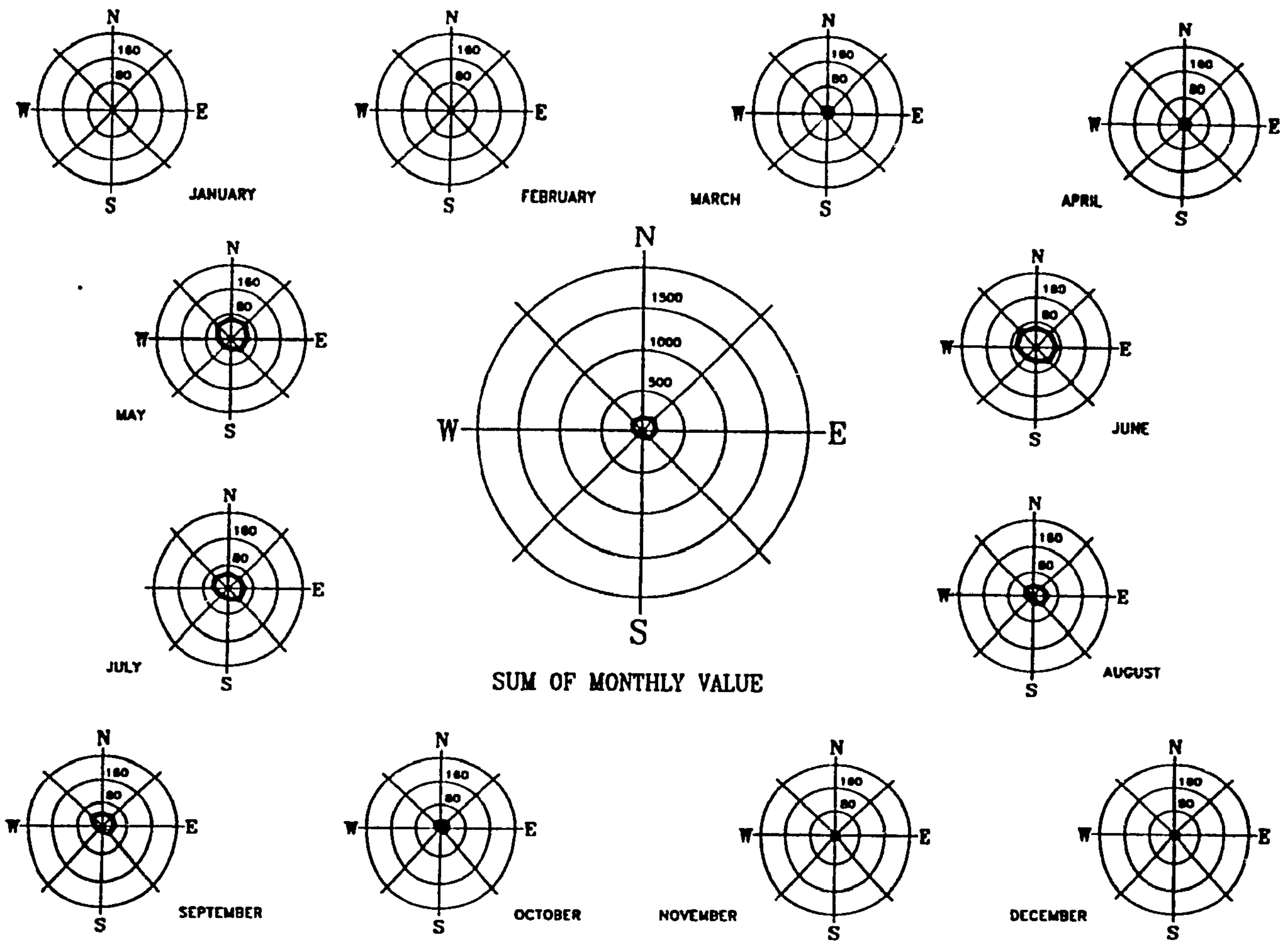


Fig. A9 Driving rain precipitation on a vertical surface (mm) - Saskatoon

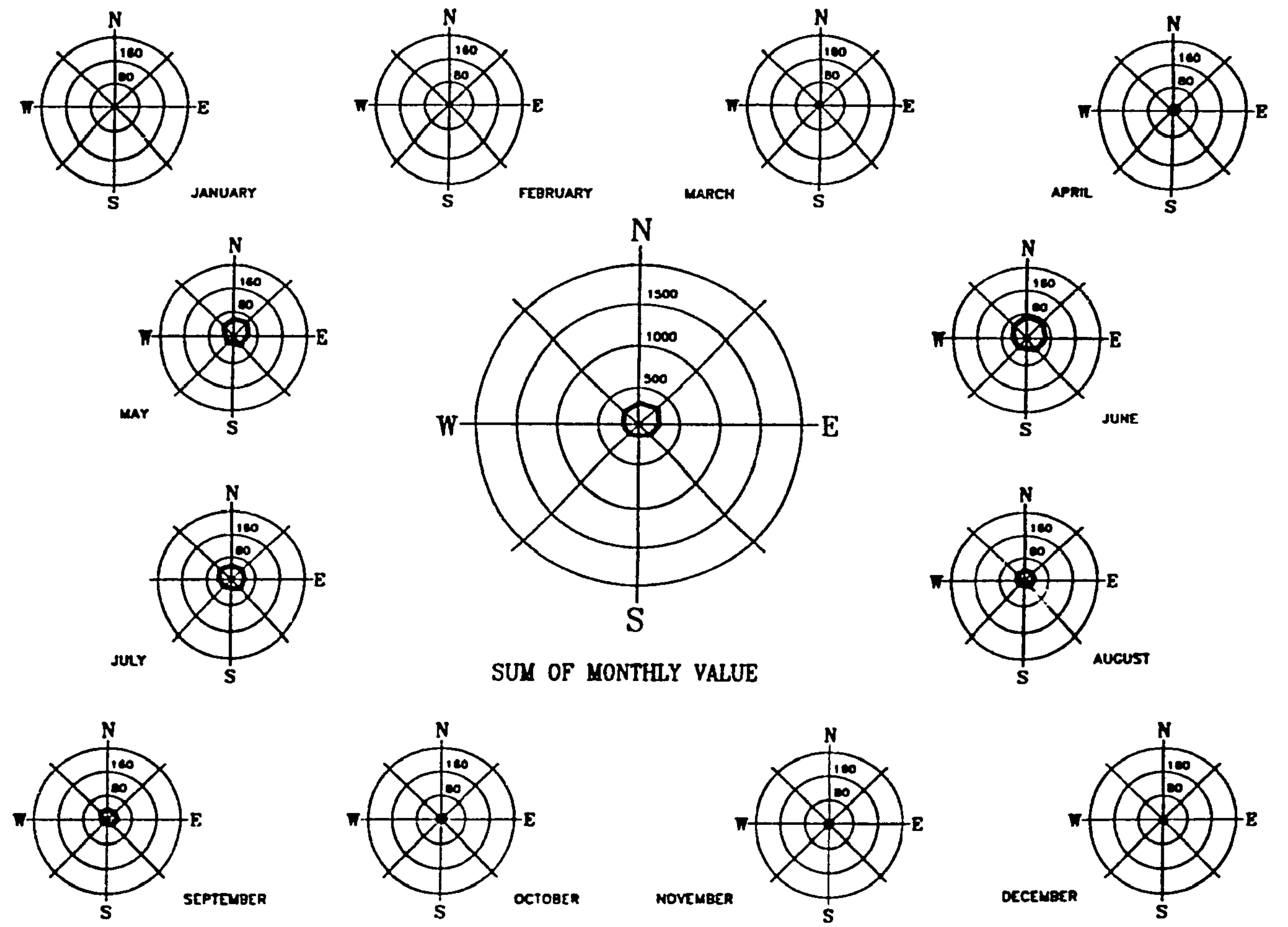


Fig. A10 Driving rain precipitation on a vertical surface (mm) - St. John's

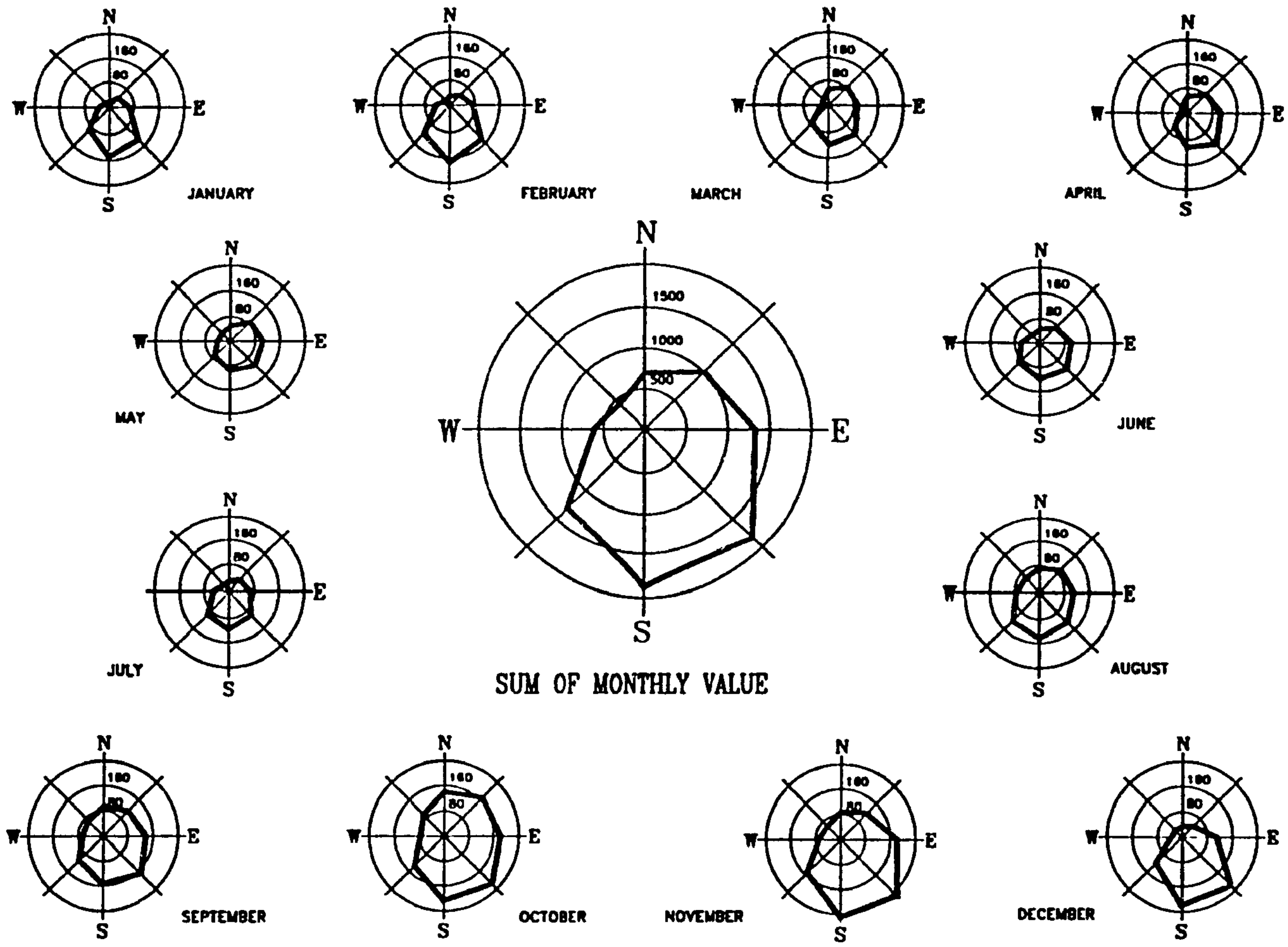


Fig. A11 Driving rain precipitation on a vertical surface (mm) - Toronto

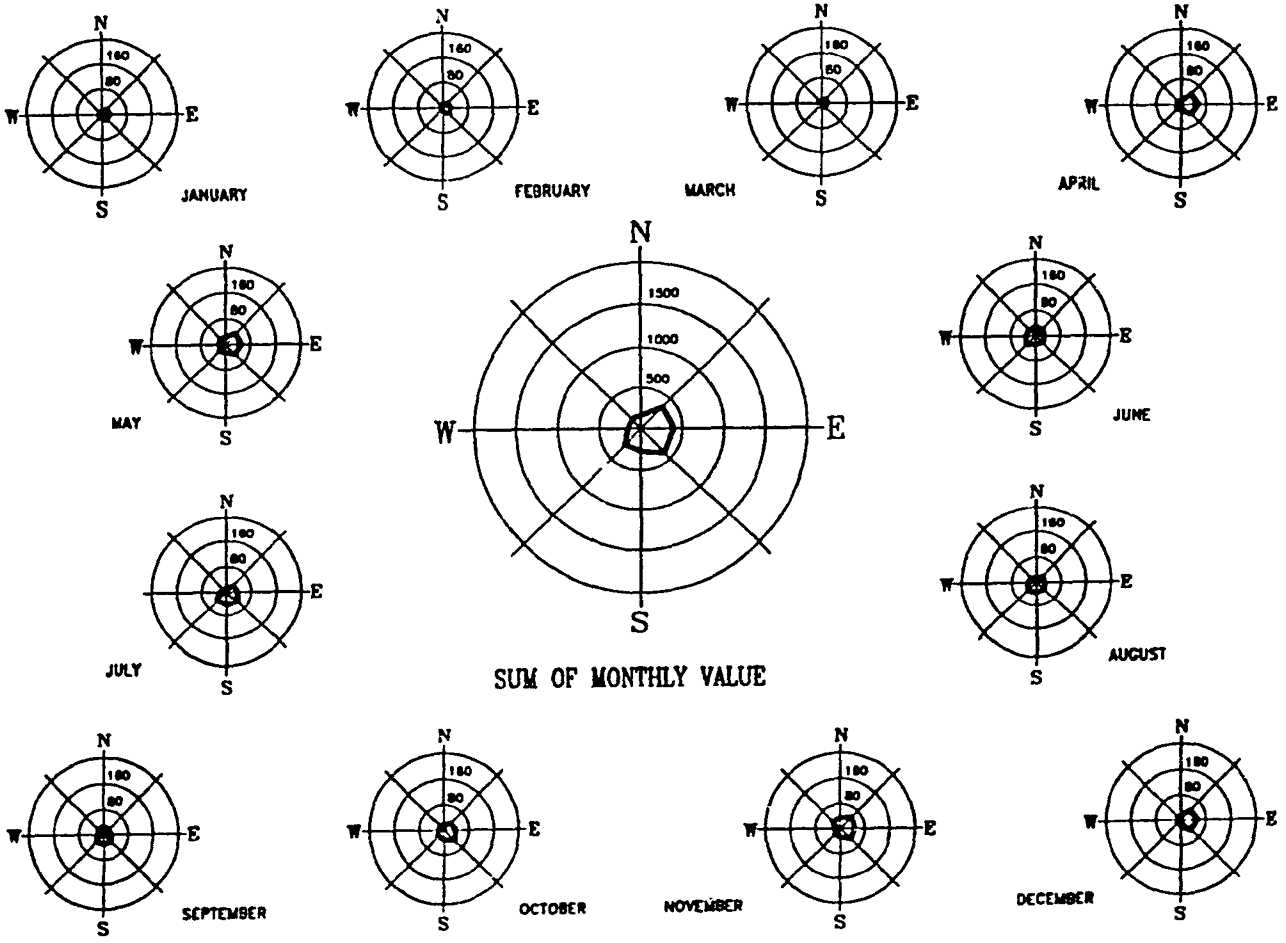


Fig. A12 Driving rain precipitation on a vertical surface (mm) - Vancouver

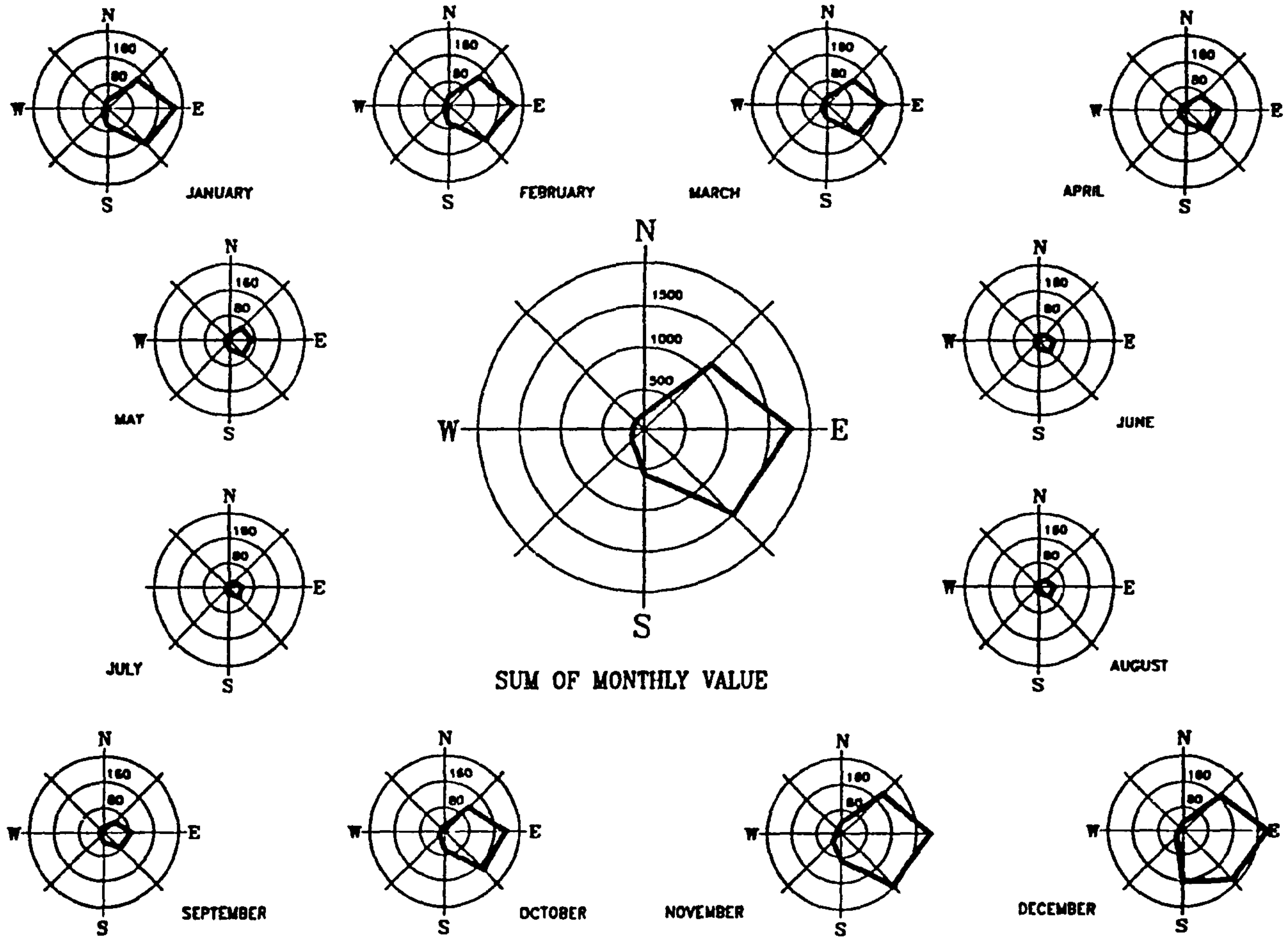


Fig. A13 Driving rain precipitation on a vertical surface (mm) - Victoria

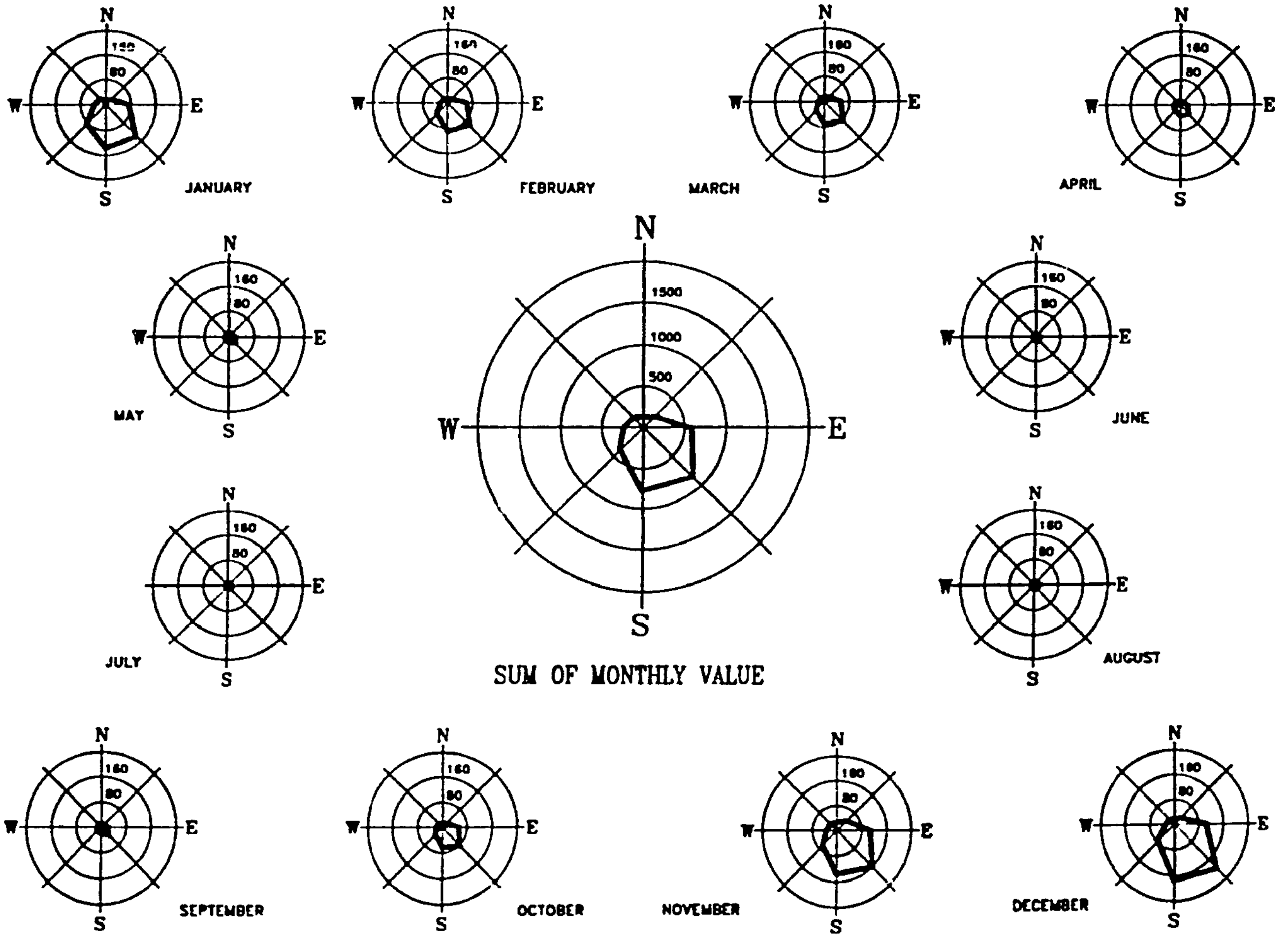


Fig. A14 Driving rain precipitation on a vertical surface (mm) - Winnipeg

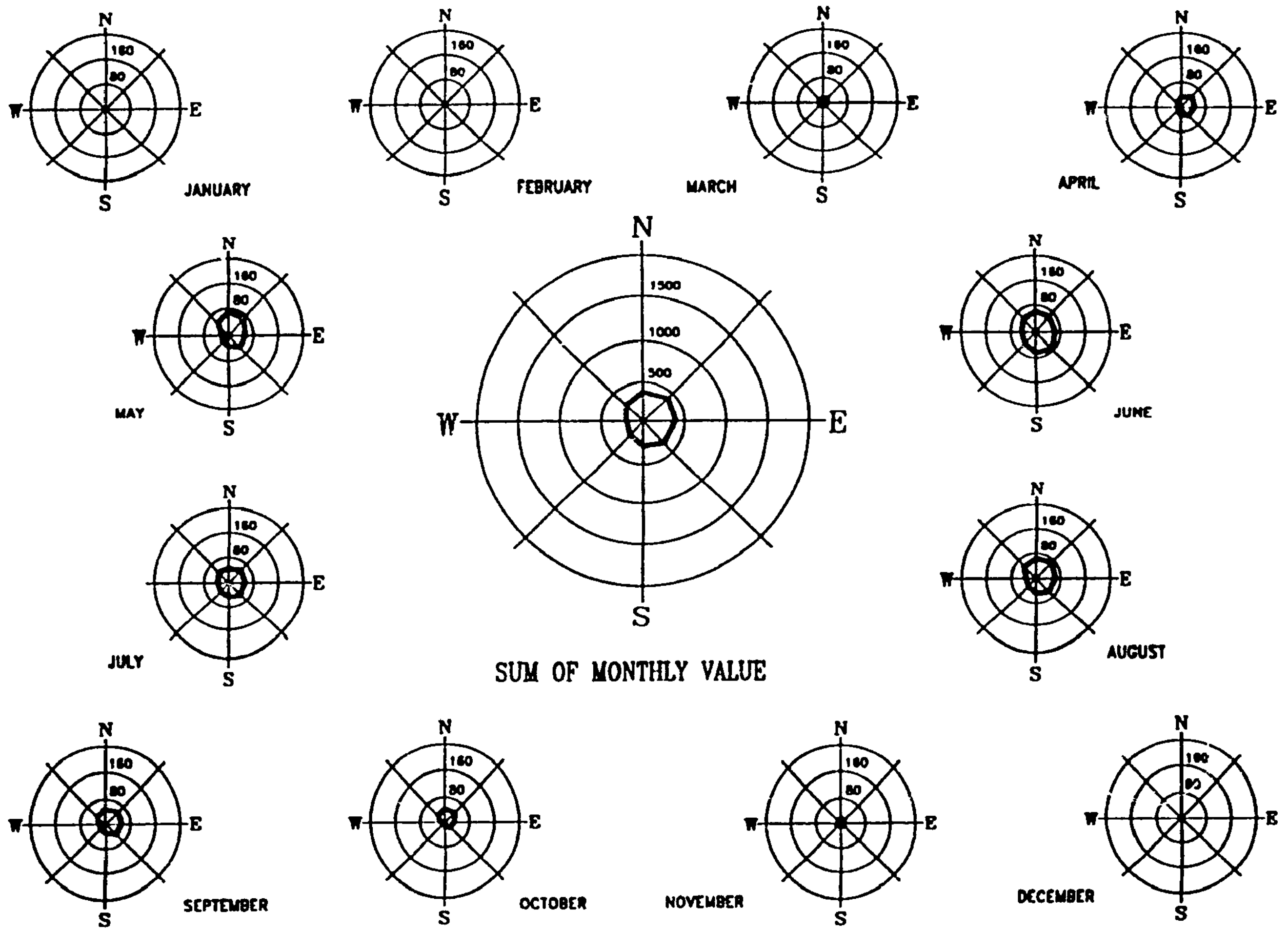


Fig. A15 Driving rain precipitation on a vertical surface (mm) - Yellowknife

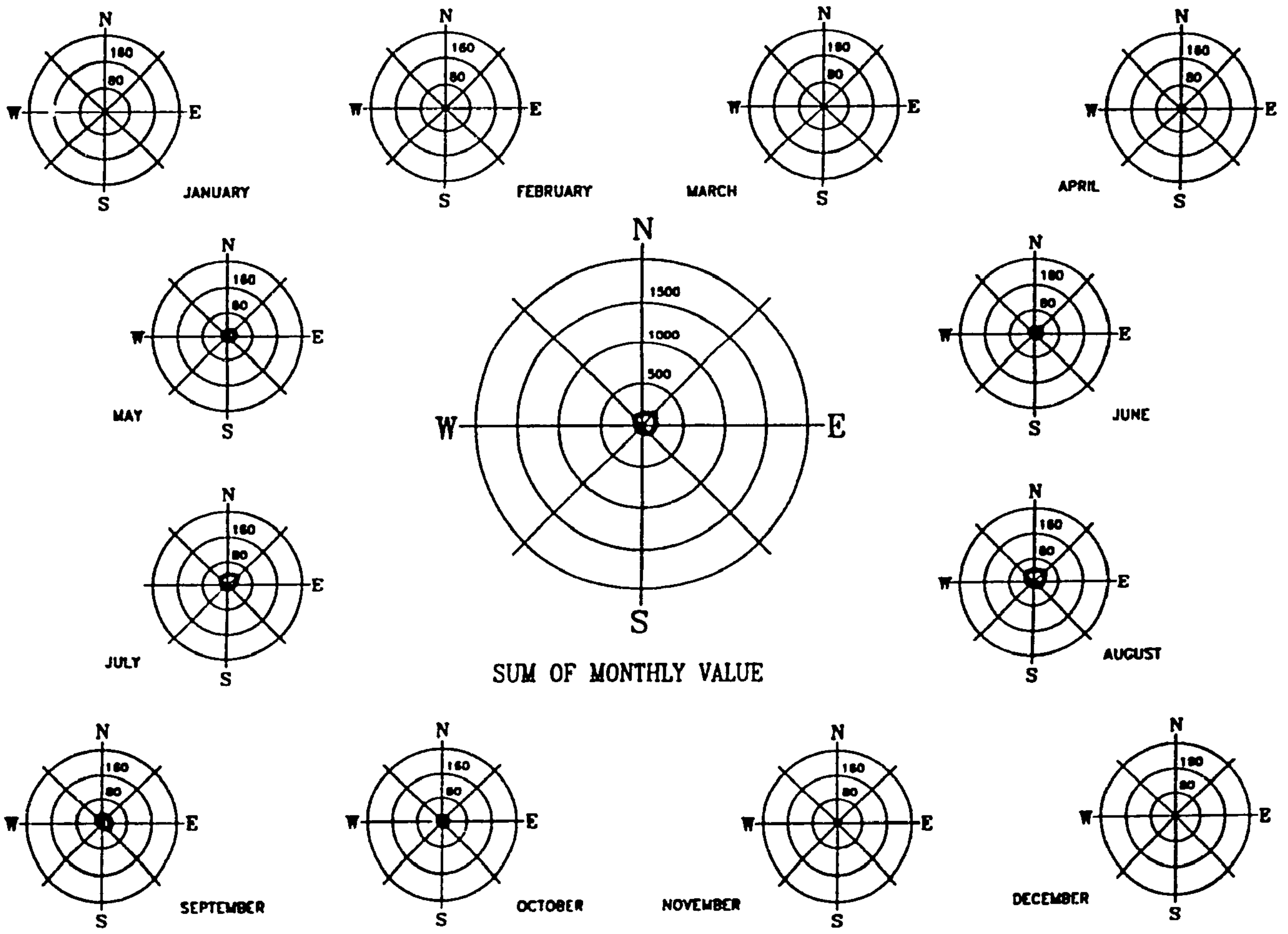


Fig. A16 Driving rain impact frequency for a vertical surface (hr) - Calgray

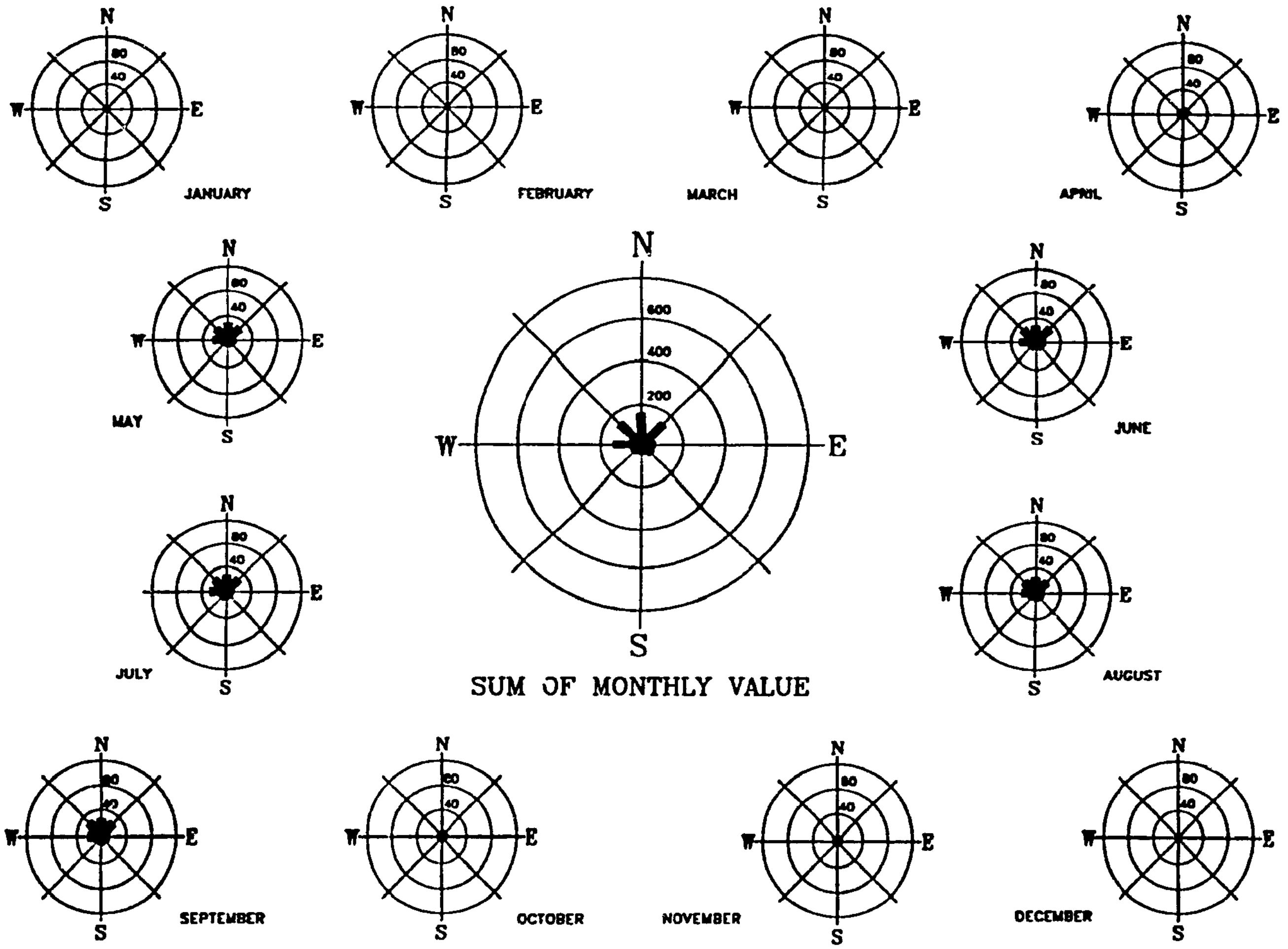


Fig. A17 Driving rain Impact frequency for a vertical surface (hr) - Edmonton

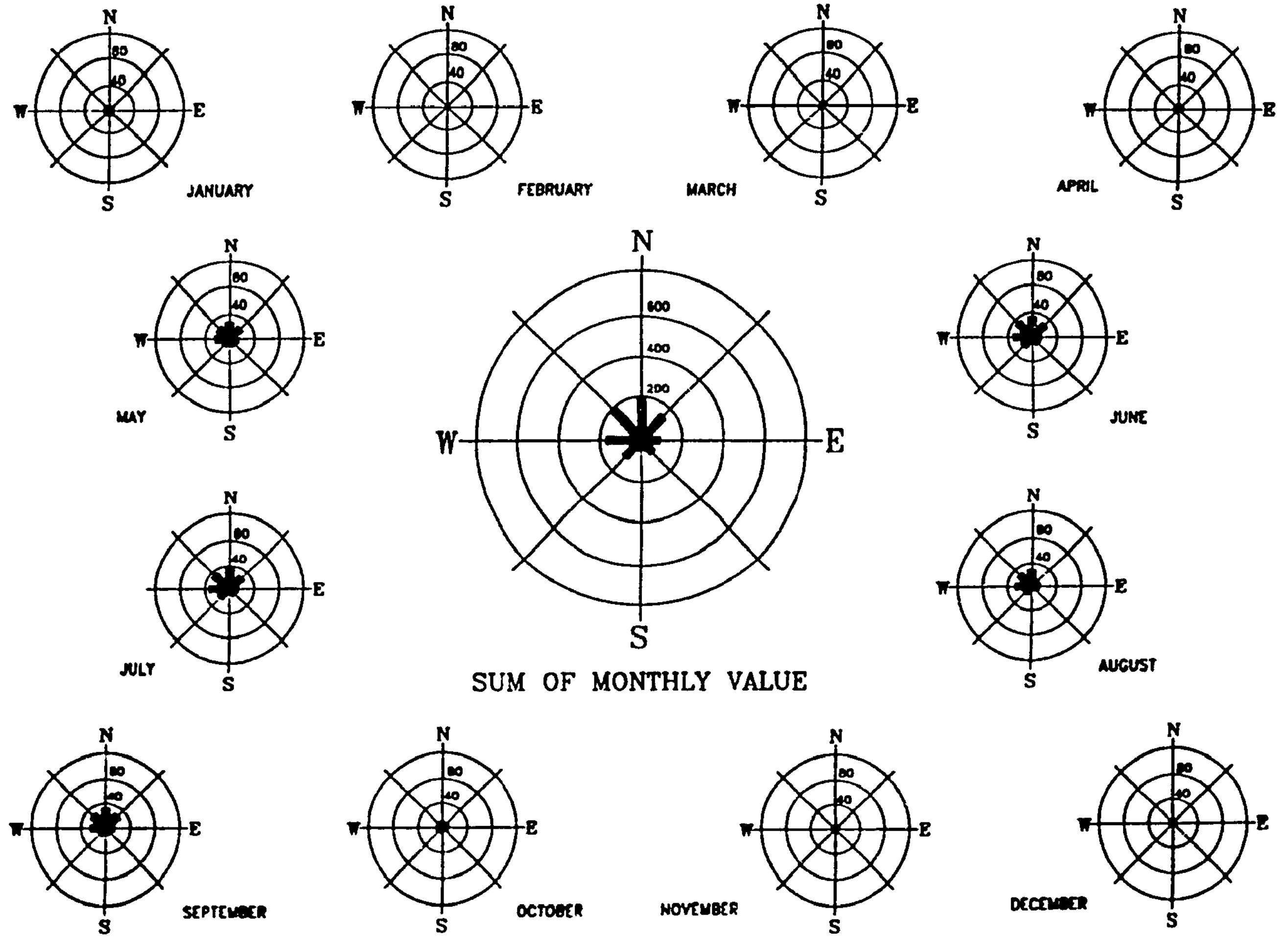


Fig. A18 Drivign rain impact frequency for a vertical surface (hr) - Fredericton

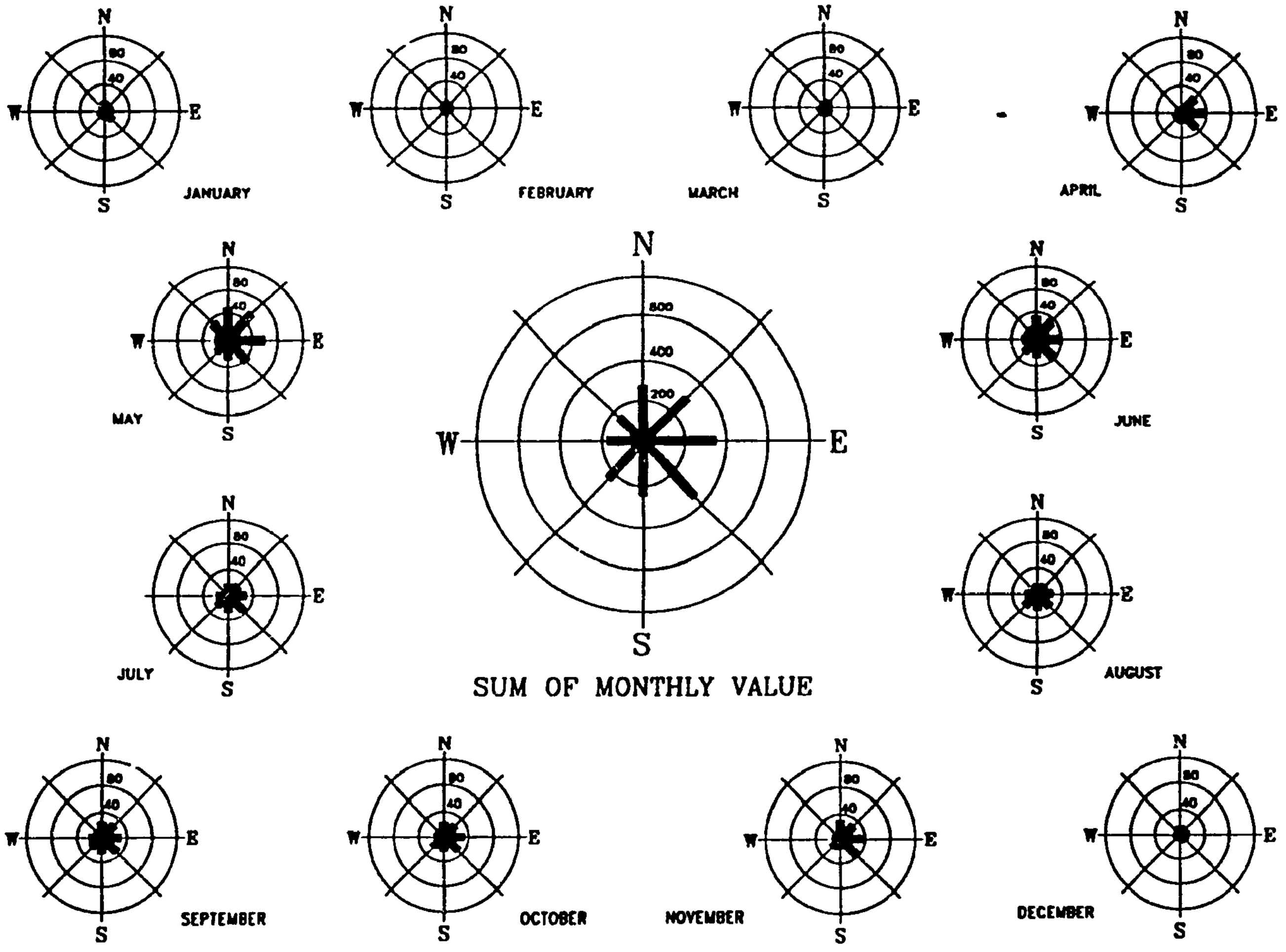


Fig. A19 Driving rain impact frequency for a vertical surface (hr) - Halifax

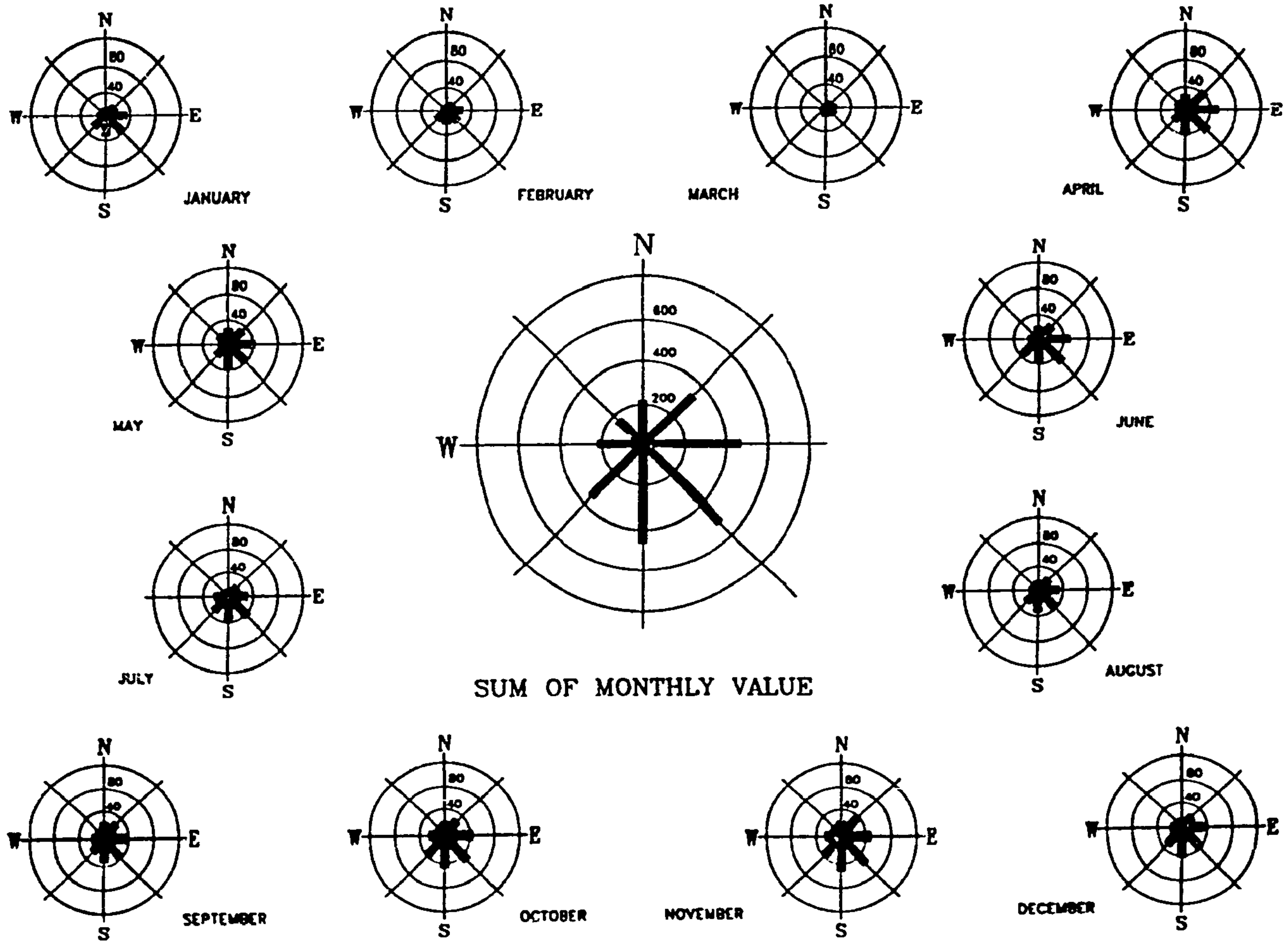


Fig. A20 Driving rain impact frequency for a vertical surface (hr) - Montréal

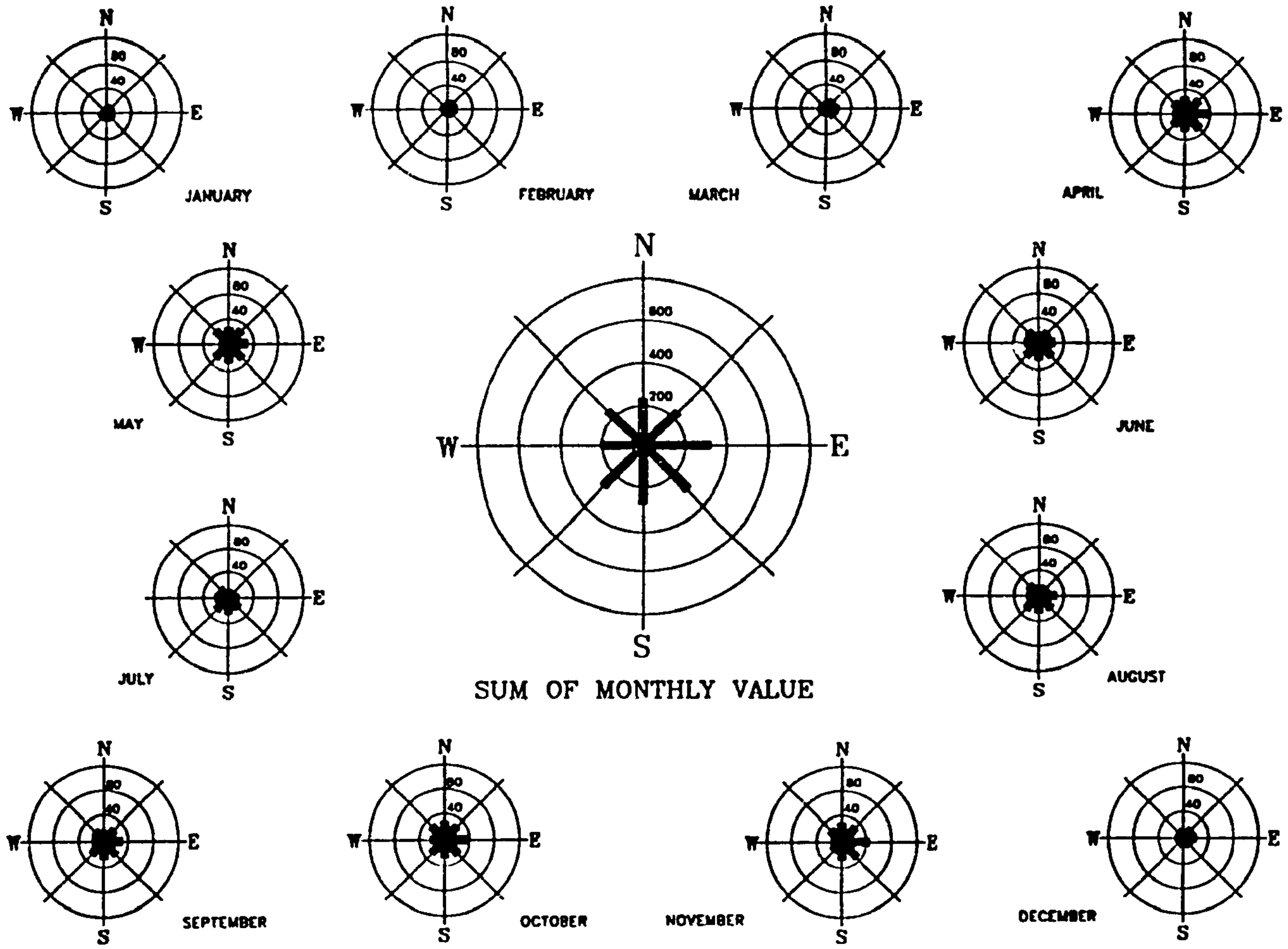


Fig. A21 Driving rain impact frequency for a verticla surface (hr) - Ottawa

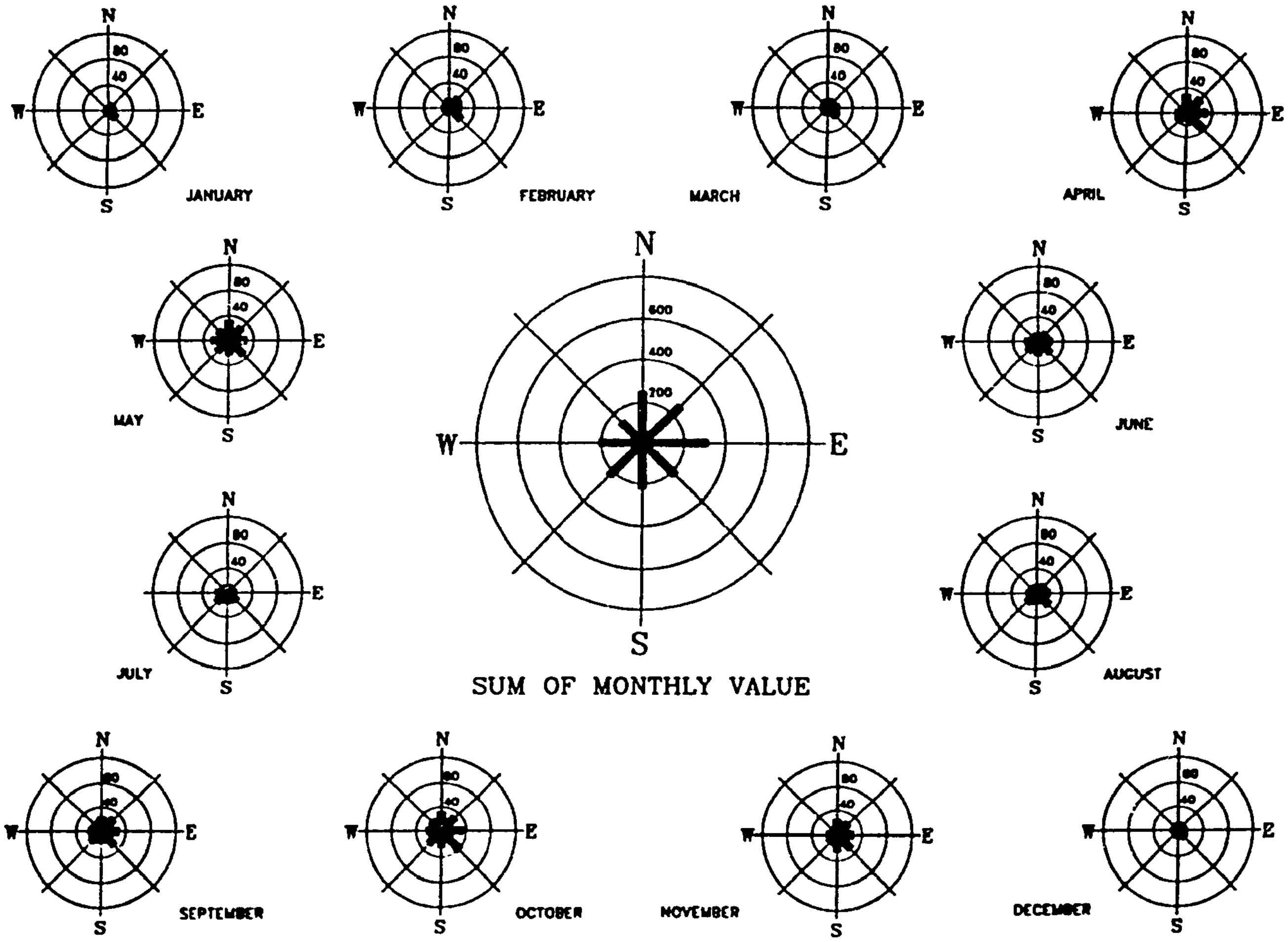


Fig. A22 Driving rain impact frequency for a vertical surface (hr) - Quebec City

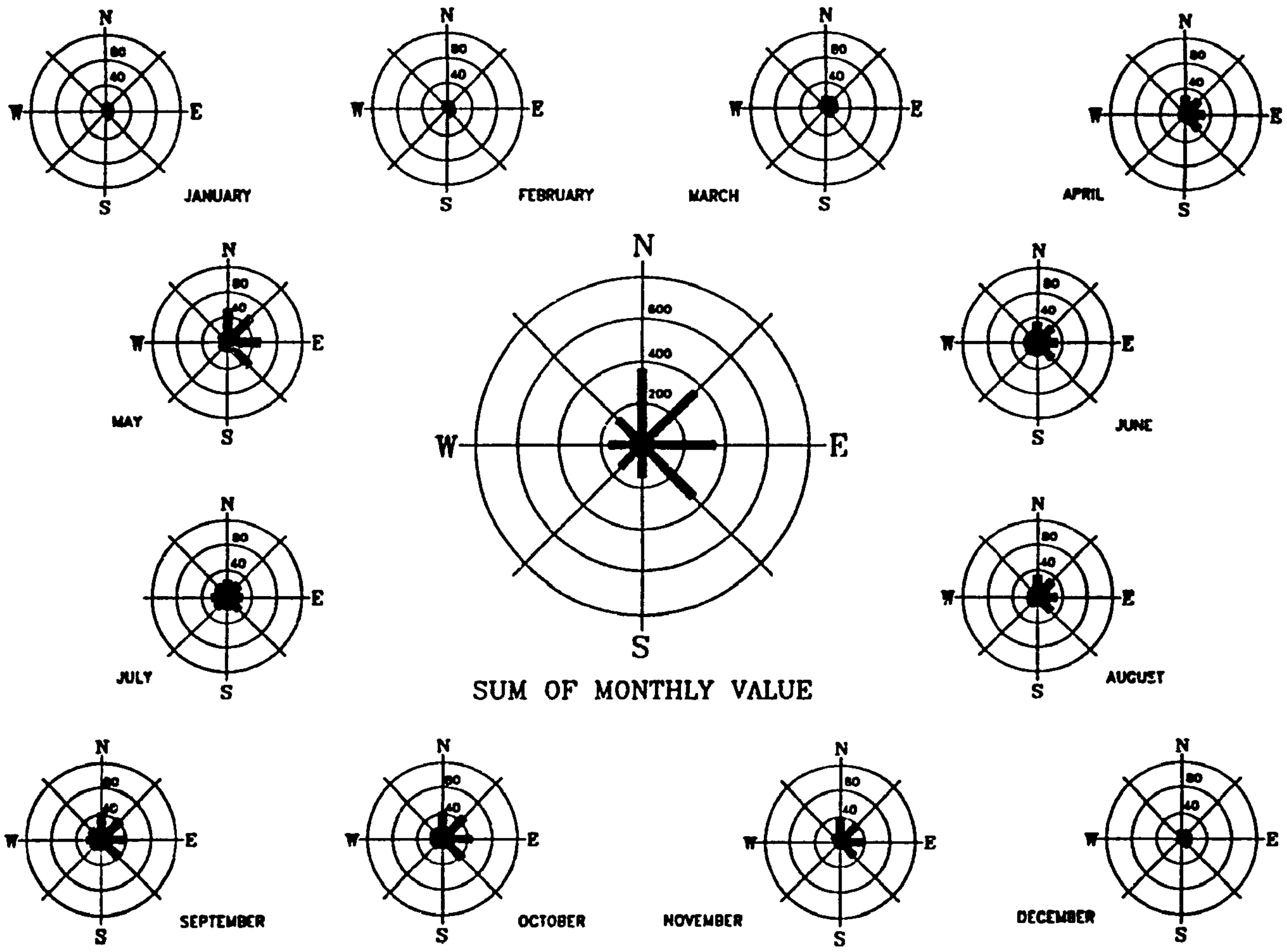


Fig. A23 Driving rain impact frequency for a vertical surface (hr) - Regina

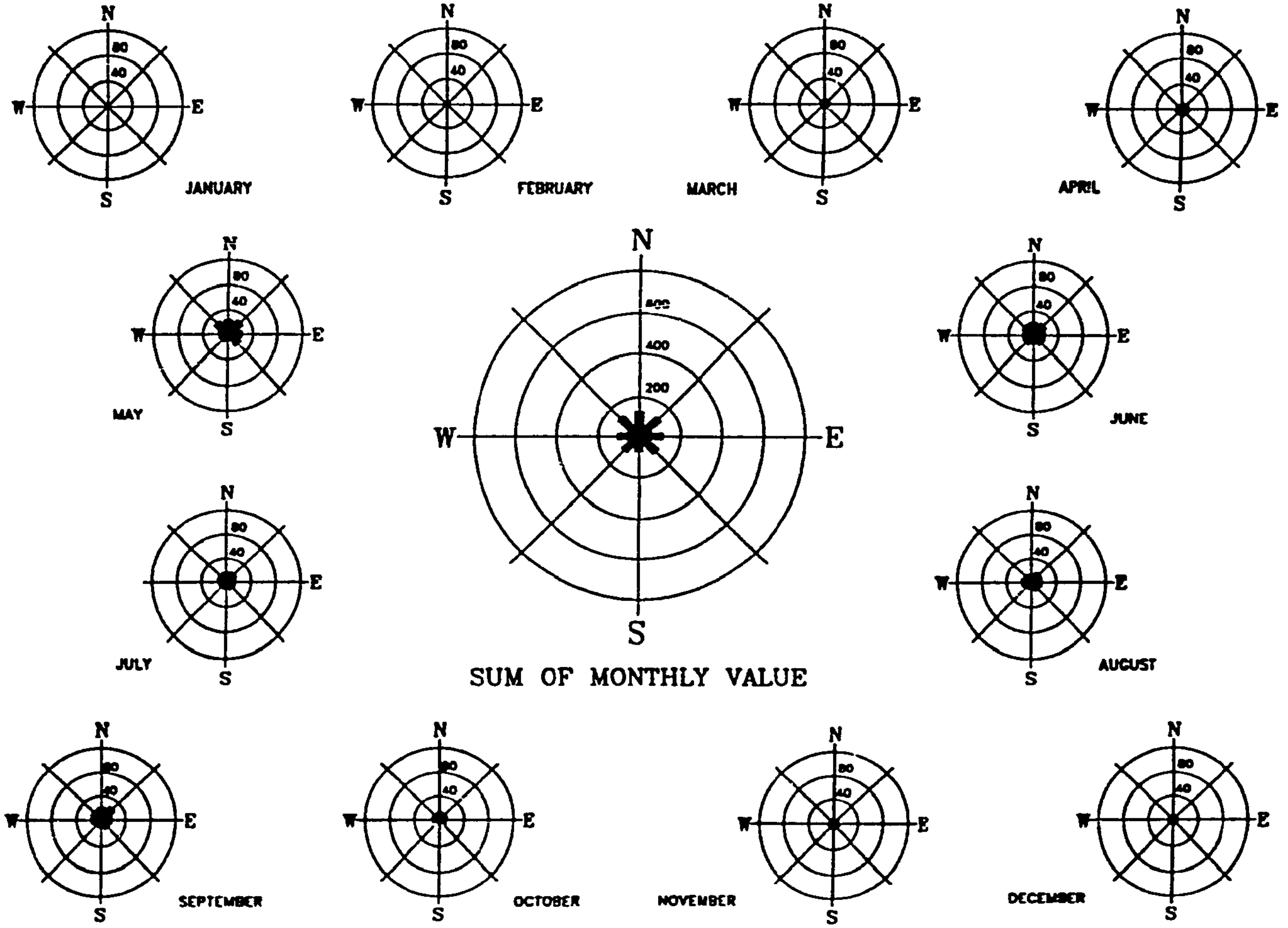


Fig. A24 Driving rain impact frequency for a verticla surface (hr) - Saskatoon

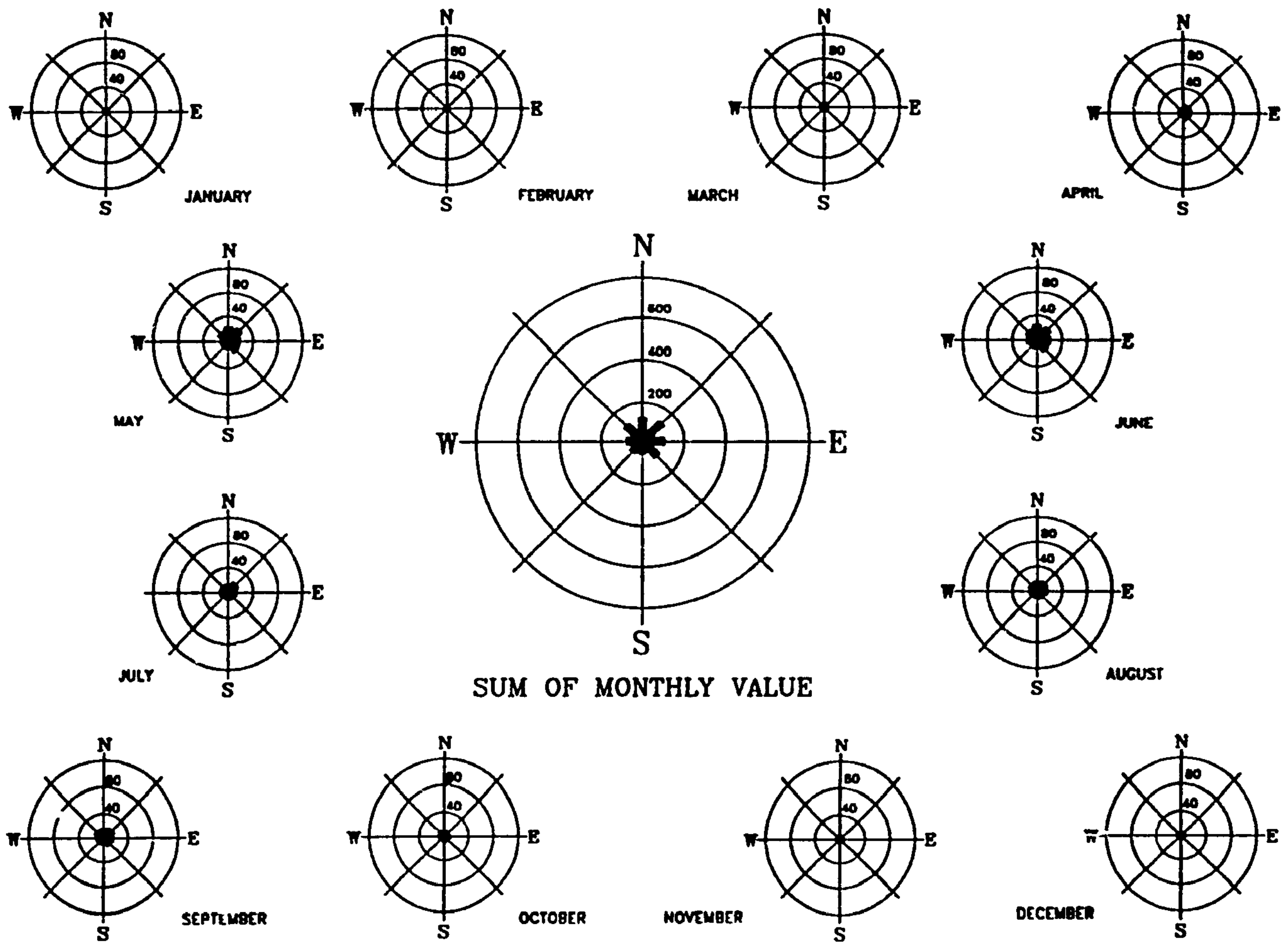


Fig. A25 Driving rain impact frequency for a vertical surface (hr) - St. John's

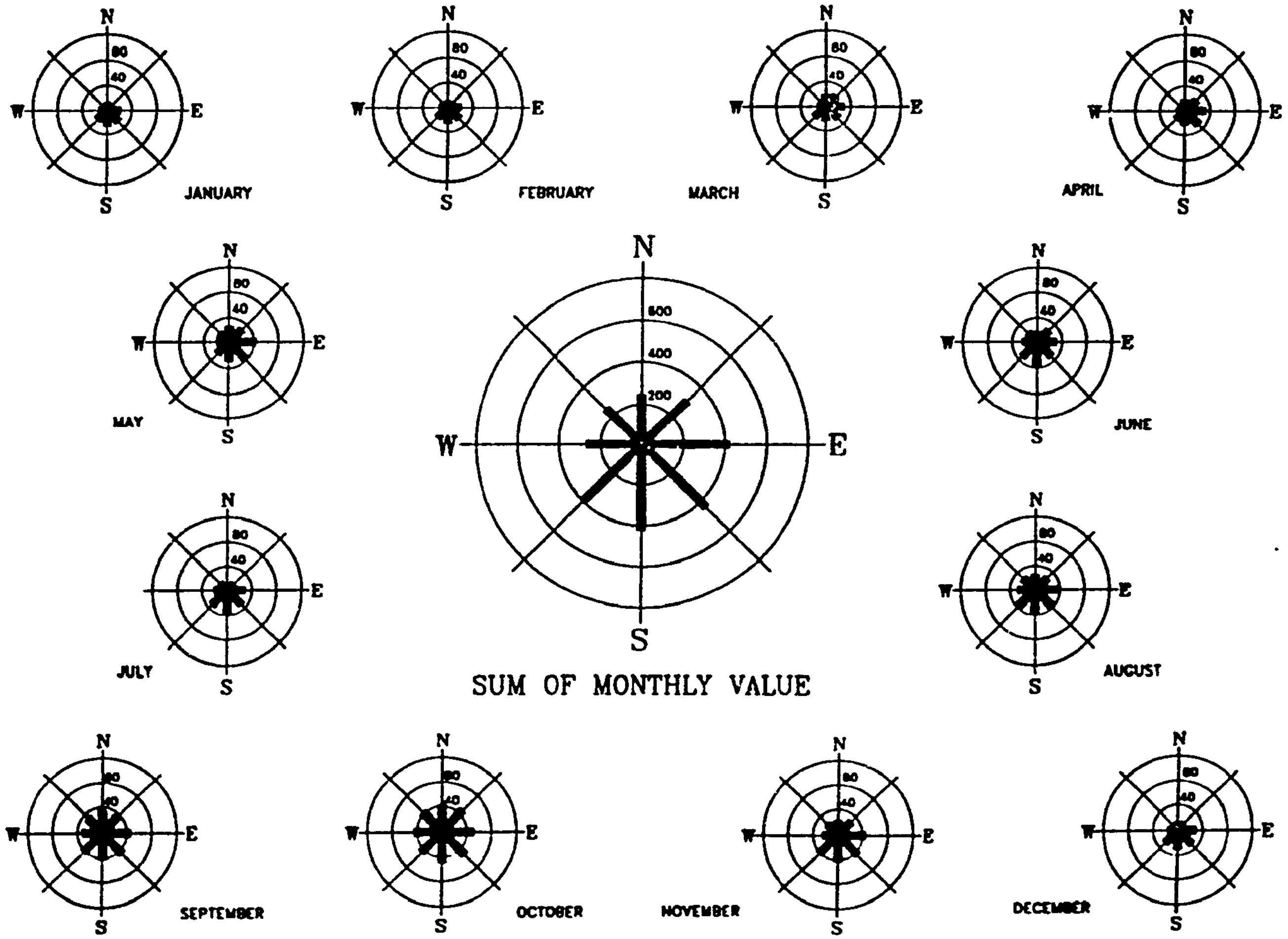


Fig. A26 Driving rain impact frequency for a vertical surface (hr) - Toronto

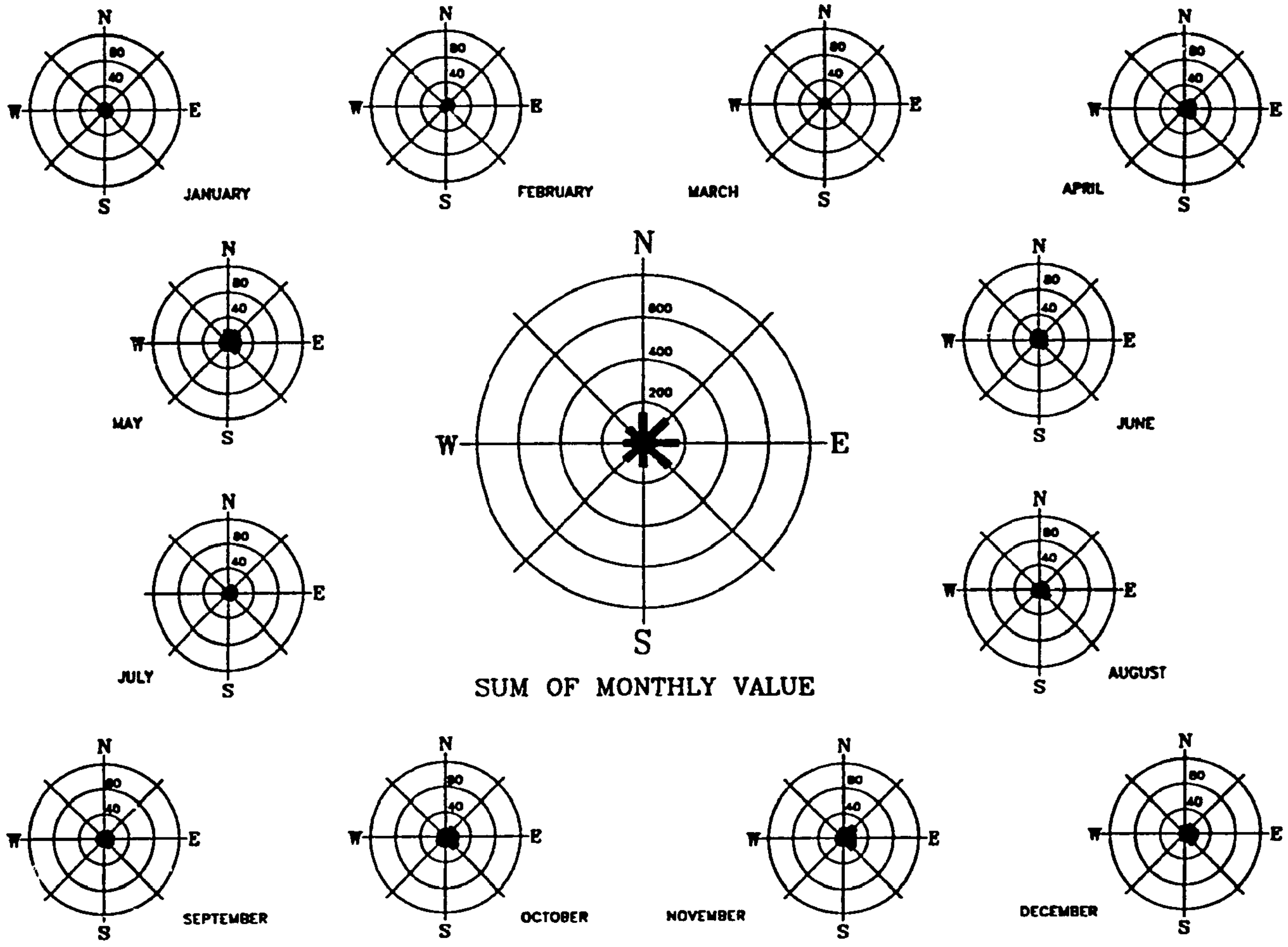


Fig. A27 Driving rain impact frequency for a verticla surface (hr) - Vancouver

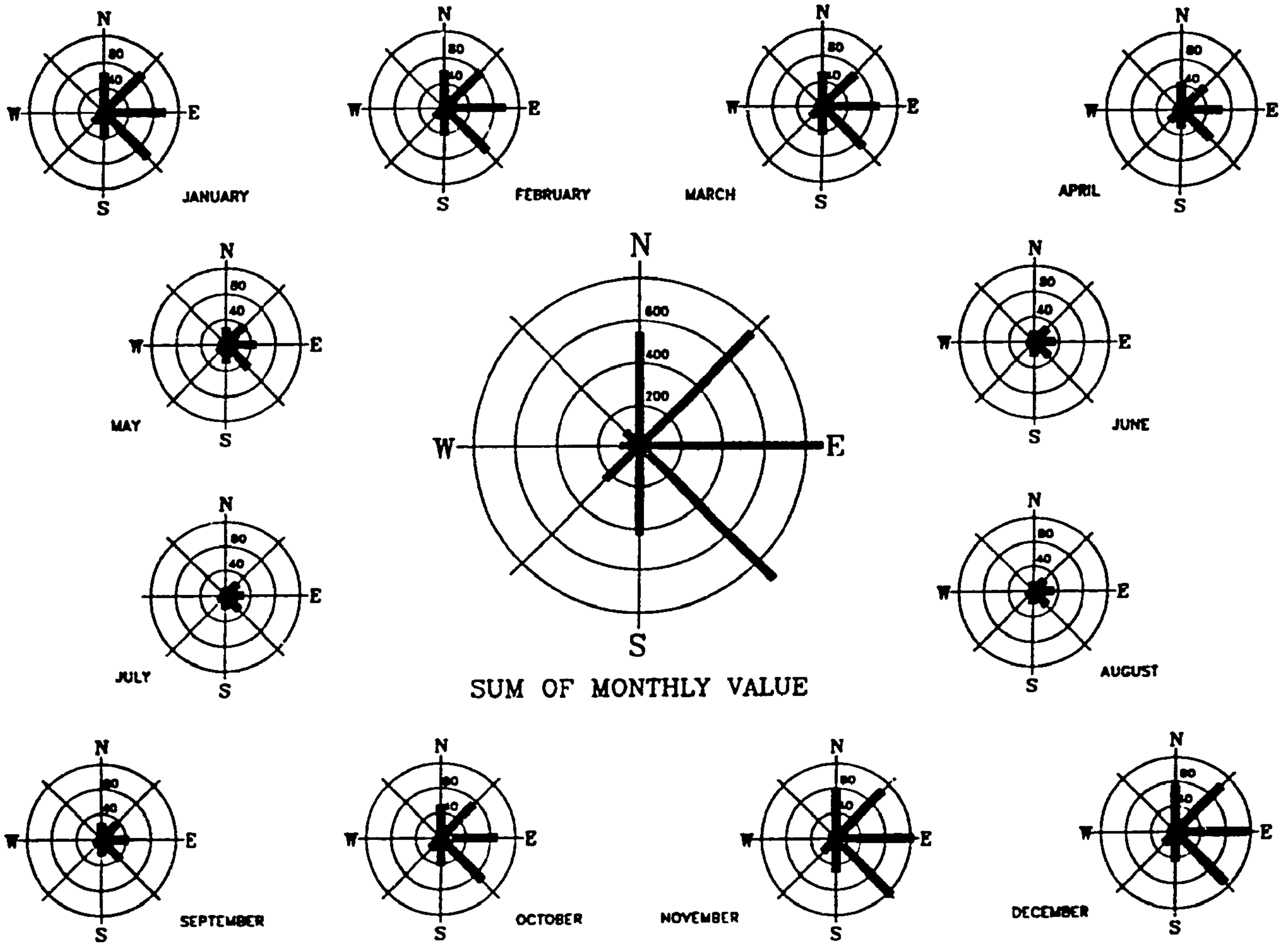


Fig. A28 Driving rain impact frequency for a vertical surface (hr) - victoria

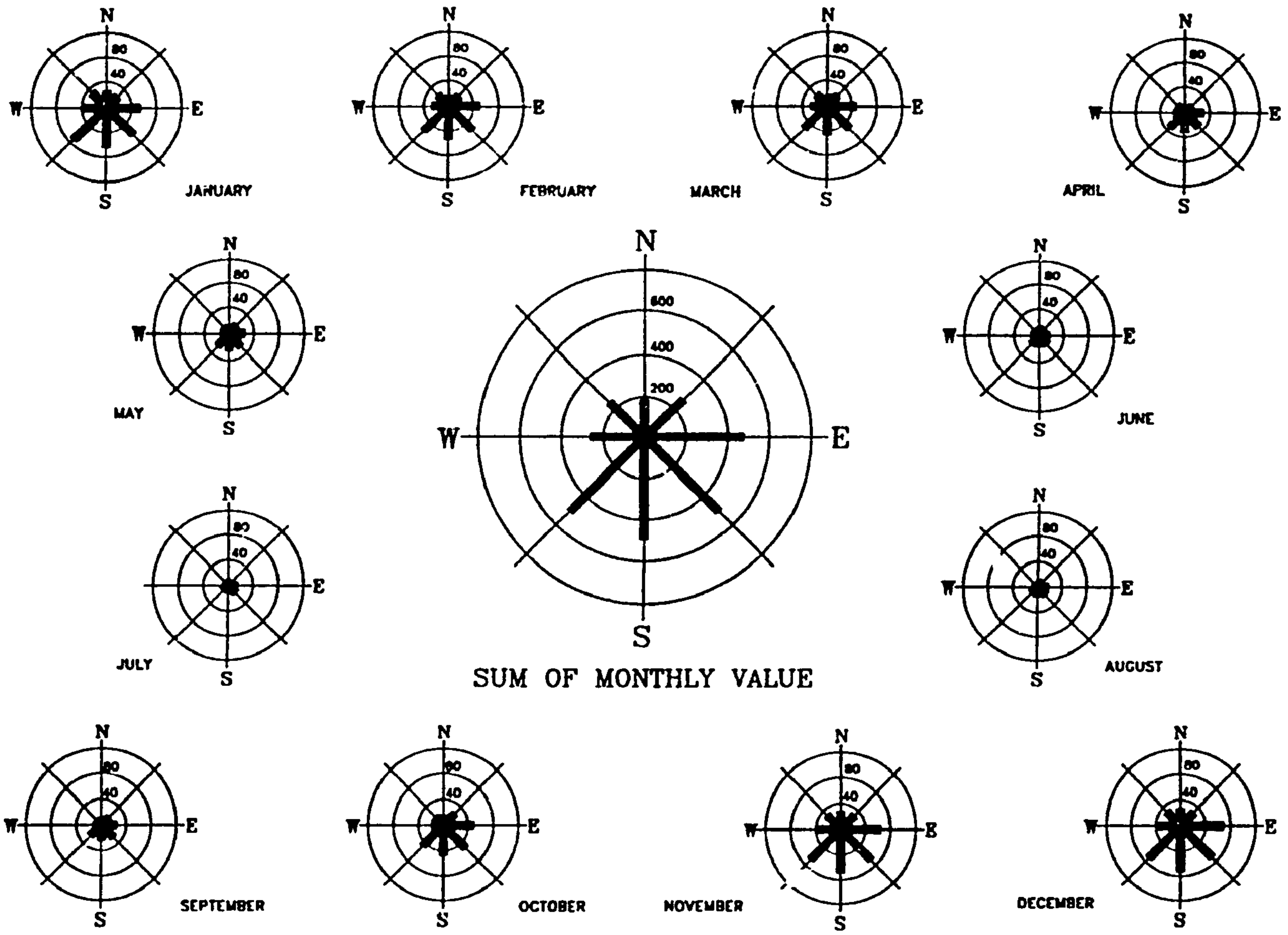


Fig. A29 Driving rain impact frequency for a vertical surface (hr) - Winnipeg

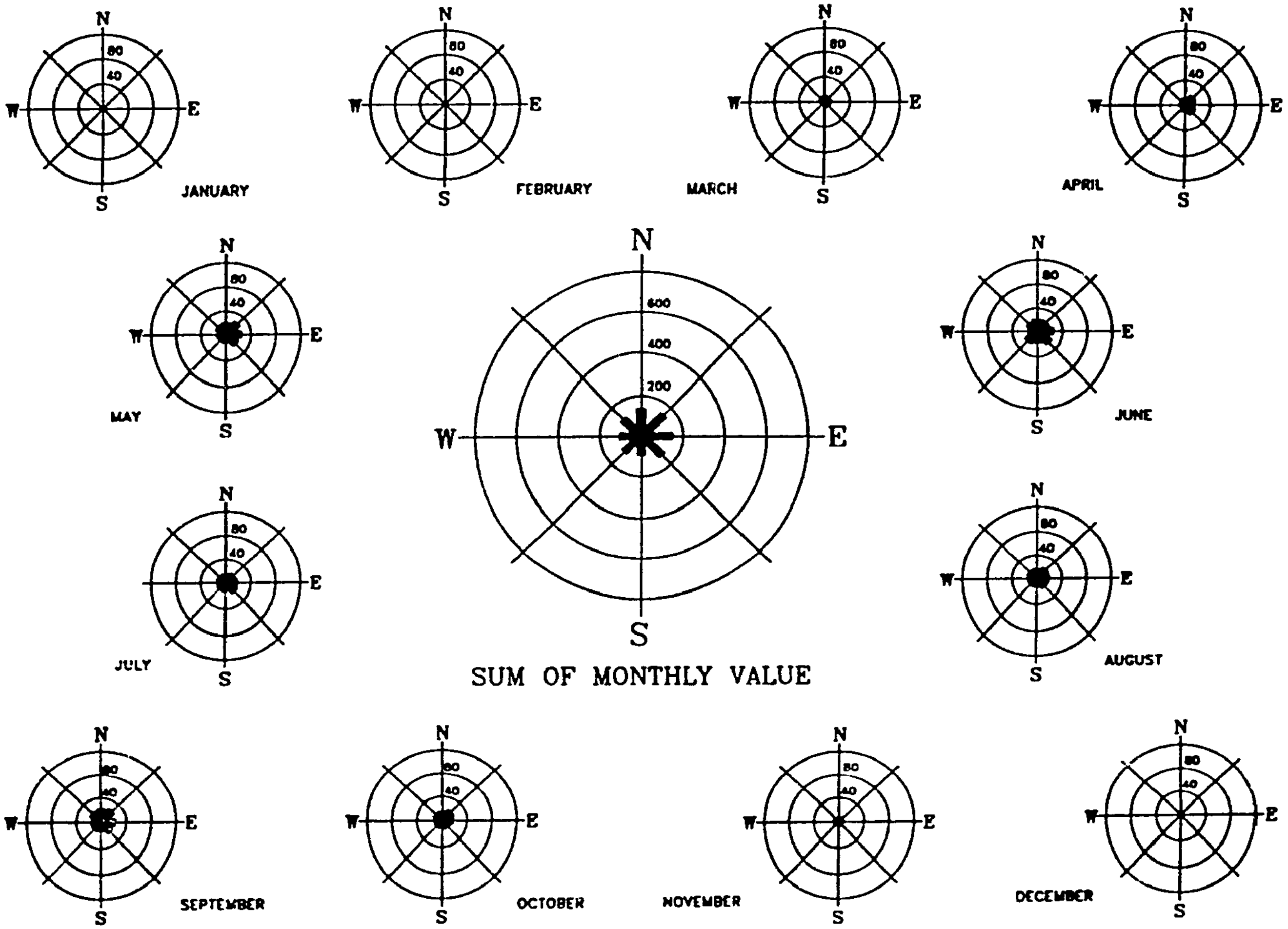


Fig. A30 Driving rain impact frequency for a vertical surface (hr) - yellowknife

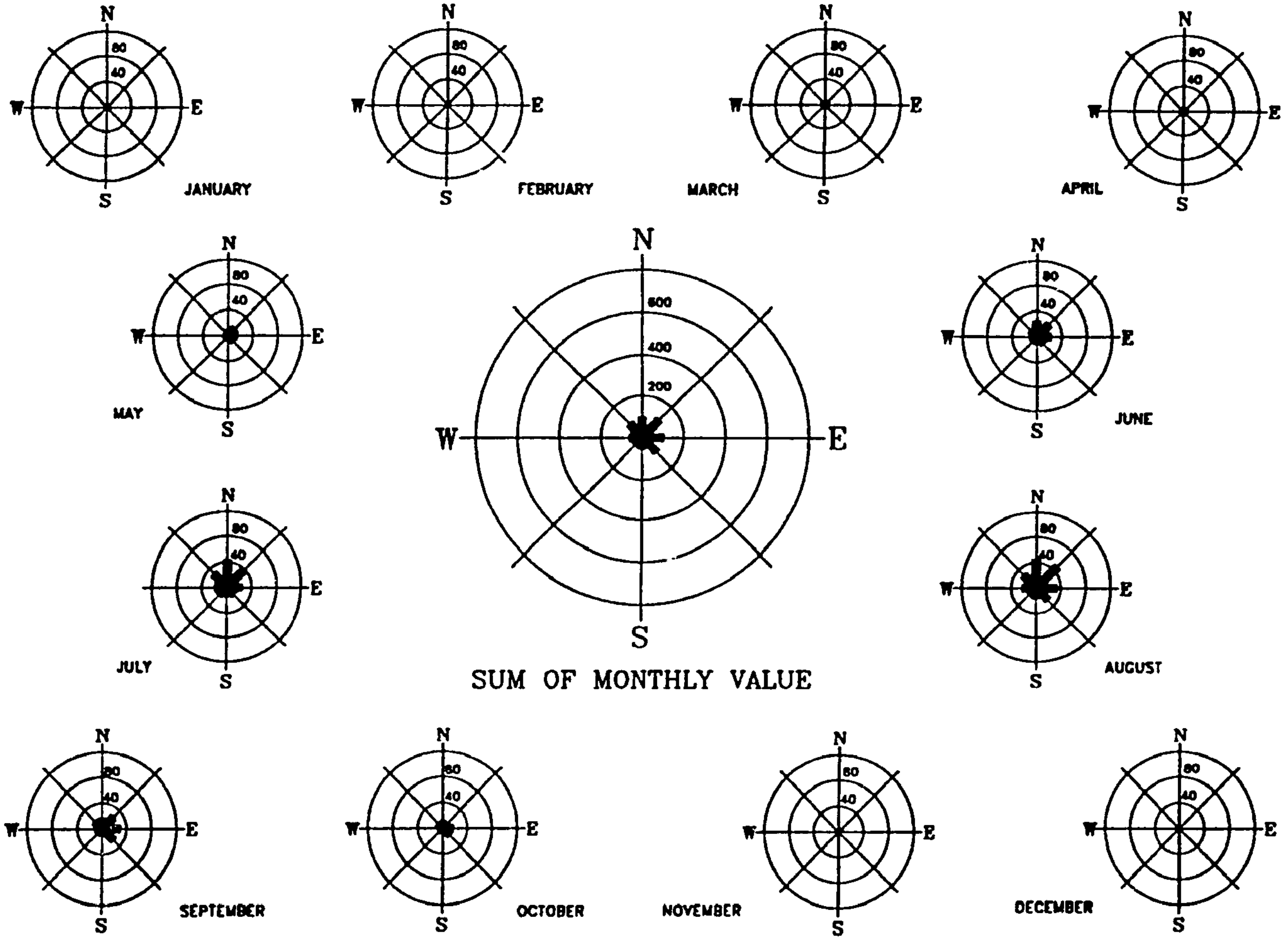


Fig. A31 Driving rain impact intensity on a vertical surface (mm/hr) - Calgary

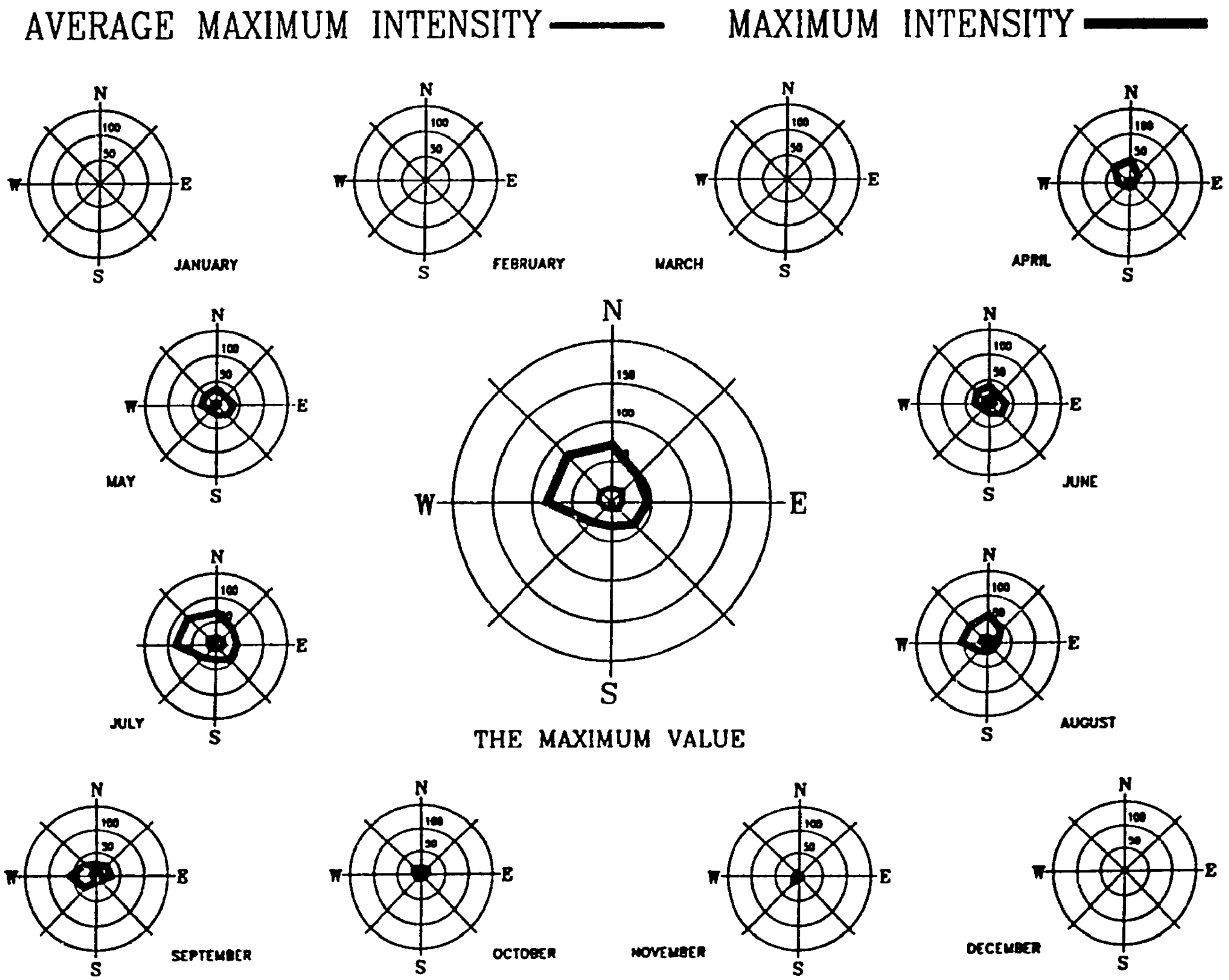


Fig. A32 Driving rain impact intenstiy on a vertical surface (mm/hr) - Edmonton

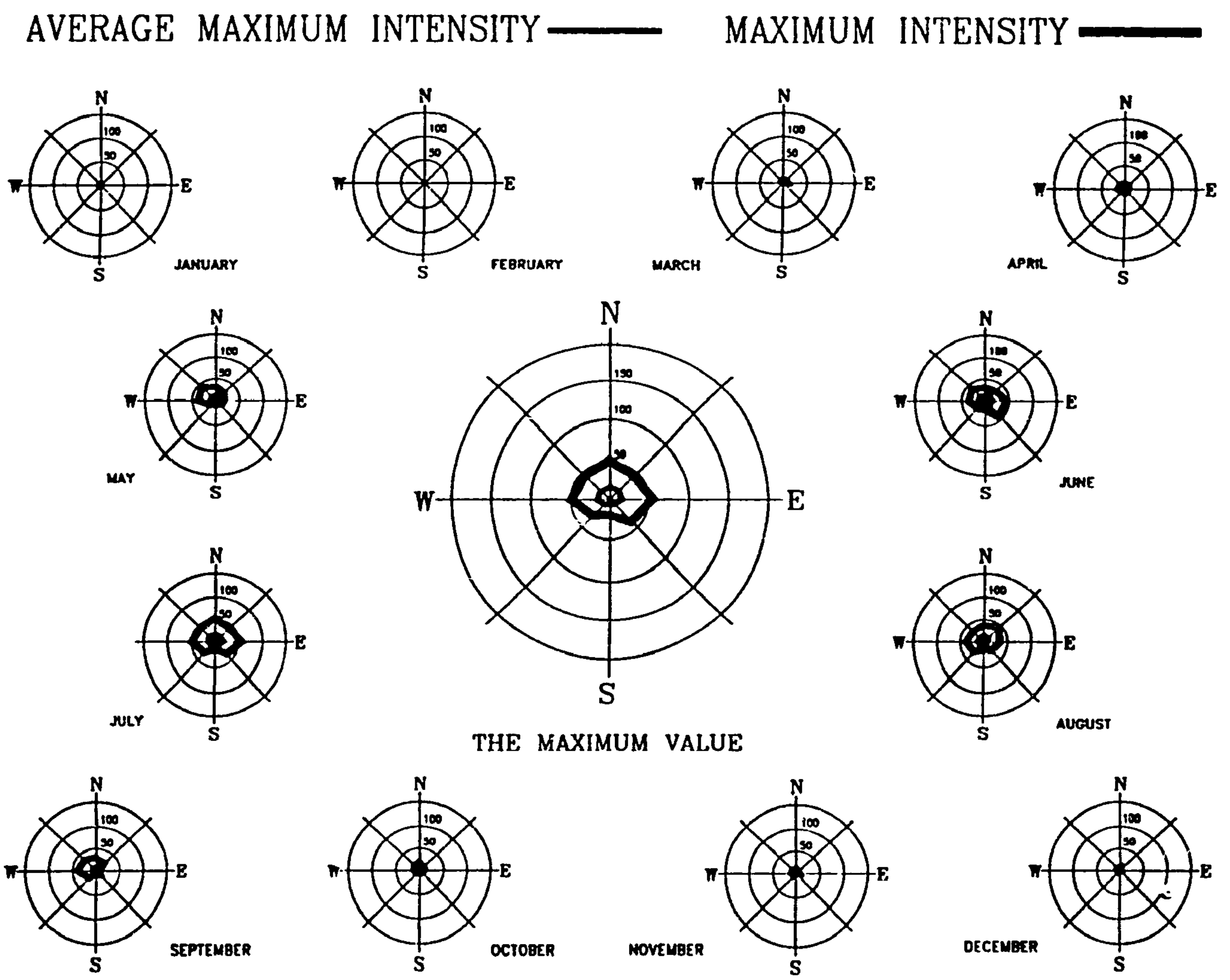


Fig A33 Driving rain impact intensity on a vertical surface (mm/hr) - Fredericton

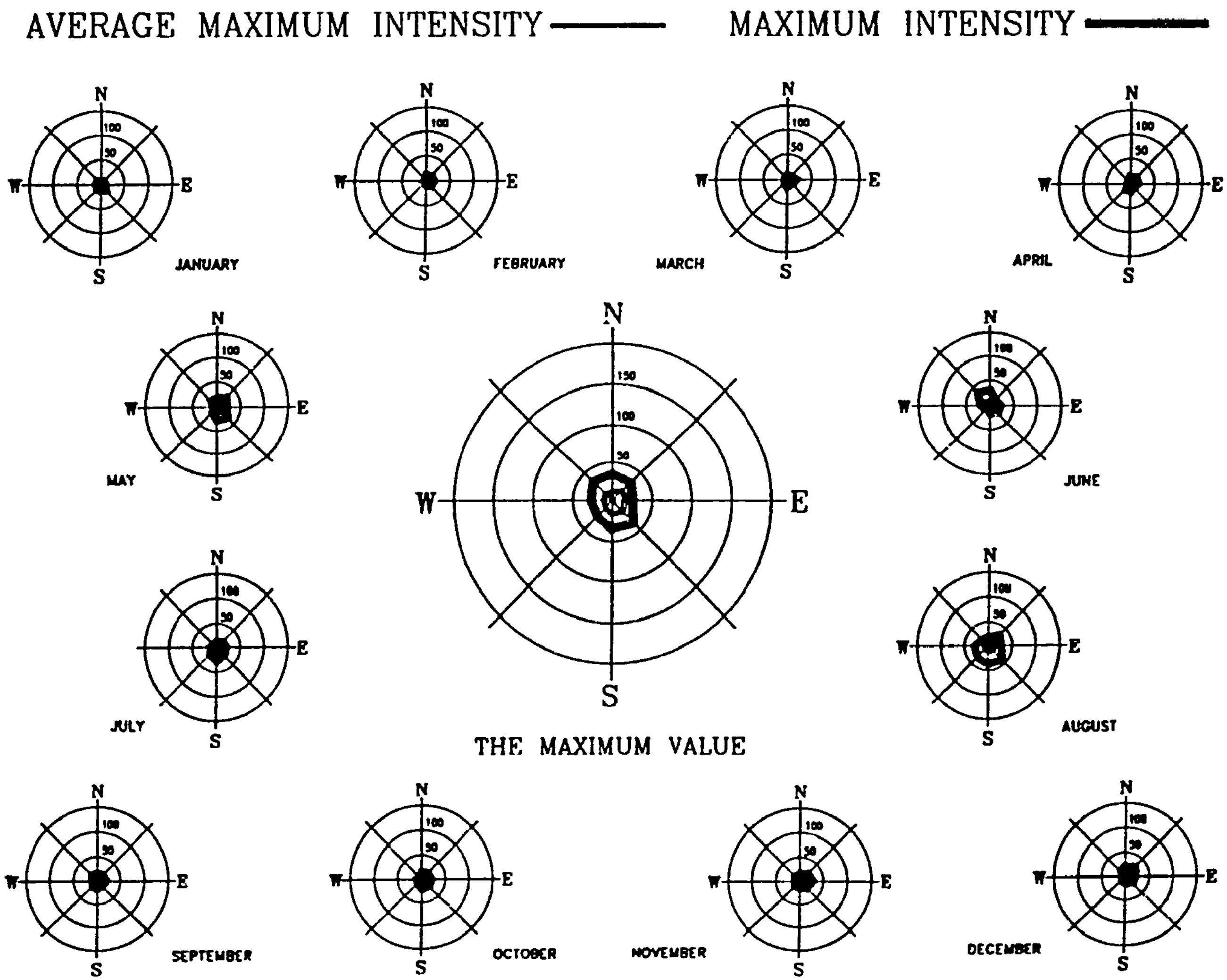


Fig. A34 Driving rain impact intensity on a vertical surface (mm/hr) - Halifax

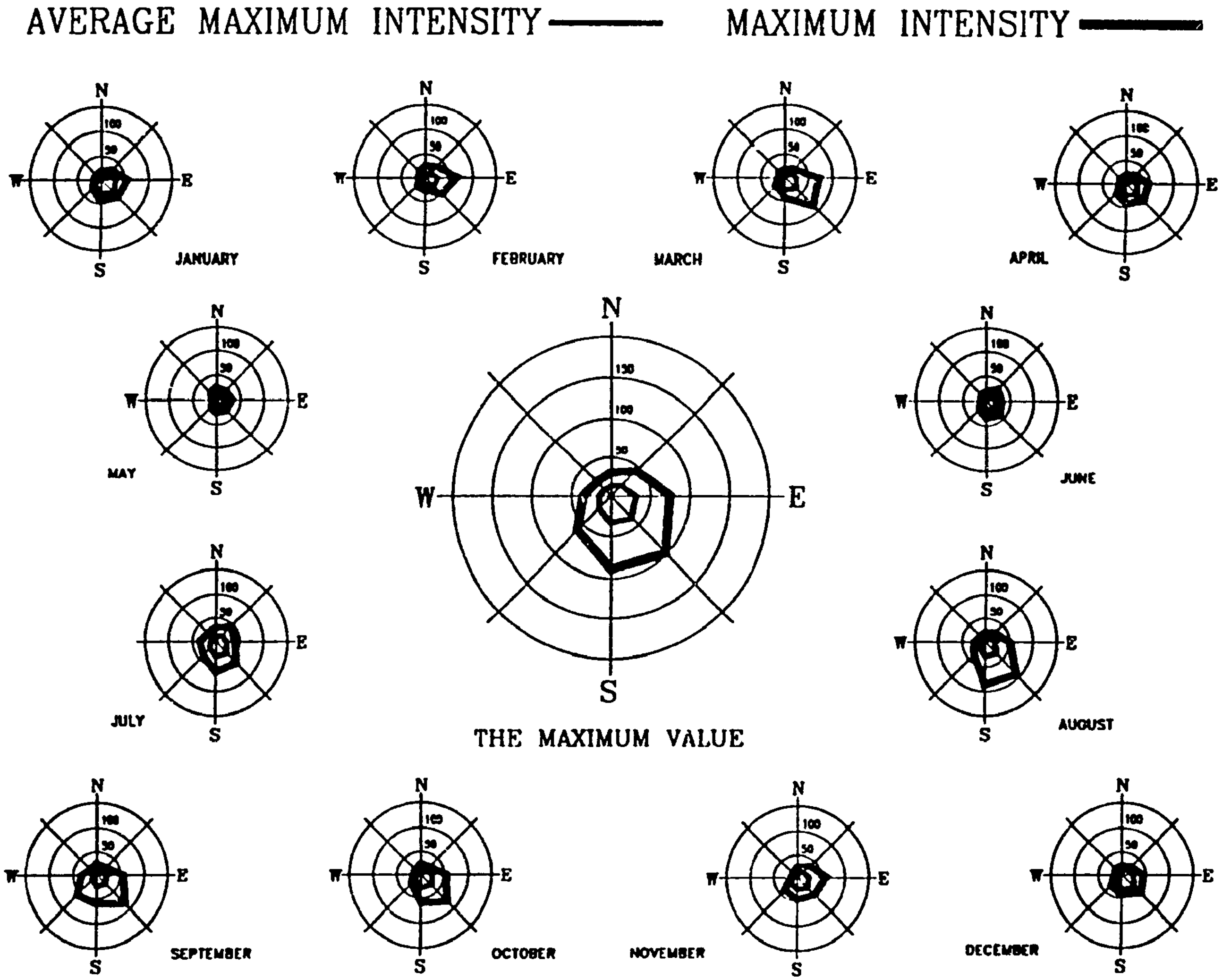


Fig. A35 Driving rain impact intensity on a vertical surface (mm/hr) - Montréal

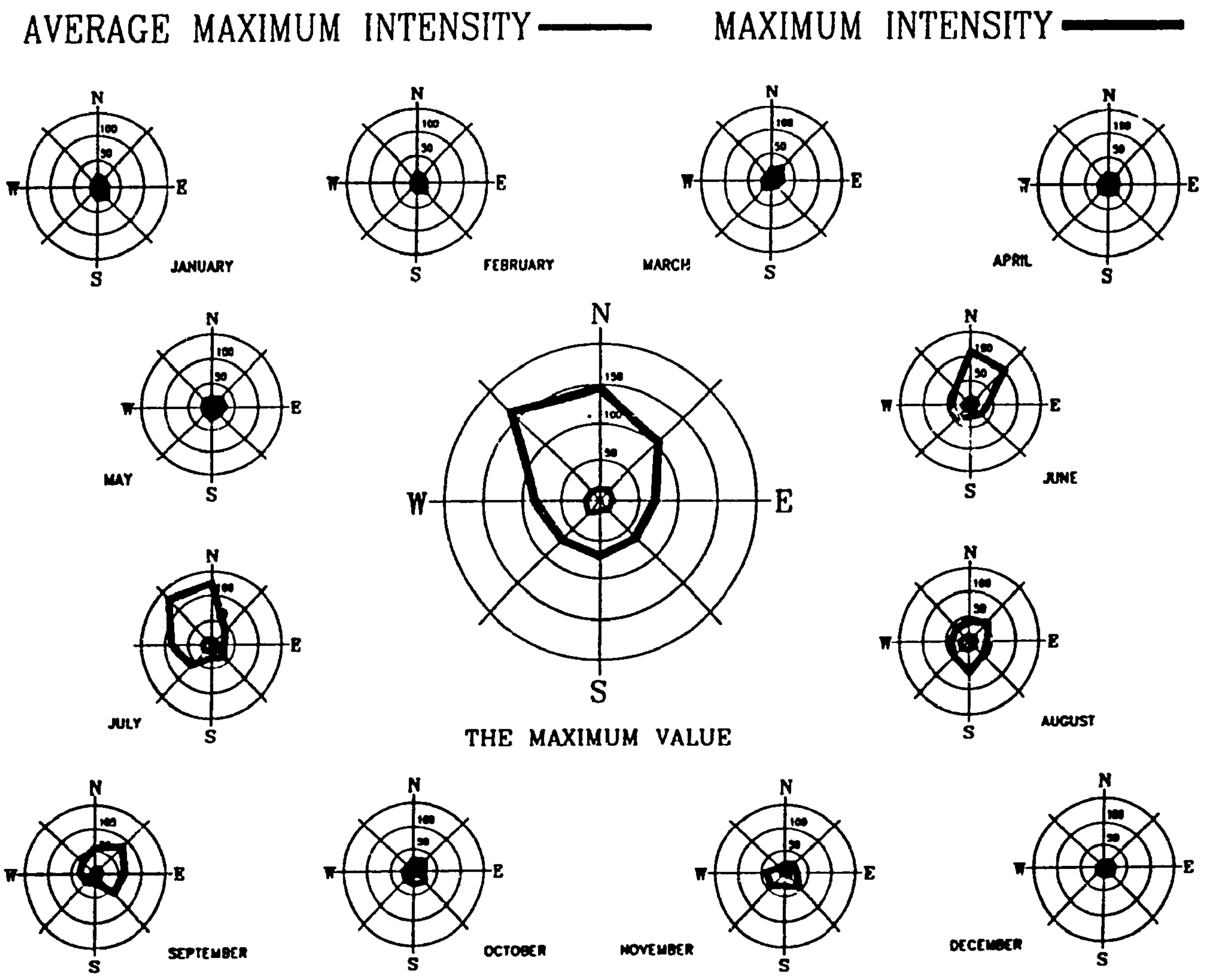


Fig. A36 Driving rain impact intensity on a vertical surface (mm/hr) - Ottawa

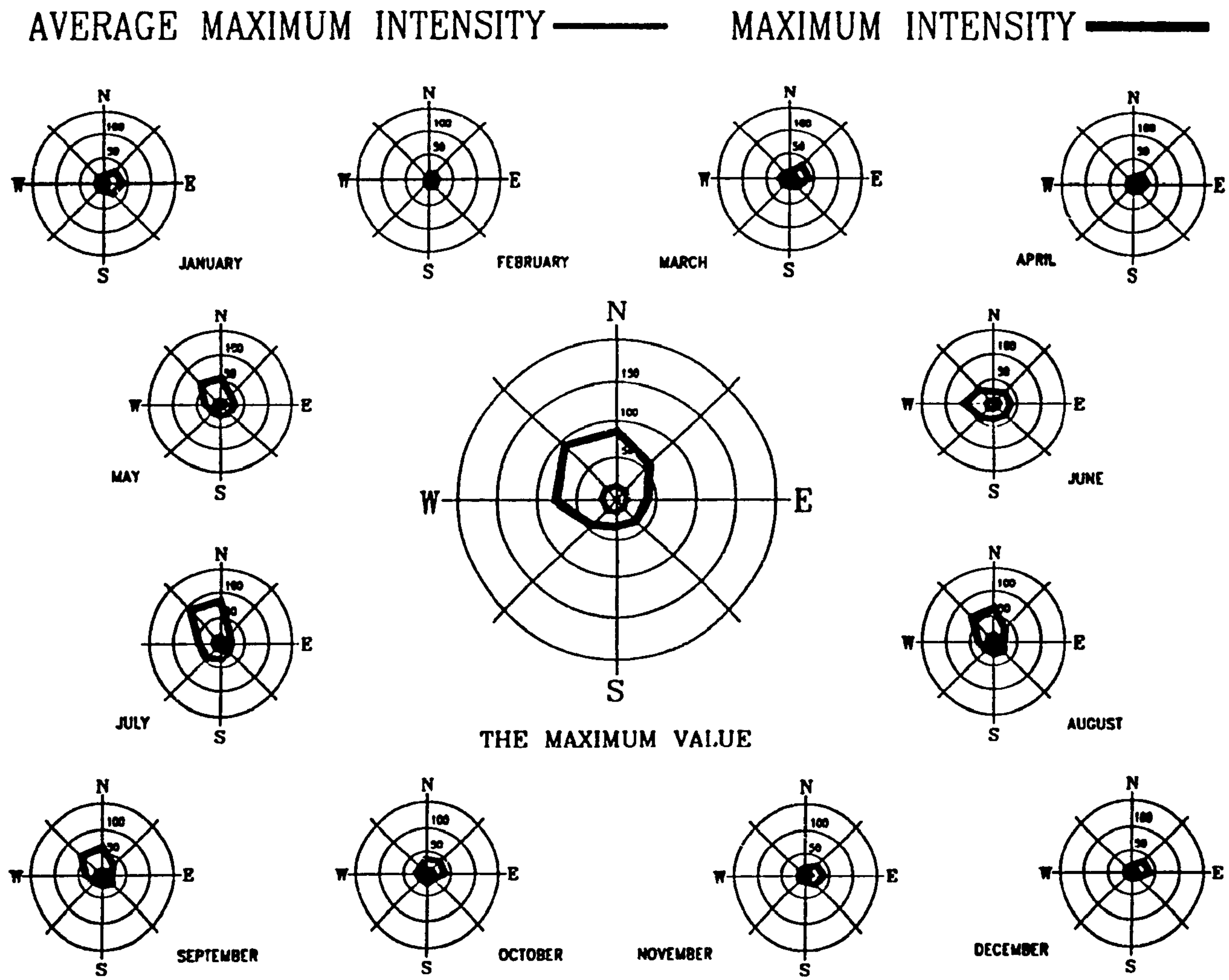


Fig A37 Driving rain impact intensity on a vertical surface (mm/hr) - Quebec City

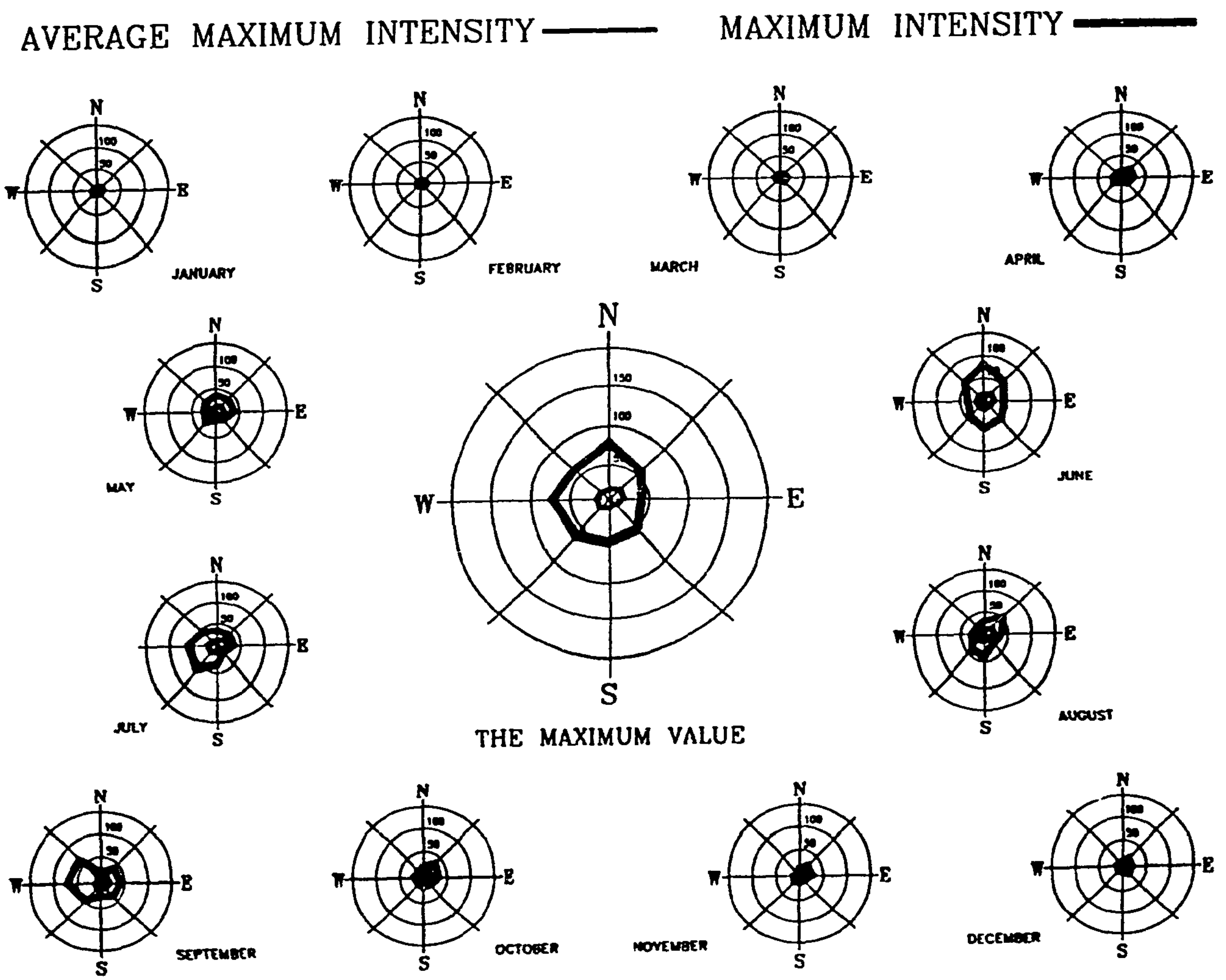


Fig. A38 Driving rain impact intensity on a vertical surface (mm/hr) - Regina

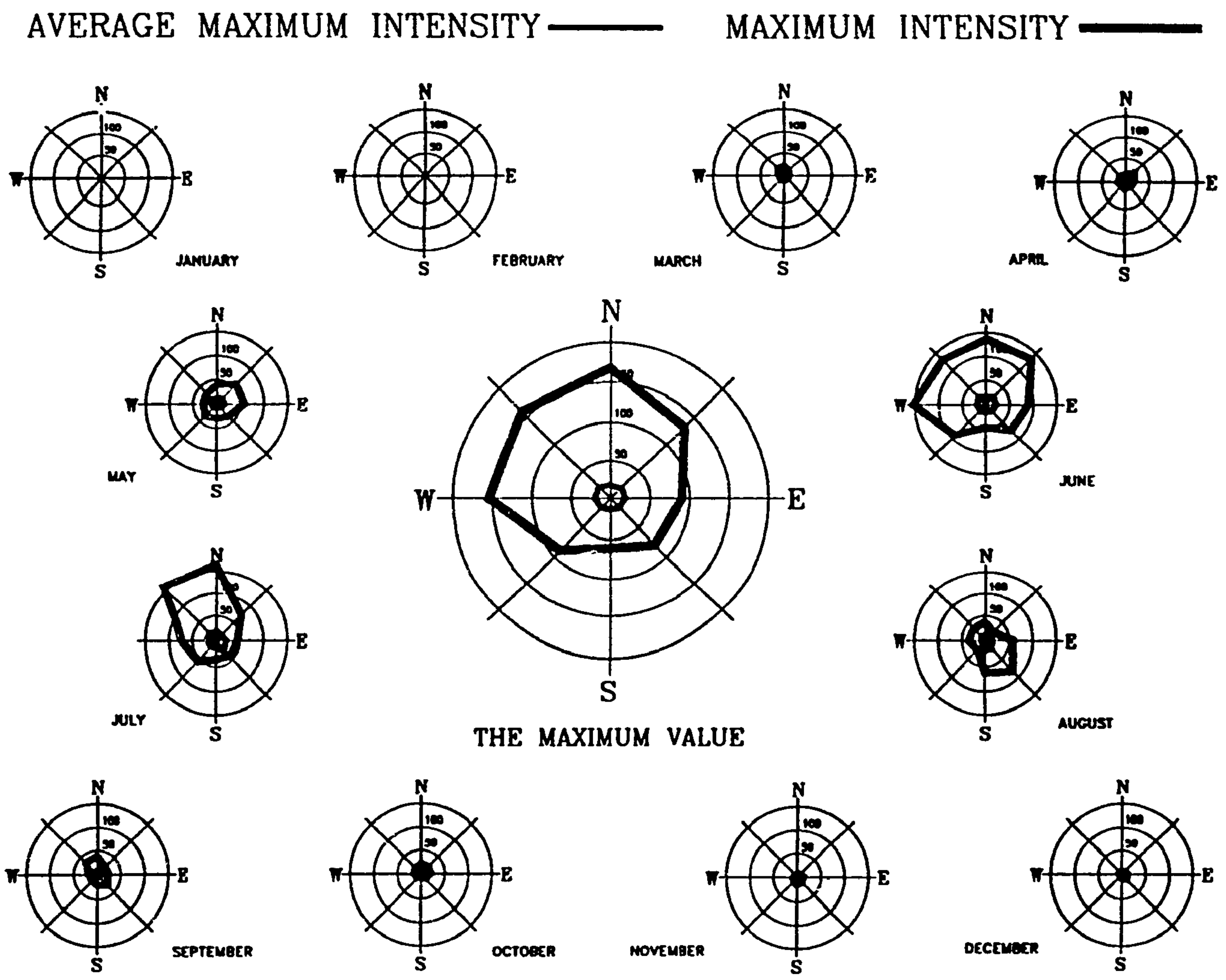


Fig. A39 Driving rain impact intensity on a vertical surface (mm/hr) - Saskatoon

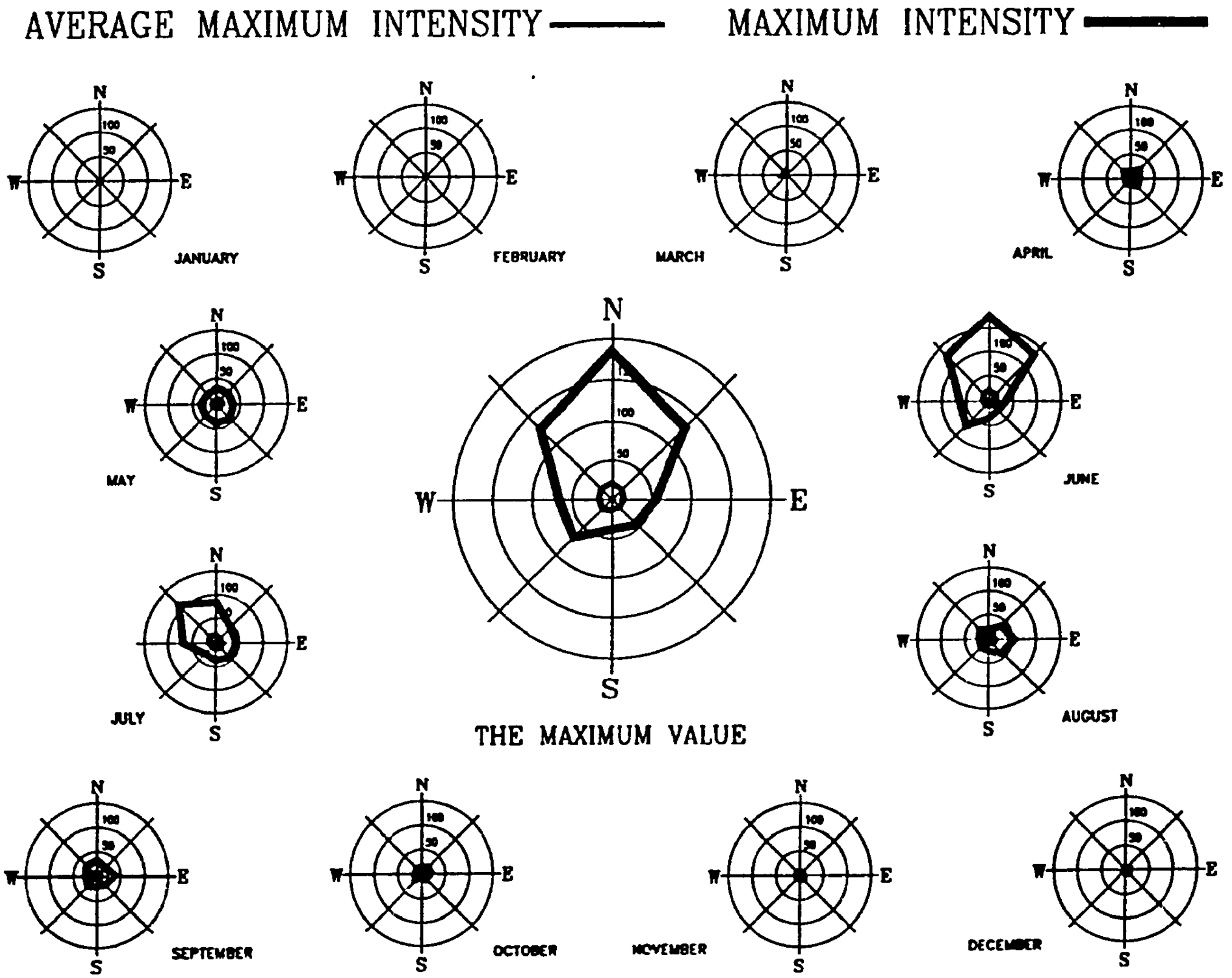


Fig. A40 Driving rain impact intensity on a vertical surface (mm/hr) - St. John's

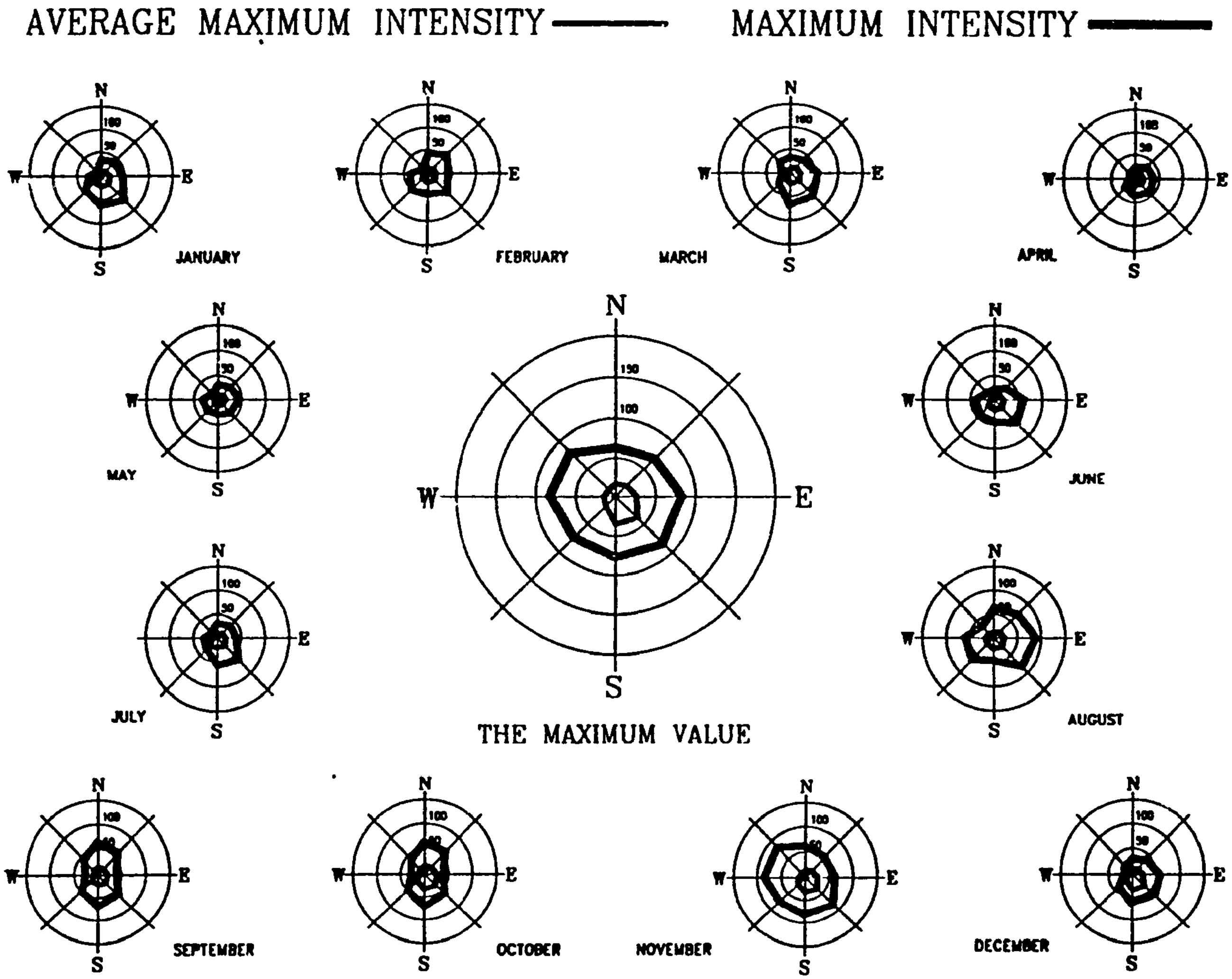


Fig. A41 Driving rain impact intensity on a vertical surface (mm/hr) - Toronto

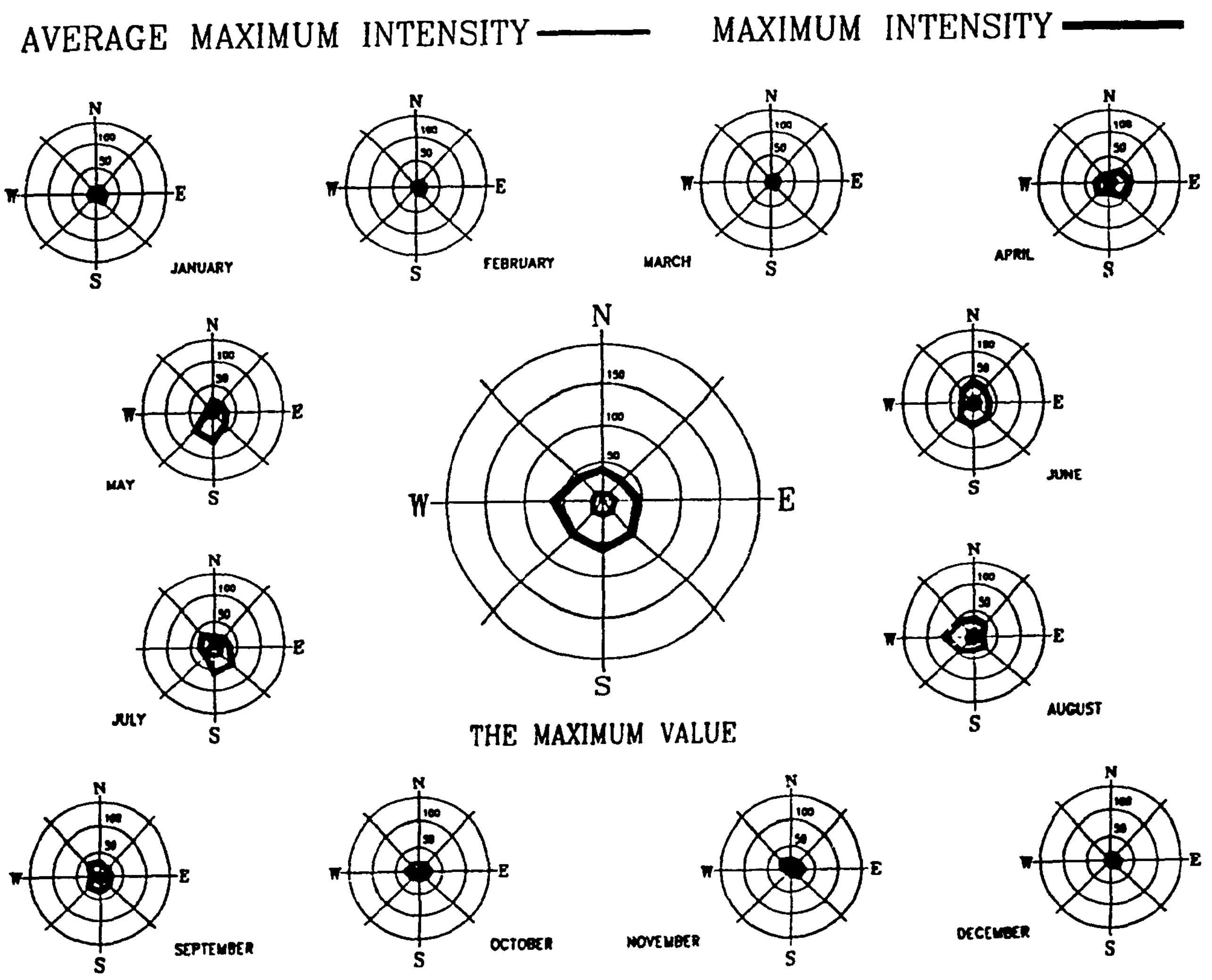


Fig. A42 Driving rain impact intensity on a vertical surface (mm/hr) - Vancouver

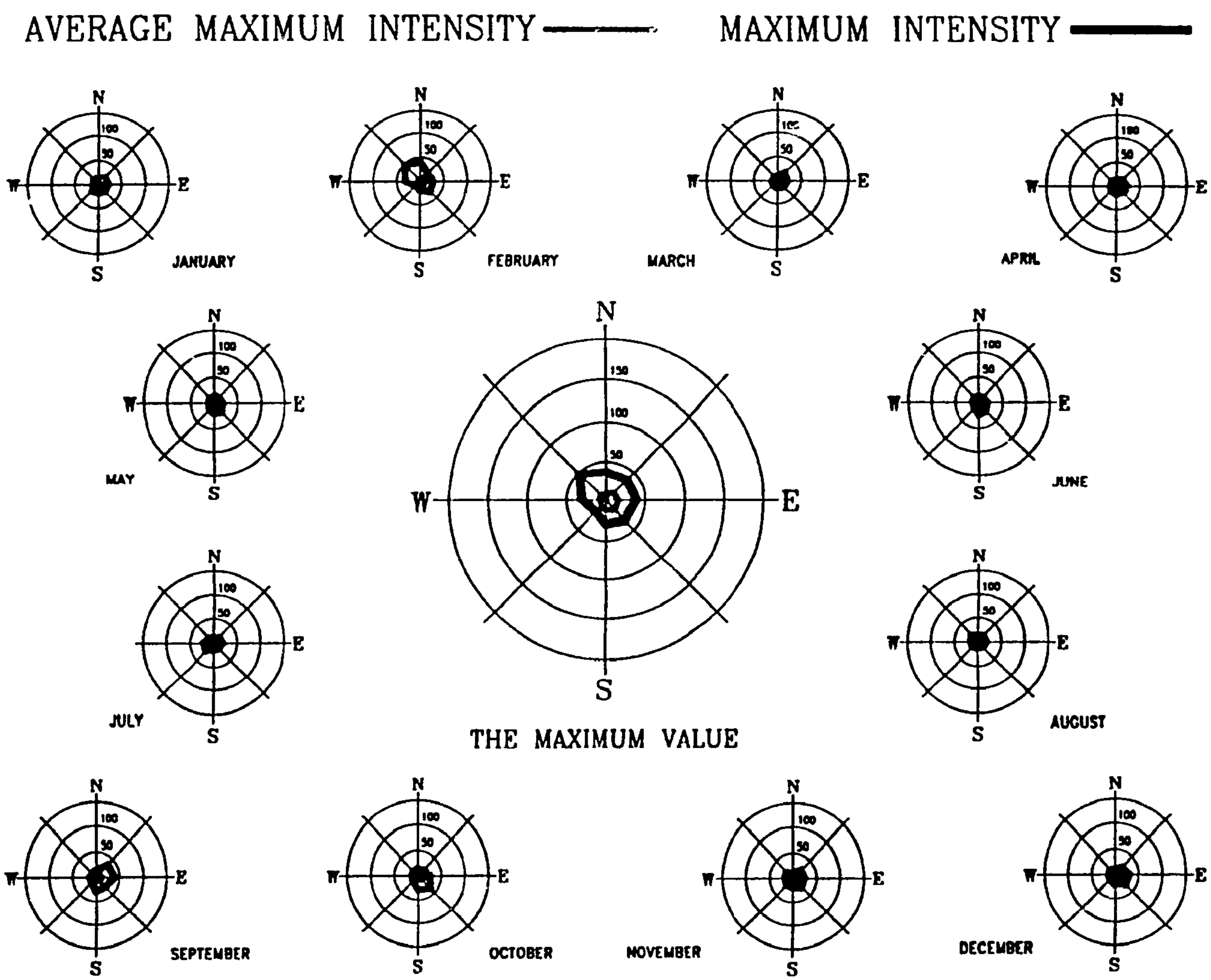


Fig. A43 Driving rain impact intensity on a vertical surface (mm/hr) - Victoria

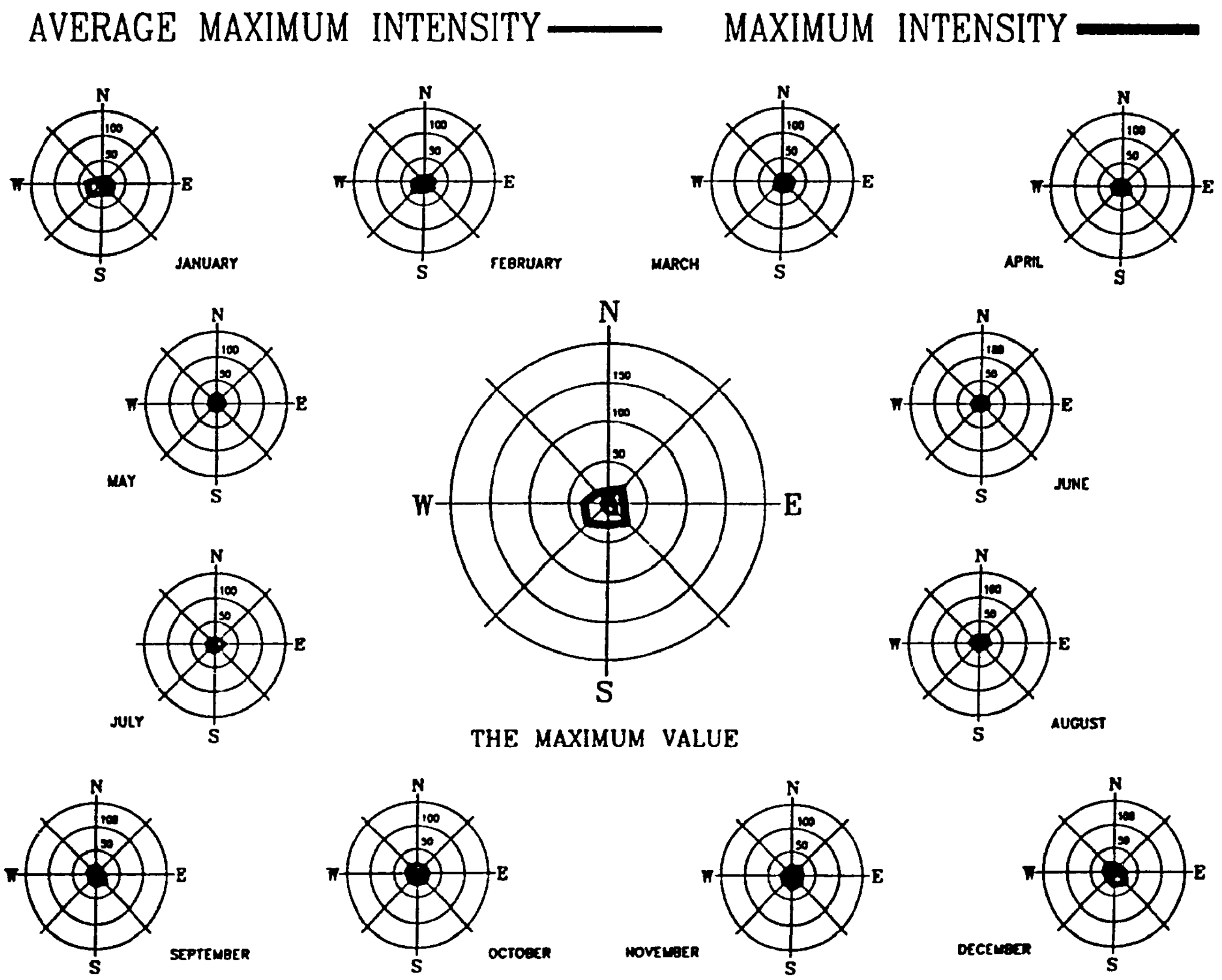


Fig. A44 Driving rain impact intensity on a vertical surface (mm/hr) - Winnipeg

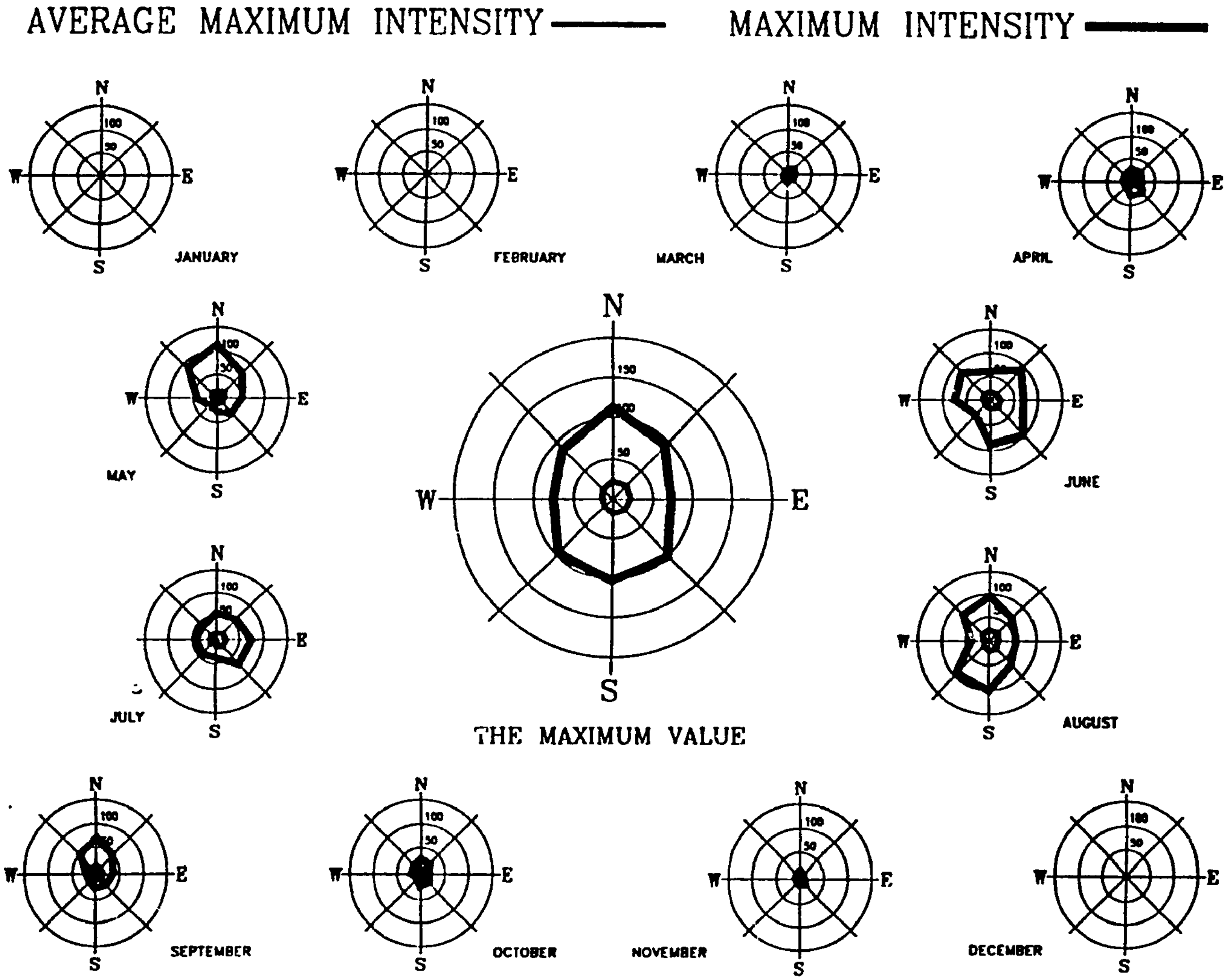


Fig. A45 Driving rain impact intenstiy on a vertical surface (mm/hr) - Yellowknife

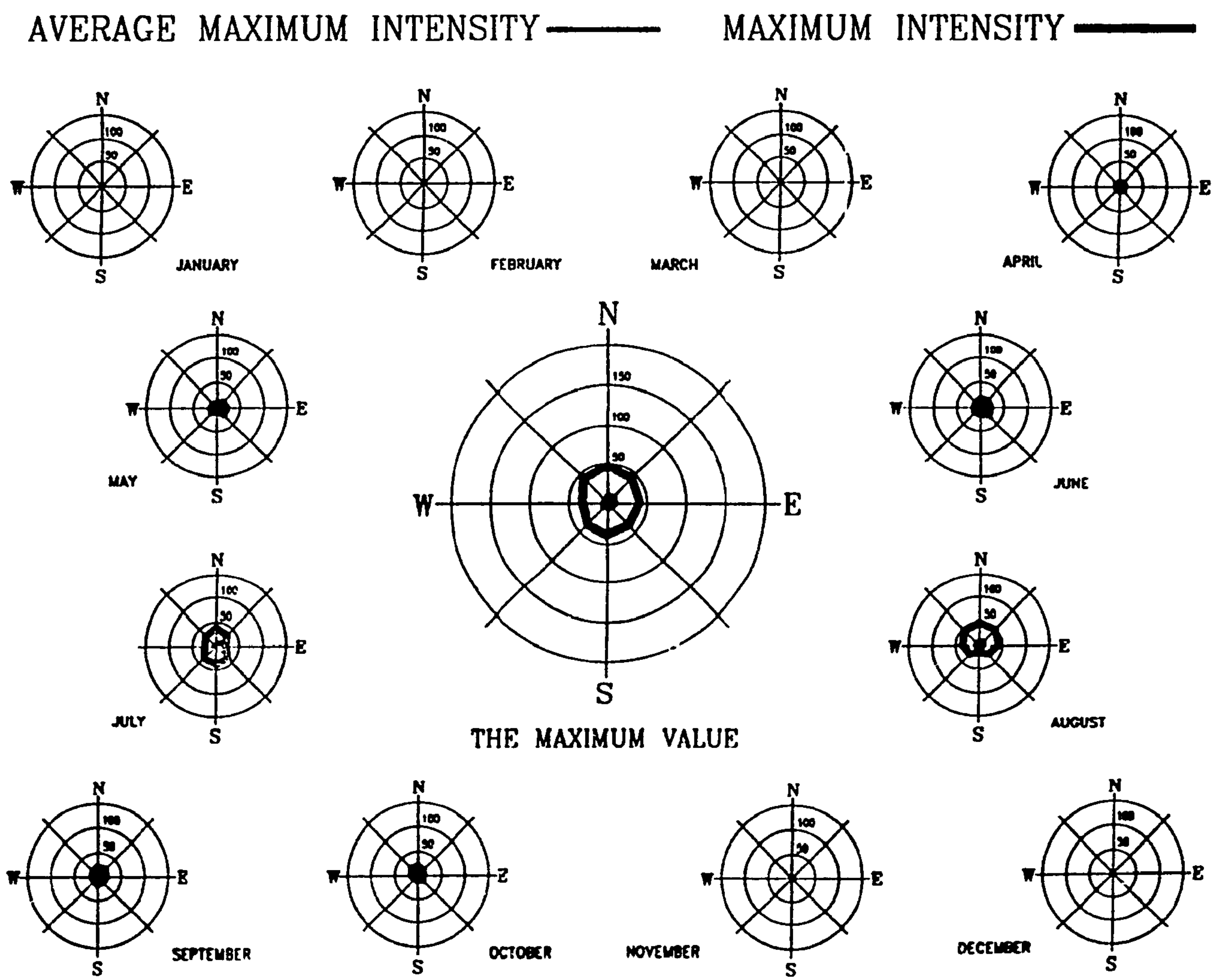


Fig. A46 Driving rain impact duration for a vertical surface (hr) - Calgary

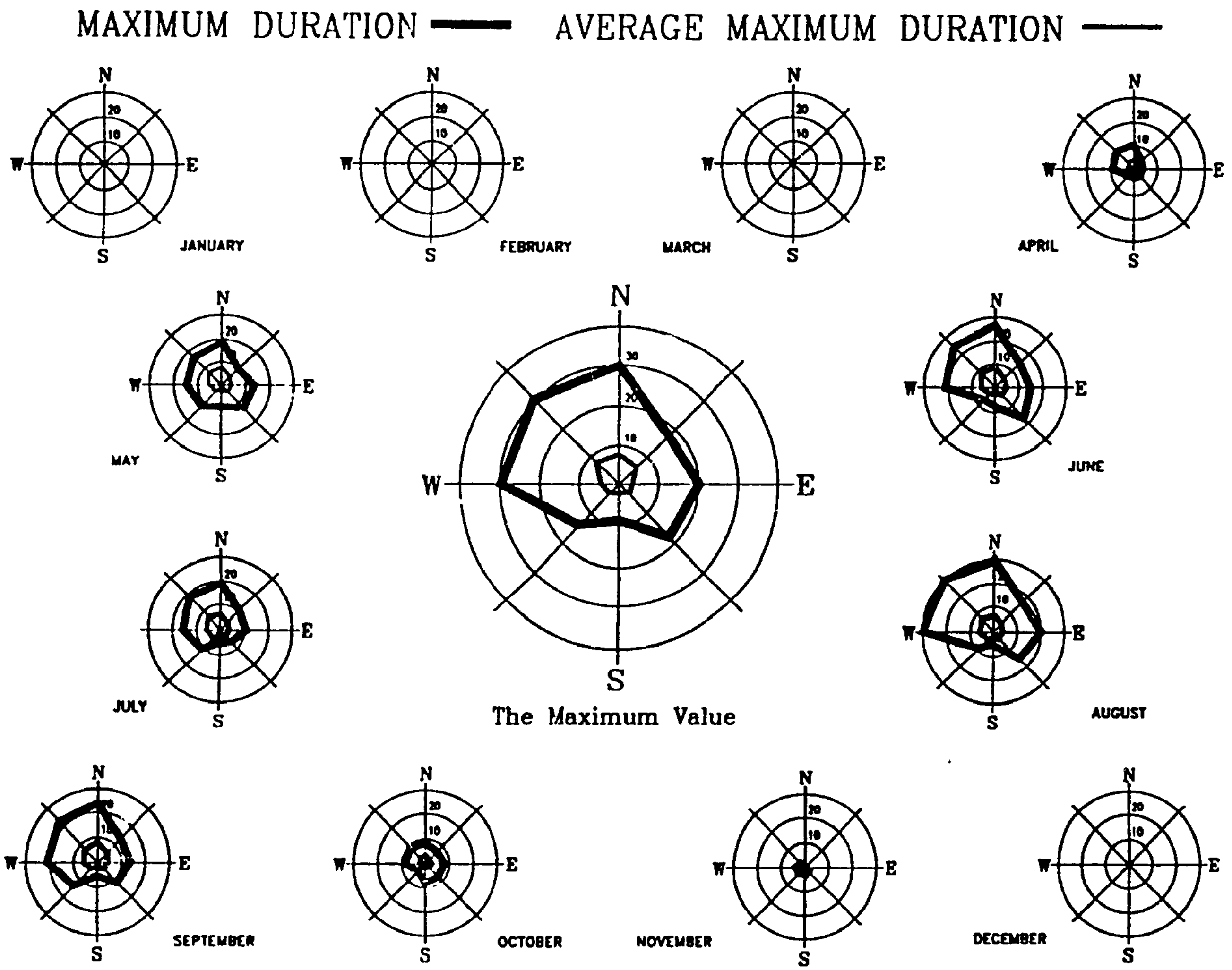


Fig. A47 Driving rain impact duration for a vertical surface (hr) - Edmonton

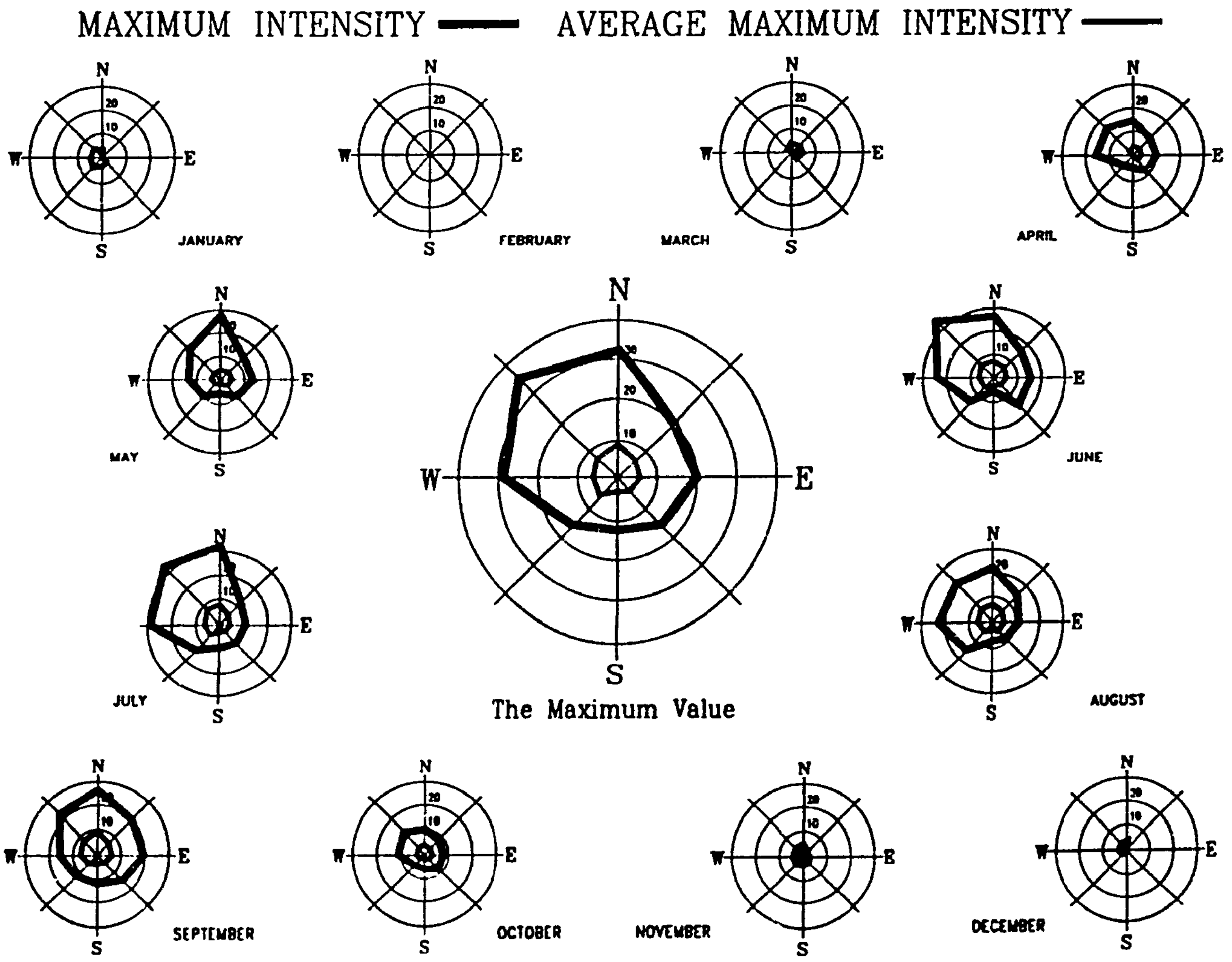


Fig. A48 Driving rain impact duration on a vertical surface (hr) - Fredericton

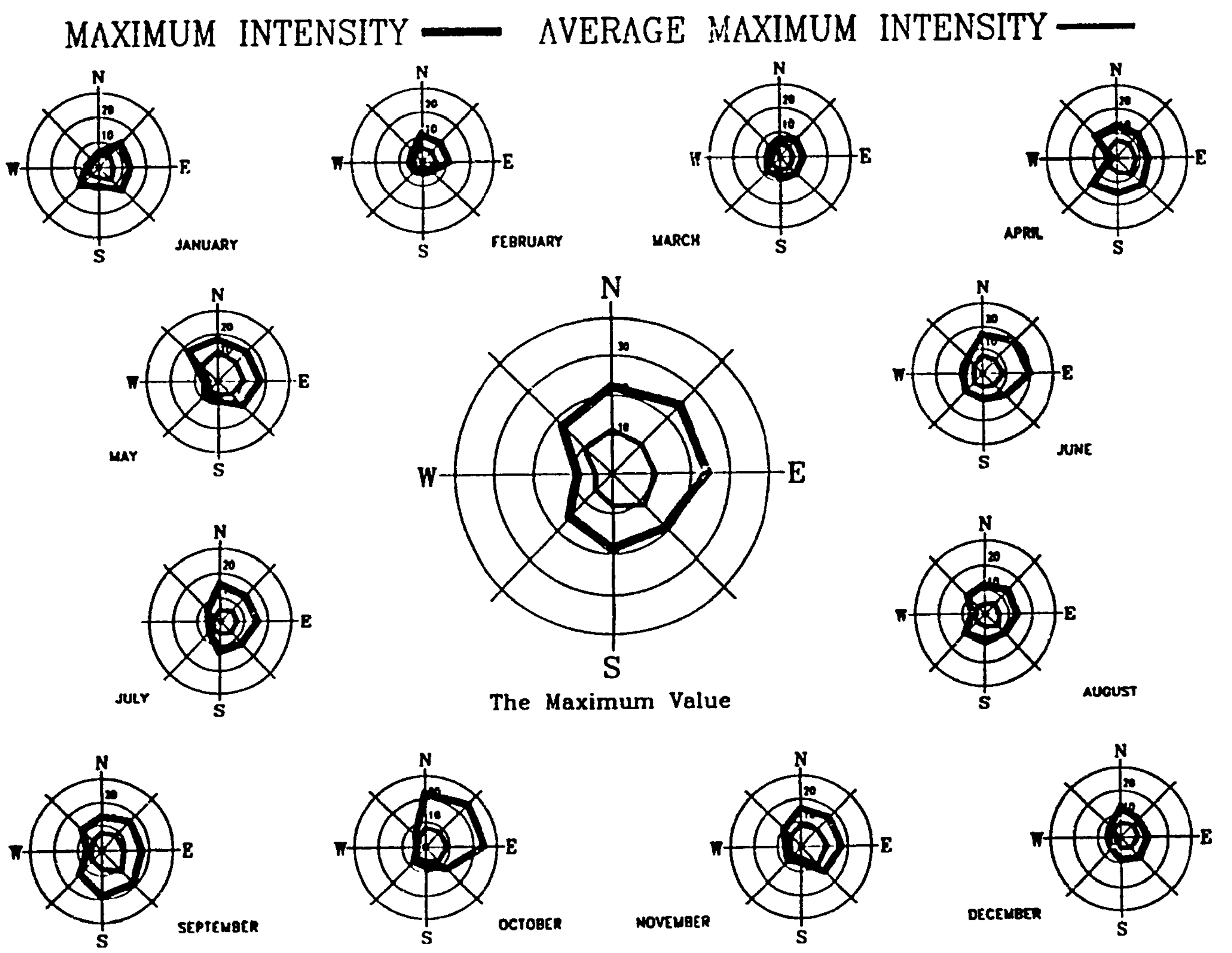


Fig A49 Driving rain impact duration for a vertical surface (hr) - Halifax

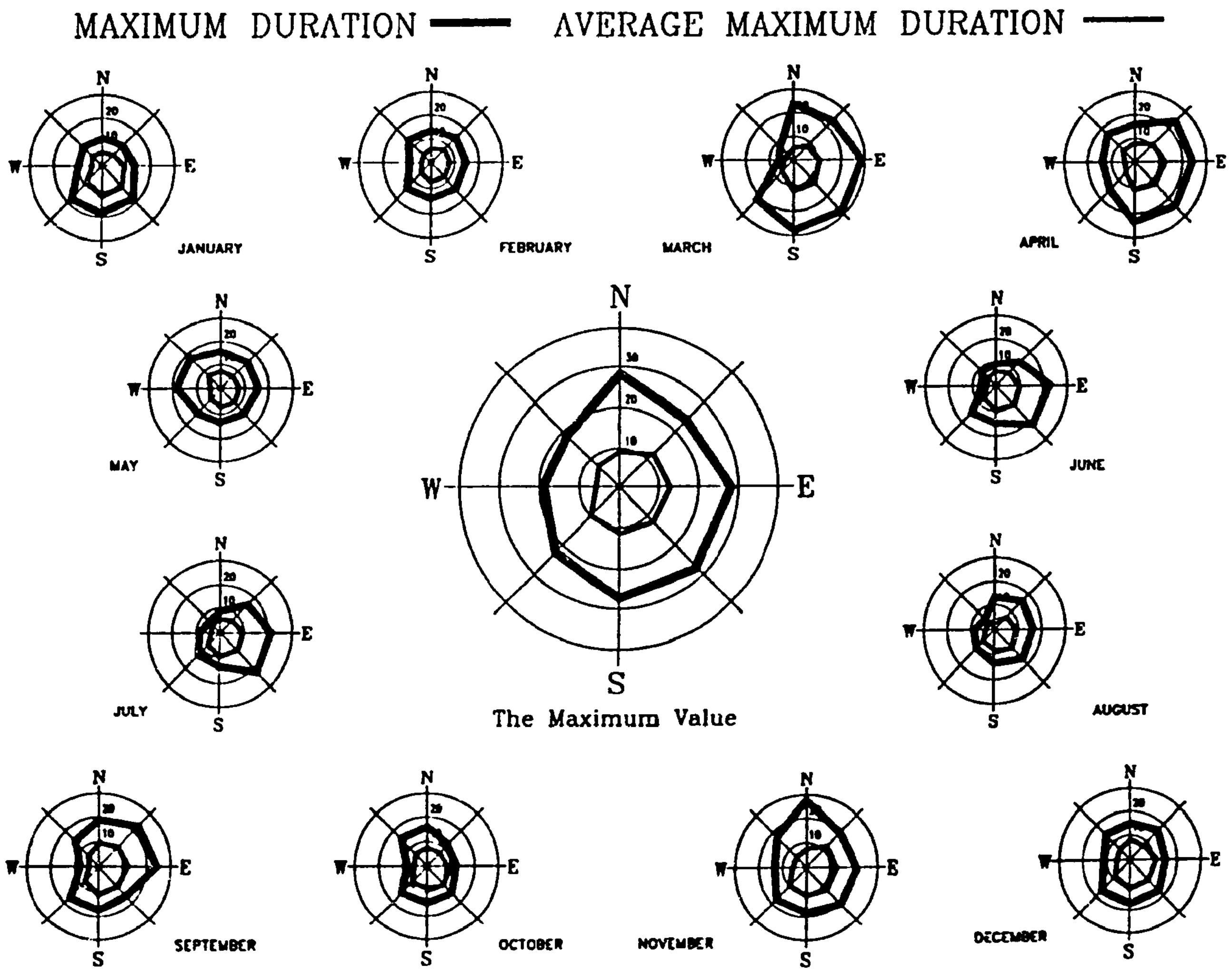


Fig. A50 Driving rain impact duration for a vertical surface (hr) - Montréal

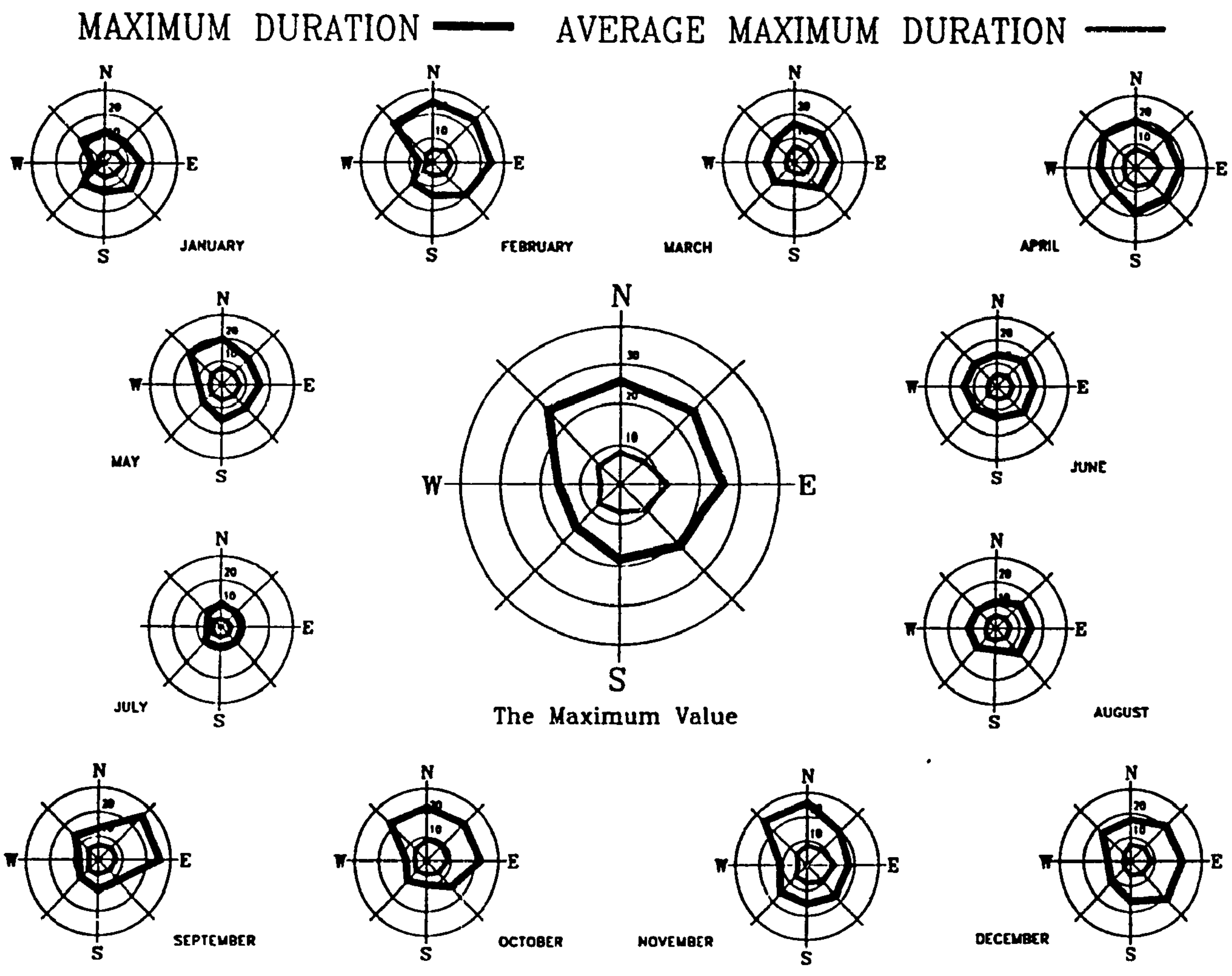


Fig A51 Driving rain impact duration for a vertical surface (hr) - Ottawa

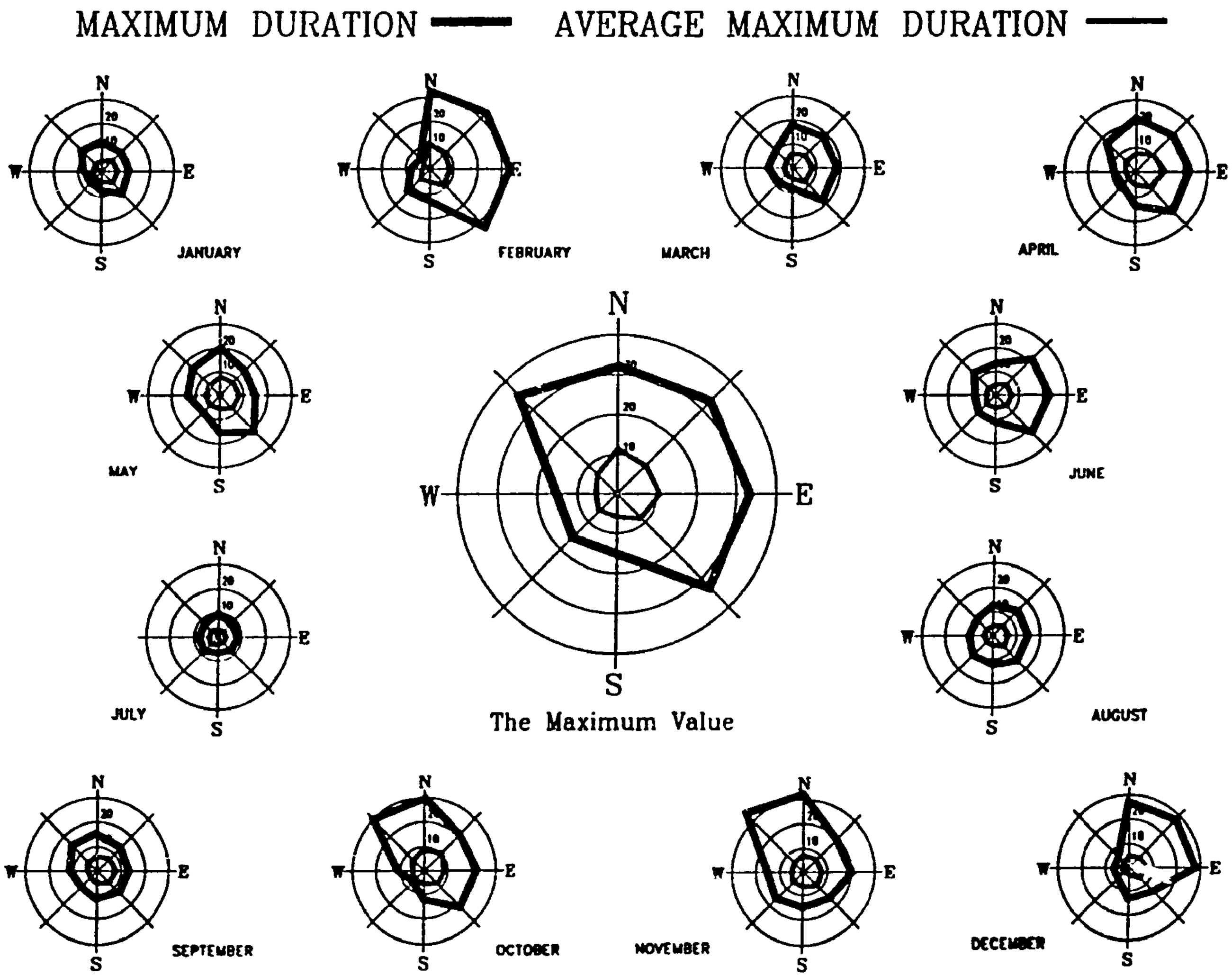


Fig. A52 Driving rain impact duration for a vertical surface (hr) - Quebec City

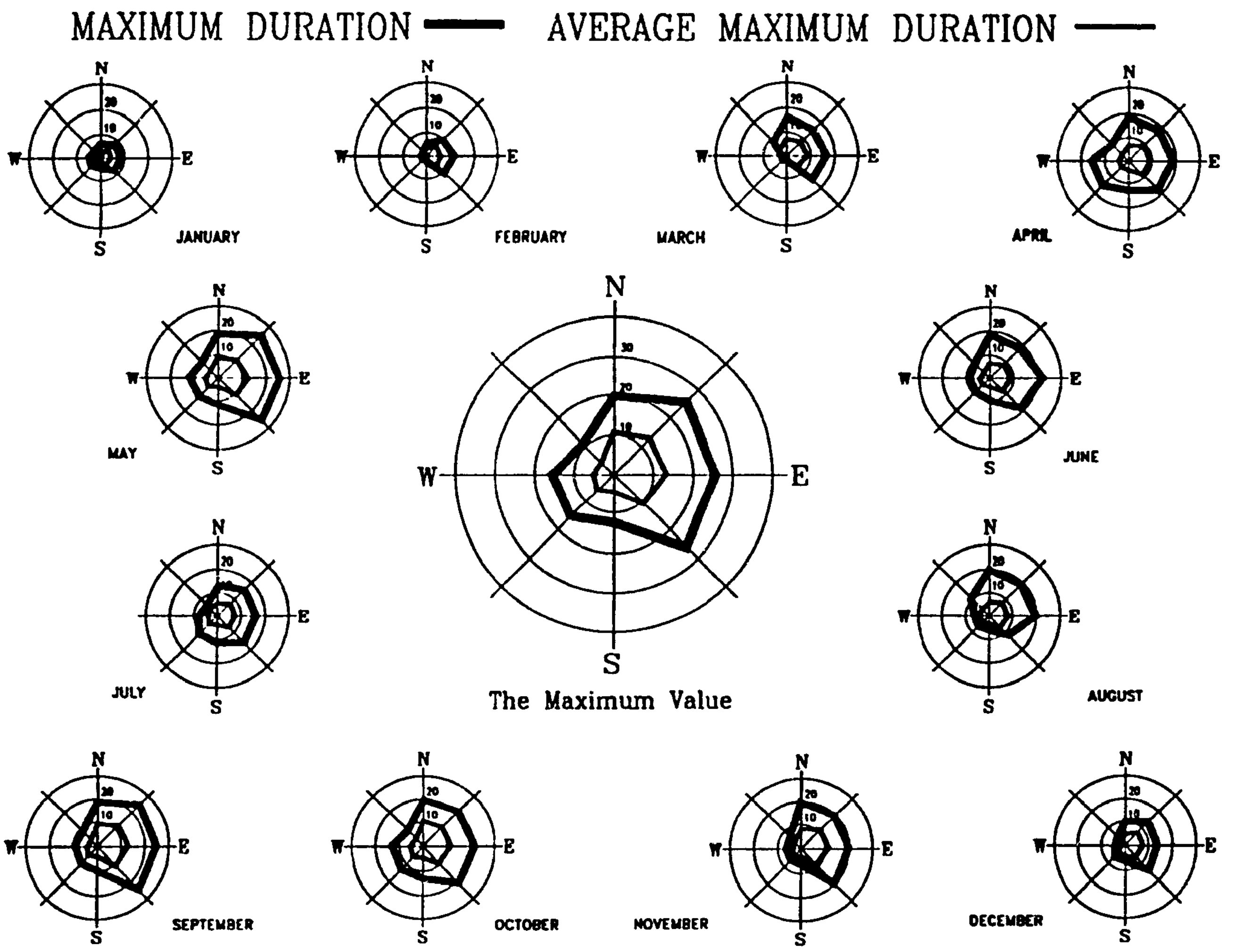


Fig. A53 Driving rain impact duration for a vertical surface (hr) - Regina

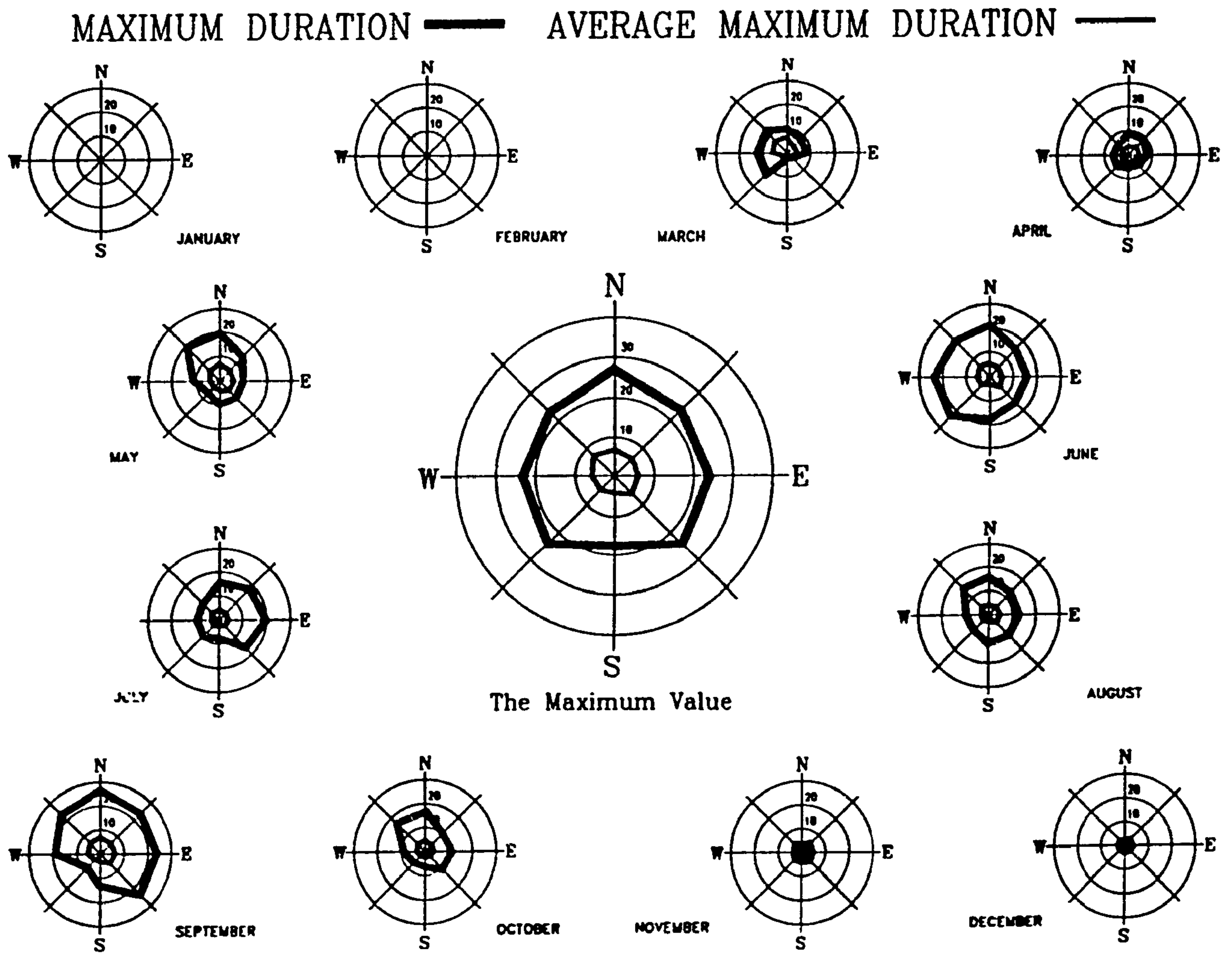


Fig. A54 Driving rain impact duration for a vertical surface (hr) - Saskatoon

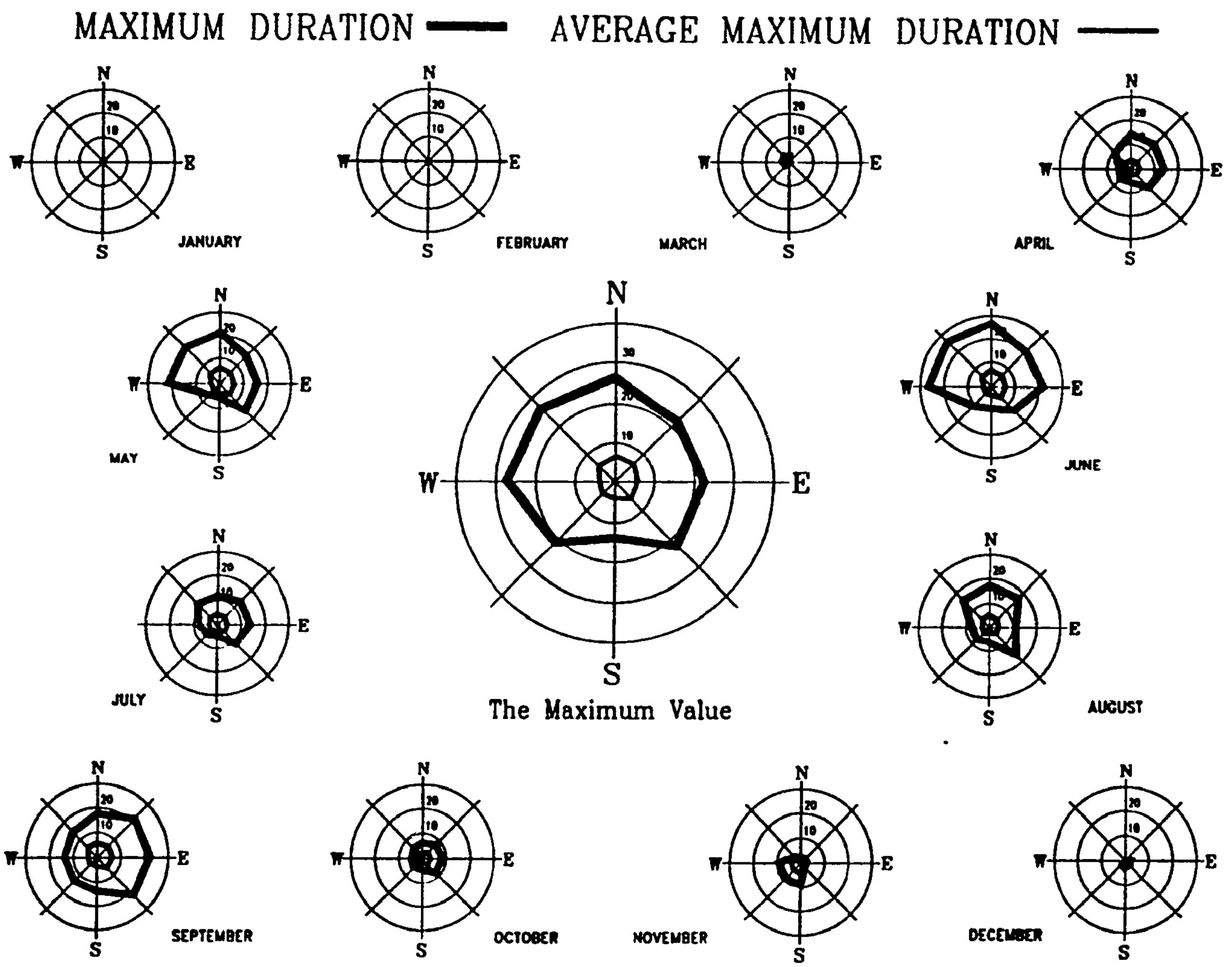


Fig. A55 Driving rain impact duration on a vertical surface (hr) - St. John's

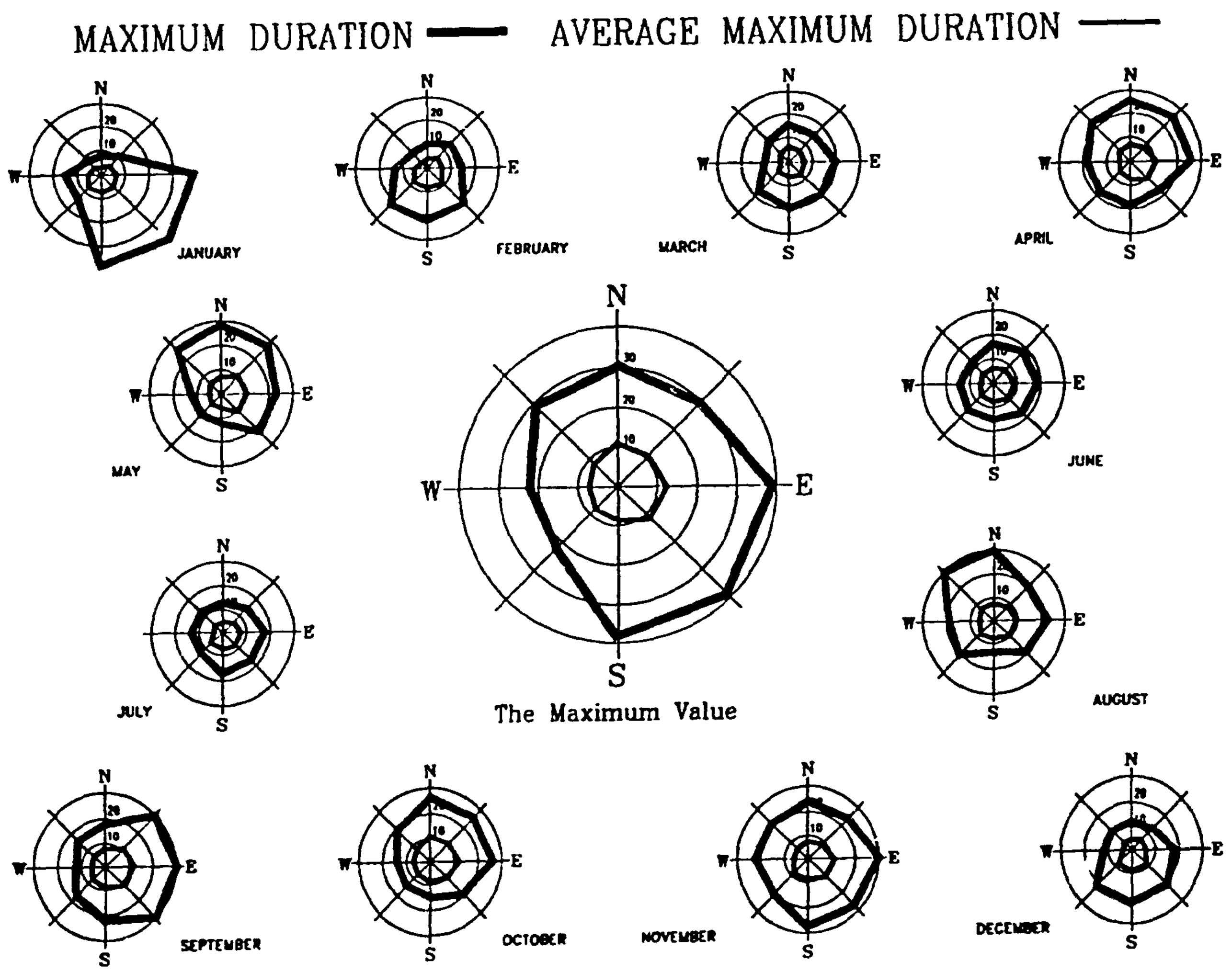


Fig. A56 Driving rain impact duration on a vertical surface (hr) - Toronto

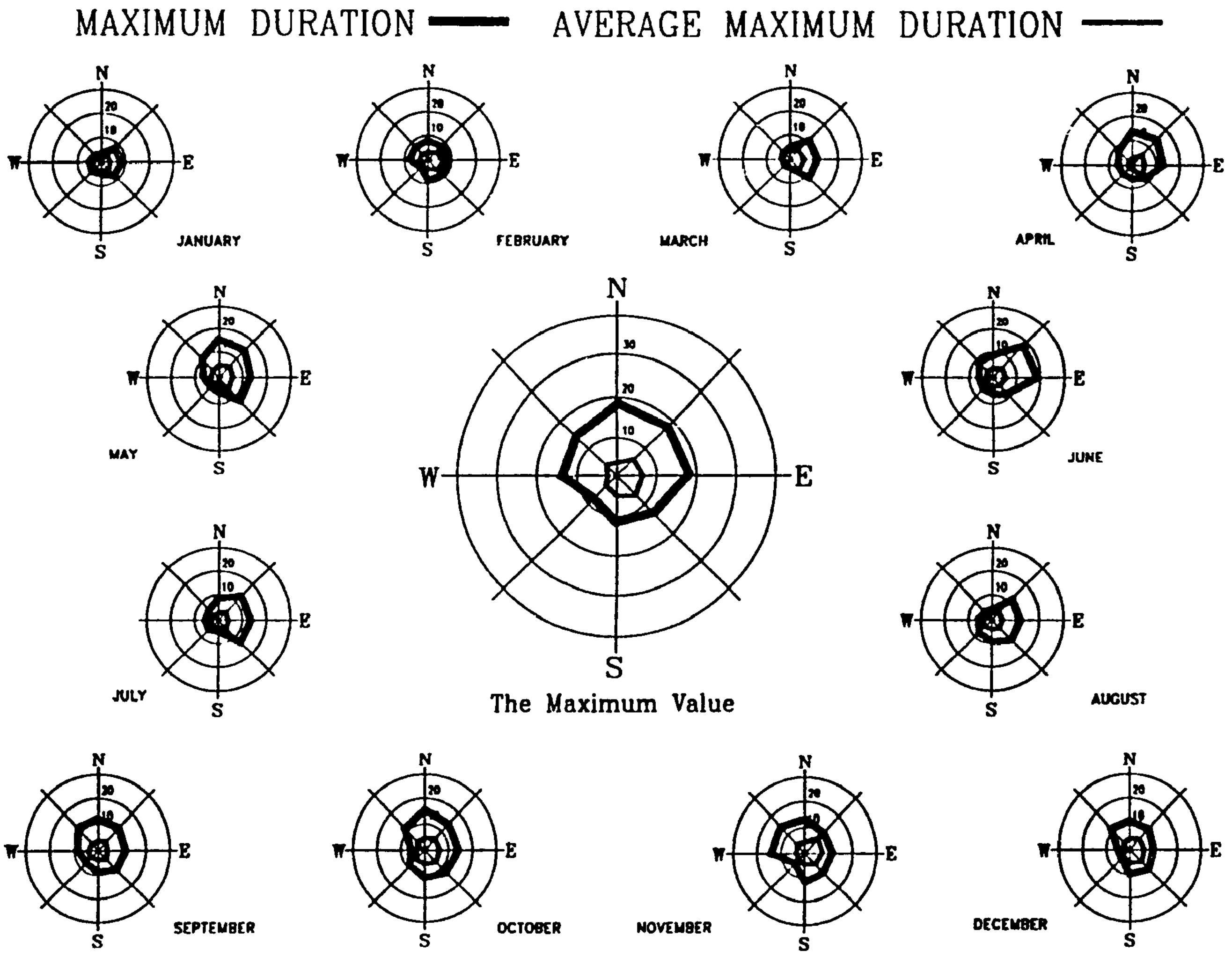


Fig. A57 Driving rain impact duration for a vertical surface (hr) - Vancouver

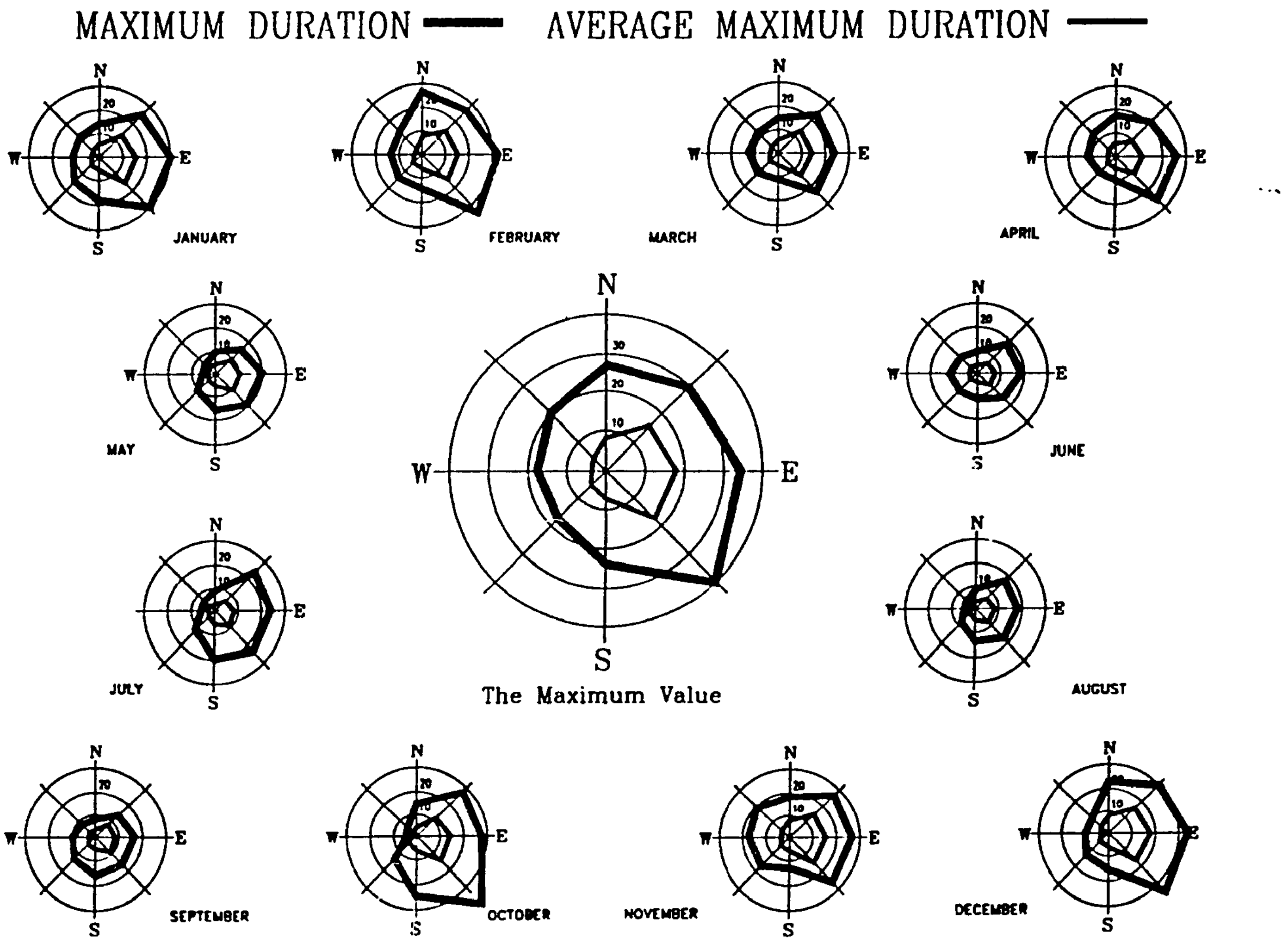


Fig. A58 Driving rain impact duration on a vertical surface (hr) - Victoria

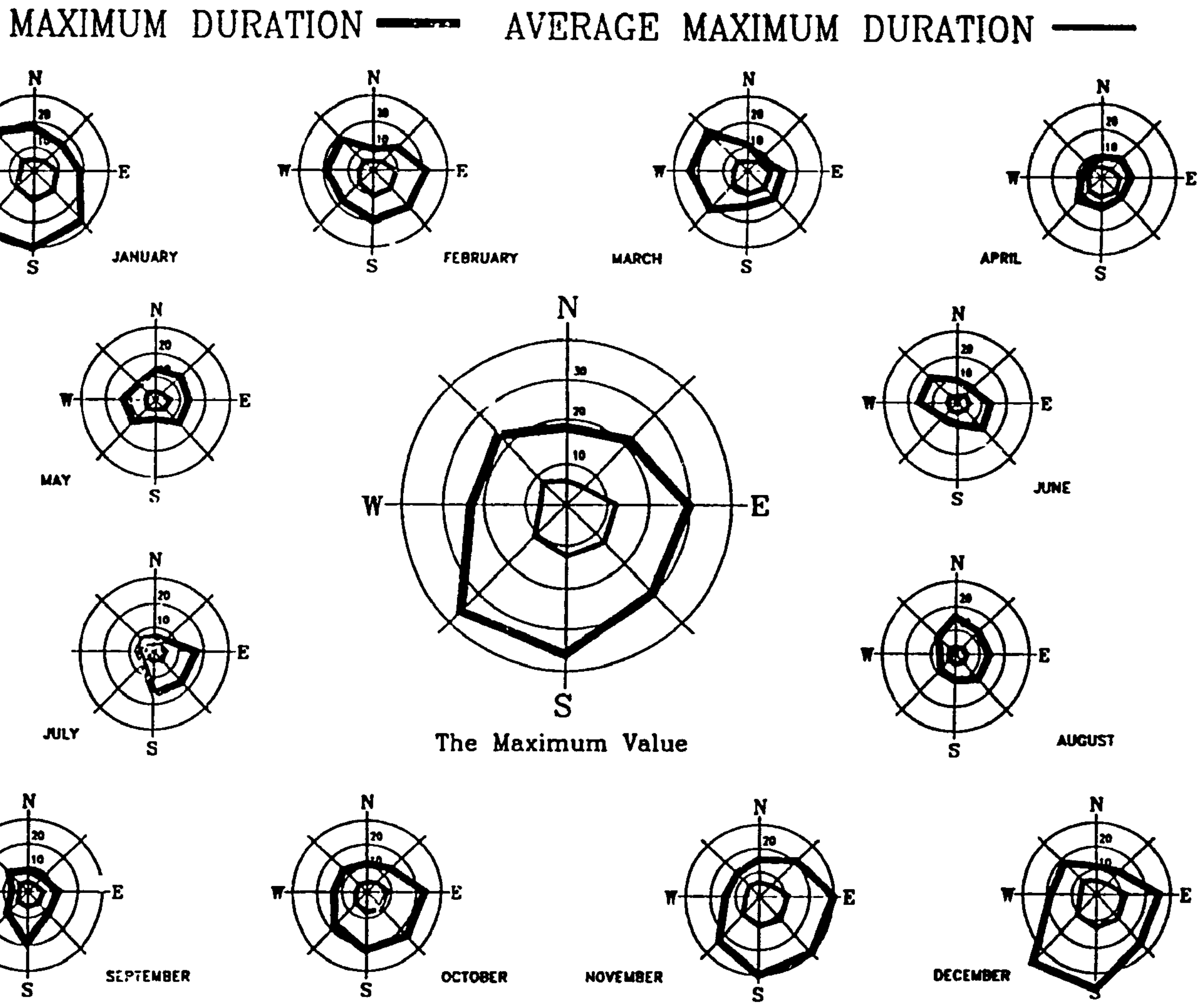


Fig. A59 Driving rain impact duration on a vertical surface (hr) - Winnipeg

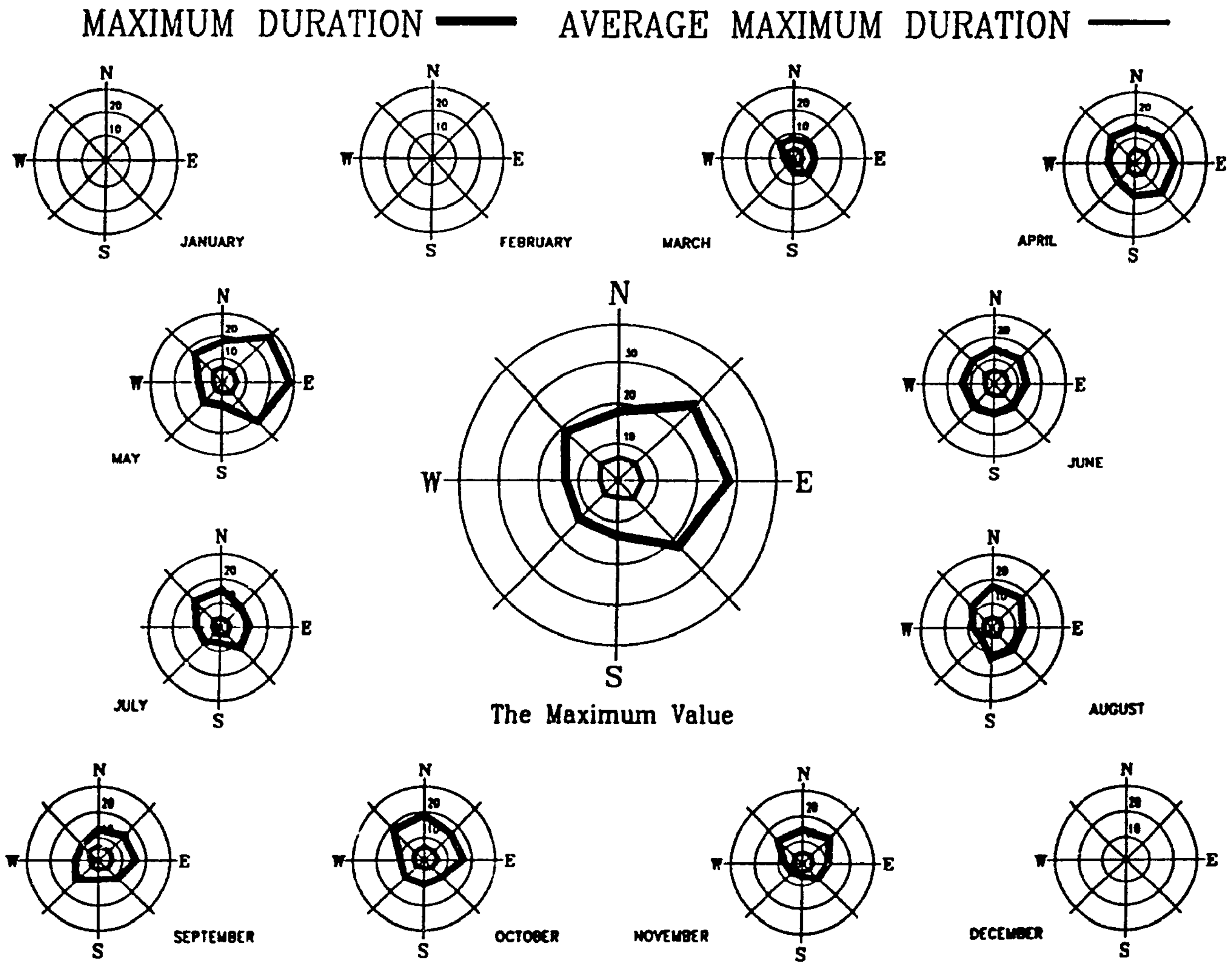
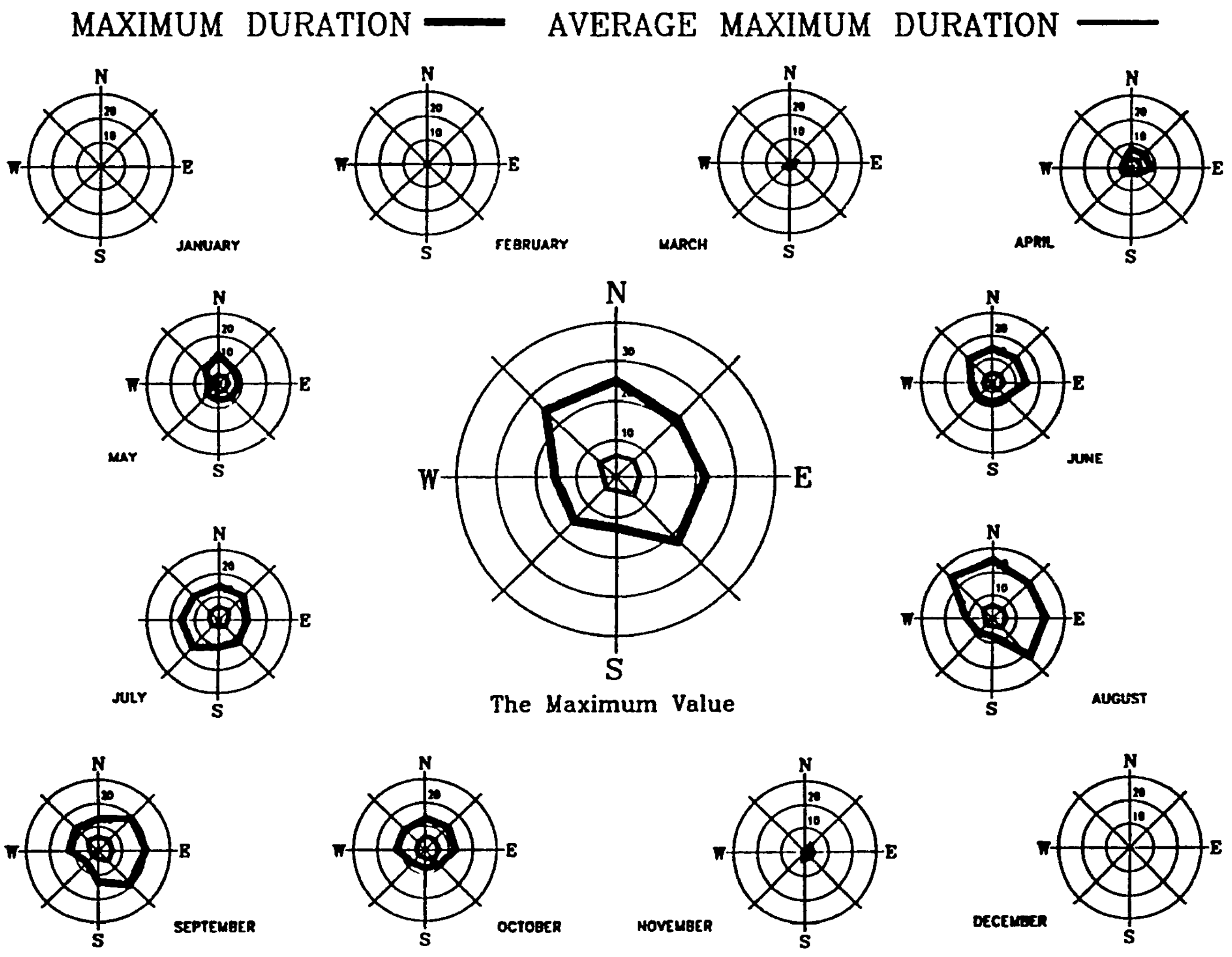


Fig. A60 Driving rain impact duration on a vertical surface (hr) - Yellowknife



Appendix III: Programs

Part A: Program for Computing The Driving Rain Precipitation, Intensity And Frequency on Vertical Surface

```
*************************************************************
                 program INTDRI300
*
*          this program is to comput the directional
*          rain frequency, rain precipitation and
*          intensity on each directional facade
*
*************************************************************
      parameter(PI=3.1415926)

*
      integer    stat1, stat2, u, signal,
     +           rye, rmon, rday,
     +           wye, wmon, wday, rye1, wye1,
     +           rmon1, wmon1, I, M, J, K,
     +           rain(24), winddr(24), windsp(24)
*
       real      gtr, gtsp, gth, gah, gyear, ypre(8),
     +           yth(8), ang,
     +           mtsp(8), mtr(8), mth(8), hin(8),
     +           mpre(8), mtin(8), mmth(8), maxhin(8),
     +           typre(8), tyth(8), year(8)

       real      tmpre(12,8), tmtin(12,8), tmmth(12,8),
     +           month(12,8), most(12,8), amost(12,8)

       real      tmtsp(12,8), tmtr(12,8), tmth(12,8),
     +           gmost(8), gamost(8), tmax(12,8)

       real      ayf(8), ampre(12,8), amin(12,8), amf(12,8),
     +           amsp(12,8), amr(12,8), aypre(8), sampre(8),
     +           samf(8)

       character*30 filnm1, filnm2, filnm3, site
******************************************************************************
c  hin(N):     hourly driving rain intensity on vertical surface for
c                each direction for a hour
c  maxhin(N):  maximum driving rain intensity on vertical surface for each
c                direction within one hour
c  most(M,N):  maximum driving rain intensity on vertical surface for each
c                direction for each specific month in whole period of time
******************************************************************************
       print*, ' enter the file name of rain data'
```

```
      read (*,'(A)') filnm1
      print*, ' enter the file name of wind data'
      read (*,'(A)') filnm2
      open (unit=10,file=filnm1,form='unformatted',status='old')
      open (unit=20,file=filnm2,form='unformatted',status='old')
*
     if (filnm1.eq.'m1018610'.and.filnm2.eq.'wh1018610') then
         site='Victoria'
         u=30
         filnm3='intdria.vic'
     elseif (filnm1.eq.'m1018620'.and.filnm2.eq.'wh1018620') then
         site='Victoria Airport'
         u=40
         filnm3='intdria.via'
     elseif (filnm1.eq.'m1108447'.and.filnm2.eq.'wh1108447') then
         site='Vancouver Airport'
         u=41
         filnm3='intdria.van'
     elseif (filnm1.eq.'m2204100'.and.filnm2.eq.'wh2204100') then
         site='Yellow Knife'
         u=42
         filnm3='intdria.yek'
     elseif (filnm1.eq.'m3012208'.and.filnm2.eq.'wh3012208') then
         site='Edmonton'
         u=43
         filnm3='intdria.edm'
     elseif (filnm1.eq.'m3031093'.and.filnm2.eq.'wh3031093') then
         site='Calgary'
         u=44
         filnm3='intdria.Cal'
     elseif (filnm1.eq.'m4016560'.and.filnm2.eq.'wh4016560') then
         site='Regina'
         u=45
         filnm3='intdria.reg'
     elseif (filnm1.eq.'m4057120'.and.filnm2.eq.'wh4057120') then
         site='Saskatoon'
         u=46
         filnm3='intdria.sas'
     elseif (filnm1.eq.'m5023222'.and.filnm2.eq.'wh5023222') then
         site='Winnipeg'
         u=47
         filnm3='intdria.win'
     elseif (filnm1.eq.'m6106000'.and.filnm2.eq.'wh6106000') then
         site='Ottawa International Airport'
         u=48
         filnm3='intdria.oia'
     elseif (filnm1.eq.'m6158443'.and.filnm2.eq.'wh6158443') then
         site='Toronto Downsview'
         u=49
         filnm3='intdria.tod'
     elseif (filnm1.eq.'m7016294'.and.filnm2.eq.'wh7016294') then
```

```
         site='Quebec City'
         u=50
         filnm3='intdria.quc'
      elseif (filnm1.eq.'m8101500'.and.filnm2.eq.'wh8101500') then
         site='Fredoricton'
         u=51
         filnm3='intdria.fre'
      elseif (filnm1.eq.'m8202250'.and.filnm2.eq.'wh8202250') then
         site='Halifax International Airport'
         u=52
         filnm3='intdria.hia'
      elseif (filnm1.eq.'m8205090'.and.filnm2.eq.'wh8205090') then
         site='Dartmouth'
         u=53
         filnm3='intdria.dar'
      elseif (filnm1.eq.'m8403506'.and.filnm2.eq.'wh8403506') then
         site='St. John"s'
         u=54
         filnm3='intdria.stj'
      elseif (filnm1.eq.'m7025250'.and.filnm2.eq.'wh7025250') then
         site='Montreal Dorval Airport'
         u=55
         filnm3='intdria.mda'
      elseif (filnm1.eq.'m1000000'.and.filnm2.eq.'wh1000000') then
         site='try data'
         u=56
         filnm3='intdria.try'
      else
        print*, 'data enter error, data from different stations'
        print *, filnm1, filnm2
        go to 9999
      endif
*
      open (unit=u,file=filnm3,status='new')
      write (u,*) 'intdr3.for'
      write (u,*)
      write (u,*) site
      print*
      print 120, site
  120 format (1X,A)
      write (u,*)
      print*
*
*
        rewind (unit=10)
        rewind (unit=20)
*
        signal=1

*
```

```
      call readformat(rye,rmon,rday,rain,wye,
     +                 wmon,wday,winddr,windsp,signal)
      write (u,*) ' FROM '
      write (u,130) rye, rmon, rday
      print*, ' FROM '
       print 130, rye, rmon, rday
 130   format (1X,I3,2X,I2,2X,I2)
*
  10 rye1=rye
    wye1=wye
*
    do 12 N=1,8
      ypre(N)=0
      yth(N)=0
 12  continue

  15 if (rye1.eq.rye.and.wye1.eq.wye) then
         rmon1=rmon
         wmon1=wmon
*
         do 18 N=1,8
            mpre(N)=0
            mtin(N)=0
            mmth(N)=0

            mtsp(N)=0
            mtr(N)=0
            mth(N)=0
            maxhin(N)=0
  18        continue
***********************************************************************
* CACULATE MONTHLY WINDSPEED AND RAIN PERCIPITATION
***********************************************************************
  20      if (rmon1.eq.rmon.and.wmon1.eq.wmon) then
            do 28 I=1,24
              if (rain(I).gt 0) then

                do 22 N=1,8
                  hin(N)=0.0
  22             continue

                gtr=rain(I)/10000.0+gtr
                gtsp=windsp(I)*10.0/36.0+gtsp
                gth=gth+1
*
          if (winddr(I).gt.0.and.winddr(I).le.4.5) then
              N=1
              ang=(2.0*PI/36.0)*winddr(I)
          endif
          if (winddr(I).gt.4.5.and.winddr(I).le.9) then
              N=2
```

```
             ang=(2.0*PI/36.0)*winddr(I)-(PI/4.0)
          endif
          if (winddr(I).gt.9.and.winddr(I).le.13.5) then
             N=3
             ang=(2.0*PI/36.0)*winddr(I)-(PI/2.0)
          endif
          if (winddr(I).gt.13.5.and.winddr(I).le.18) then
             N=4
             ang=(2.0*PI/36.0)*winddr(I)-(PI*3.0/4.0)
          endif
          if (winddr(I).gt.18.and.winddr(I).le.22.5) then
             N=5
             ang=(2.0*PI/36.0)*winddr(I)-PI
          endif
          if (winddr(I).gt.22.5.and.winddr(I).le.27) then
             N=6
             ang=(2.0*PI/36.0)*winddr(I)-(PI*5.0/4.0)
          endif
          if (winddr(I).gt.27.and.winddr(I).le.31.5) then
             N=7
             ang=(2.0*PI/36.0)*winddr(I)-(PI*6.0/4.0)
          endif
          if (winddr(I).gt.31.5.and.winddr(I).le.36) then
             N=8
             ang=(2.0*PI/36.0)*winddr(I)-(PI*7.0/4.0)
          endif
*

                J=N+1
                if (J.eq.9) then
                   J=1
                endif

                K=N-1
                if (K.eq.0) then
                   K=8
                endif

                L=K-1
                if (L.eq.0) then
                   L=8
                endif

                hin(L)=(2.0/9.0)*windsp(I)*(10.0/36.0)
     +             *((rain(I)/10000.0)**(8.0/9.0))
     +             *cos(ang+PI/4.0)
                hin(K)=(2.0/9.0)*windsp(I)*(10.0/36.0)
     +             *((rain(I)/10000.0)**(8.0/9.0))
     +             *cos(ang)
                hin(N)=(2.0/9.0)*windsp(I)*(10.0/36.0)
     +             *((rain(I)/10000.0)**(8.0/9.0))
```

```
     +              *cos(PI/4.0-ang)
                 hin(J)=(2.0/9.0)*windsp(I)*(10.0/36.0)
     +              *((rain(I)/10000.0)**(8.0/9.0))
     +              *cos(PI/2.0-ang)

                 do 25 N=1,8
                 if (hin(N).gt.maxhin(N)) then
                   maxhin(N)=hin(N)
                 endif
 25              continue

                 do 26 N=1,8
                   if (hin(N).gt.0) then
                     mpre(N)=mpre(N)+hin(N)
                     mtin(N)=mtin(N)+hin(N)
                     mmth(N)=mmth(N)+1
                   endif
 26              continue

             endif
 28        continue
*
          call readformat(rye,rmon,rday,rain,
     +                       wye,wmon,wday,winddr,
     +                       windsp,signal)
*
*************************************************************************
*  CACULATE YEARLY WINDSPEED AND RAIN PERCIPITATION
*************************************************************************
          if (signal.eq.0) then
           do 29 N=1,8
             if (mmth(N).gt.0) then
                 ypre(N)=ypre(N)+mpre(N)
                 yth(N)=yth(N)+mmth(N)
             endif
 29        continue
*************************************************************************
*   CACULATE YEARLY WIND SPEED AND RAIN PERCIPITATION FOR EACH
*   SPACIFIC MONTH
*************************************************************************
         do 31 M=1,12
            if (rmon1.eq.M) then
              do 32 N=1,8
                if (mmth(N).gt.0) then
                  tmpre(M,N)=mpre(N)+tmpre(M,N)
                  tmtin(M,N)=mtin(N)+tmtin(M,N)
                  tmmth(M,N)=mmth(N)+tmmth(M,N)
                  month(M,N)=month(M,N)+1

                  tmax(M,N)=maxhin(N)+tmax(M,N)
```

```
                    if (maxhin(N).gt.most(M,N)) then
                       most(M,N)=maxhin(N)
                    endif
                  endif
 32              continue
               endif
 31         continue
**********************************************************************
*     SUM UP YEARLY DRIVING RAIN PRECIPITATION ON VERTICAL SURFACE
**********************************************************************
         gyear=gyear+1

         do 33 N=1,8
           typre(N)=ypre(N)+typre(N)
           tyth(N)=tyth(N)+yth(N)
           year(N)=year(N)+1
 33      continue

**********************************************************************
*
       go to 99
*
       else
          go to 20
       endif
*
       endif
*      write(u,*) rye, rmon
       print*, rye, rmon
**********************************************************************
*  SUM UP MONTHLY RAIN PRECIPITATION ON VERTICAL SURFACE
**********************************************************************
            do 37 N=1,8
               if (mmth(N).gt.0) then
                 ypre(N)=ypre(N)+mpre(N)
                 yth(N)=yth(N)+mmth(N)
               endif
 37         continue
**********************************************************************
*    CACULATE DRIVING RAIN INTENSITY AND PRECIPITATION ON EACH
*    DIRECTIONAL FACADE FOR EACH SPECIFIC MONTH
**********************************************************************
            do 38 M=1,12
              if (rmon1.eq.M) then
                do 39 N=1,8
                 if (mmth(N).gt.0) then
                   tmpre(M,N)=mpre(N)+tmpre(M,N)
                   tmtin(M,N)=mtin(N)+tmtin(M,N)
                   tmmth(M,N)=mmth(N)+tmmth(M,N)
                   month(M,N)=month(M,N)+1
```

```
                    tmax(M,N)=maxhin(N)+tmax(M,N)

                    if (maxhin(N).gt.most(M,N)) then
                       most(M,N)=maxhin(N)
                    endif
                 endif
  39            continue
              endif
  38        continue

*********************************************************************
        go to 15
     endif
*********************************************************************
*    SUM UP THE YEARLY DIRECTIONAL DRIVING RAIN PRECIPITATION
*********************************************************************
        gyear=gyear+1

        do 40 N=1,8
           typre(N)=ypre(N)+typre(N)
           tyth(N)=tyth(N)+yth(N)
           year(N)=year(N)+1
 40     continue
*********************************************************************
     go to 10
*********************************************************************
 99  gasp=gtsp/gth
     gayr=gtr/gyear
     gah=gth/gyear
*********************************************************************
*    THE YEARLY DIRECTIONAL RAIN PRECIPITATION AND FREQUENCY
*********************************************************************
     do 45 N=1,8
       aypre(N)=typre(N)/year(N)
       ayf(N)=tyth(N)/year(N)
 45  continue
*********************************************************************
*    THE MONTHLY RAIN PRECIPITATION AND INTENSITY ON DIRECTIONAL
*     VERTICAL SURFACE
*********************************************************************

     do 46 M=1,12
       do 47 N=1,8
       if (month(M,N).gt.0) then
          ampre(M,N)=tmpre(M,N)/month(M,N)
          amin(M,N)=tmtin(M,N)/tmmth(M,N)
          amf(M,N)=tmmth(M,N)/month(M,N)
          amost(M,N)=tmax(M,N)/month(M,N)

*           if (tmth(M,N).gt.0) then
*         amsp(M,N)=tmtsp(M,N)/tmth(M,N)
```

```
*           amr(M,N)=tmtr(M,N)/month(M,N)
*              endif

        endif
 47      continue
 46   continue
*************************************************************************
* SUM OF THE MONTHLY DIRECTIONAL PRECIPITATION AND RAIN HOURS
*************************************************************************
       do 51 N=1,8
         do 52 M=1,12
           sampre(N)=sampre(N)+ampre(M,N)
           samf(N)=samf(N)+amf(M,N)
 52      continue
 51   continue
*************************************************************************
* SELECT LARGEST INTENSITY FOR EACH DIRECTION
*************************************************************************
       do 48 N=1,8
         do 49 M=1,12
           if (amost(M,N).gt.gamost(N)) then
              gamost(N)=amost(M,N)
           endif
           if (most(M,N).gt.gmost(N)) then
              gmost(N)=most(M,N)
           endif
 49      continue
 48   continue
*************************************************************************
       write (u,*) ' TO '
       write (u,130) rye, rmon, rday
       write (u,*)
       write (u,*) 'average yearly rain precipitation (horizantal) during
      + the wind is'
       write (u,140) gayr
 140  format (1x,f10.8,' m ')
       write (u,*)
       write (u,*) ' average windspeed during the rain is '
       write (u,150) gasp
 150  format (1x,f12.5,' m/s ')
       write (u,*)
*      write (u,*) ' yearly DRI is '
*      write (u,160) gydri
 160  format (1x,f12.5,' m*m/s year ')
       write (u,*)
       write (u,*) ' the average number of hours of driving rain in
      +             one year is'
       write (u,170) gah
 170  format (1x,f12.2, ' hours ')
       print*, ' TO '
       print 130, rye, rmon, rday
```

```
      print*
      print*, 'average yearly rain precipitation during the wind is '
      print 140, gayr
      print*
      print*, ' average windspeed during the wind is '
      print 150, gasp
      print*
*
      write (u,*)
      write (u,*) 'driving rain intensity on each directional
     + facade for each specific months'
       call output2(u,amin)
*
      write (u,*)
      write (u,*) 'driving rain pecivpitation on each directional
     + facade for each specific months'
       call output2(u,ampre)
*
      write (u,*)
      write (u,*) 'number of hours of each directional driving
     + rain in each month'
       call output2(u,amf)
*
      write (u,*)
      write (u,*) 'average driving rain intensity on each
     + directional facade for each month'
       call output2(u,inmm)
*
      write (u,*)
      write (u,*) 'the average maximum driving rain intensity on vertical
     + surface for each direction for each month'
       call output2(u, amost)
*
      write (u,*)
      write (u,*) 'the maximum driving rain intensity on vertical surface
     + for each direction for each month in whole period of time'
       call output2(u, most)
*
      write (u,*)
      write (u,*)' the maximum average maximum intensity values for each
     + directions'
       call output1(u, gamost)
*
      write (u,*)
      write (u,*)'the maximum maximum intensity values for each
     + direction'
       call output1(u, gmost)
*
      write (u,*)
      write (u,*)'the sum of monthly directional precipitation on
```

```
     + the facade (mm)'
       call output1(u, sampre)
*
      write (u,*)
      write (u,*)'the sum of monthly directional hours of effect time
     + of rain (hr)'
       call output1(u, samf)


 9999 end
*
*-------------------------------------------------------------------*
           subroutine output1(u,output)
*
* this subroutine is a format for output the data
       integer L, N, u
       real output(8)
       L=0
       do 2  N=1,8
           L=45+L
           write (u,200) L, output(N)
 2      continue
 200     format (1x,I3,1x,f10.3)
       return
       end
*
*-------------------------------------------------------------------*
           subroutine output2(u,output)
*
* this subroutine is a format for output the data
       integer L, M, N, u
       real output(12, 8)
       do 2 M=1,12
          L=0
          do 4 N=1,8
              L=45+L
              write(u,200) L, output(M, N)
 4         continue
 2      continue
 200     format (1x,I3,1x,f10.3)
       return
       end
*
*-------------------------------------------------------------------*
          subroutine output3(u,output)
* this subroutine is a format for output the data
       integer L, M, N, u, output(12,8)
       do 2 M=1,12
           L=0
           do 4 N=1,8
                 L=45+L
```

```
                    write(u,300) L, output(M,N)
 4               continue
 2          continue
 300         format (1x,I3,1x,I5)
           return
           end
*
*-------------------------------------------------------------------------*
             subroutine output4(u,output)
*  this subroutine is format for output the data
            integer L, N, u, output(8)
            L=0
            do 2 N=1,8
                L=45+L
                write(u,300) L, output(N)
 2          continue
 300         format (1x,I3,1x,I5)
            return
            end
*
*-------------------------------------------------------------------------*
                subroutine readformat(rye,rmon,rday,rain,
    +                                    wye,wmon,wday,winddr,
    +                                    windsp,signal)
*
* this subroutine is a reading format for the data from
*      the Environnment of Canada
*
          integer rye, rmon, rday,  rain(24), wye, wmon, wday,
    +                   winddr(24), windsp(24), rdate,
    +                   wdate, signal, I, mid(24)
*
          signal=1
*
 1         read(10,end=20) rye, rmon, rday, null, rain
          read(20,end=20) wye, wmon, wday, null, winddr
          read(20,end=20) null, null, null, null, windsp
*
          rdate=rye*10000+rmon*100+rday
          wdate=wye*10000+wmon*100+wday
*
  10   if (rdate.ne.wdate) then
           if (rdate.gt.wdate) then
              read(20, end=20) wye, wmon, wday, null, winddr
              read(20 ,end=20) null, null, null, null, windsp
              wdate=wye*10000+wmon*100+wday
           else
              read(10,end=20) rye, rmon, rday, fl, rain
              rdate=rye*10000+rmon*100+rday
           endif
           go to 10
```

```
       endif
*
       if (rdate.ge.9710101) then
         do 2 I=1,24
           mid(I)=winddr(I)
           winddr(I)=windsp(I)
           windsp(I)=mid(I)
 2       continue
       endif
*
       do 40 I=1,24
         if (rain(I).lt.0.or.rain(I).eq.0) then
           windsp(I)=0
           winddr(I)=0
         endif
 40    continuc
*
       do 50 I=1,24
         if (windsp(I).lt.0.or.windsp(I).eq.0) then
           rain(I)=0
           winddr(I)=0
         endif
 50    continue
*
       return
*
 20    signal=0
       return
       end
*
*----------------------------------------------------------------------*
```

Part B: Program for Computing The Impact Duration of Driving Rain on A Vertical Surface

```
******************************************************************************
                    program TIME2
*
*     this program is to comput the mean and maximum of
*     impact duration of driving rain for each month and
*     direction.
*
******************************************************************************
C     wsp(N,I)    hourly wind speed for each direction
C     rin(N,I)    hourly rain precipitation on ground for each
C                 direction
C     uch (N)     uncontinueal driving rain duration for each direction
C     ch(N)       continueal driving rain duration for each direction
C     mcht(N)     the sum of directional driving rain duration for a month
C     nummc(N)    numbers of driving rain for each direction
C     mmach(N)    the longest directional driving rain duration for each
C                 time in a month
C     mch(N)      the mean directional duration of driving rain in a month
C     mt(N)       the number of months which have directional driving rain
C     ycht(N)     the sume of mean monthly directional driving rain
C                 duration for a year for each direction
C     moch(M,N)   the mean directional driving rain duration for a
C                 specific month for each direction
C     momach(M,N) the maximum directional driving rain duration for specific
C                 month
C     ych(N)      the mean directional driving rain duration for a year
C                 for each direction
C     tcht(N)     the sum of yearly directional driving rain duration
C                 for wholl period of time
C     tmmach(M,N) the sum of monthly directional maximum driving rain
C                 duration for wholl period
C     tmt(M,N)    the number of specific month which have directional
C                 driving rain
C     gych(N)     the mean yearly directional driving rain duration
C     gmch(M,N)   the mean monthly directional driving rain duration for
C                 a specific month
C     gmmach(M,N) the mean maximun directional driving rain duration for
C                 a spectfic month
C     most(M,N)   the maximun directional driving rain duration for a
C                 spectfic month during this whole period
C     mmax(N)     the maximum values among gmmach(M,N)
C     max(N)      the maximum values among most(M,N)
******************************************************************************
      integer u, N, M, yt(8), tmt(12,8), ryel, rye, wyel, wye, rmon1,
     +        rmon, wmon1, wmon, winddr(24),
     +        rain(24), J, K, s, uch(8), ch(8), numc(8), mmach(8),
     +        rday, wday, mt(8), signal, windsp(24), w(8)
```

```
real  tcht(8), tmch(12,8), tmmach(12,8), moch(12,8),
+     momach(12,8), mcht(8), mch(8), ych(8), ycht(8), gych(8),
+     gmch(12,8), gmmach(12,8), most(12,8), max(8), mmax(8)

   character*30 filnm1, filnm2, filnm3, site

   print*, ' enter the file name of rain data '
   read (*, '(A)') filnm1
   print*, ' enter the file name of wind data '
   read (*, '(A)') filnm2
open (unit=10, file=filnm1, form='unformatted', status='old')
open (unit=20, file=filnm2, form='unformatted', status='old')

if (filnm1.eq.'m1018610'.and.filnm2.eq.'wh1018610') then
     site='Victoria'
     u=30
     filnm3='drdu.vic'
elseif (filnm1.eq.'m1018620'.and.filnm2.eq.'wh1018620') then
     site='Victoria Airport'
     u=40
     filnm3='drdu.via'
elseif (filnm1.eq.'m2204100'.and.filnm2.eq.'wh2204100') then
     site='Yellow Knife'
     u=41
     filnm3='drdu.yel'
elseif (filnm1.eq.'m1108447'.and.filnm2.eq.'wh1108447') then
     site='Vancouver Airport'
     u=42
     filnm3='drdu.van'
elseif (filnm1.eq.'m3012208'.and.filnm2.eq 'wh3012208') then
     site='Edmonton'
     u=43
     filnm3='drdu.edm'
elseif (filnm1.eq.'m3031093'.and.filnm2.eq.'wh3031093') then
     site='Calgary'
     u=44
     filnm3='drdu.cal'
elseif (filnm1.eq 'm4016560'.and.filnm2.eq.'wh4016560') then
     site='Regine'
     u=45
     filnm3='drdu.reg'
elseif (filnm1.eq.'m4057120'.and.filnm2.eq.'wh4057120') then
     site='Saskatoon'
     u=46
     filnm3='drdu.sas'
elseif (filnm1.eq.'m5023222'.and.filnm2.eq.'wh5023222') then
     site='Winnipeg'
     u=47
     filnm3='drdu.win'
elseif (filnm1.eq.'m6106000'.and.filnm2.eq.'wh6106000') then
     site='Ottawa International Airport'
```

```
          u=48
          filnm3='drdu.ott'
      elseif (filnm1.eq.'m6158443'.and.filnm2.eq.'wh6158443') then
          site='Toronto downsview'
          u=49
          filnm3='drdu.tor'
      elseif (filnm1.eq.'m7016294'.and.filnm2.eq.'wh7016294') then
          site='Quebec City'
          u=50
          filnm3='drdu.que'
      elseif (filnm1.eq.'m8101500'.and.filnm2.eq.'wh8101500') then
          site='fredoricton'
          u=51
          filnm3='drdu.fre'
      elseif (filnm1.eq.'m8202250'.and.filnm2.eq.'wh8202250') then
          site='Halifax Internation Airport'
          u=52
          filnm3='drdu.hal'
      elseif (filnm1.eq.'m8205090'.and.filnm2.eq.'wh8205090') then
          site='Dartmouth'
          u=53
          filnm3='drdu.dar'
      elseif (filnm1.eq.'m8403506'.and.filnm2.eq.'wh8403506') then
          site='St. John''s'
          u=54
          filnm3='drdu.stj'
      elseif (filnm1.eq.'m7025250'.and.filnm2.eq.'wh7025250') then
          site='Montreal'
          u=55
          filnm3='drdu.mon'
      elseif (filnm1.eq.'m1000000'.and.filnm2.eq.'wh1000000') then
          site='test'
          u=56
          filnm3='drdu.tst'
      else
          print*, 'data enter error, data from different stations'
          print*,  filnm1, filnm2
          go to 9999
      endif

      open (unit=u, file=filnm3, status='new')
      write (u,*) 'time2.for'
      write (u,*)
      write (u,*) site
      print*
      print 500, site
500   format (1x,A)
      write (u,*)
      print*

      rewind (unit=10)
```

```
      rewind (unit=20)

      signal=1

      do 250 N=1,8
        tcht(N)=0
        yt(N)=0
        mmax(N)=0
        max(N)=0
250   continue

      do 260 M=1,12
        do 270 N=1,8
          tmch(M,N)=0
          tmmach(M,N)=0
          tmt(M,N)=0
          most(M,N)=0
270     continue
260   continue

      call readformat(rye, rmon, rday, rain, wye, wmon, wday,
     +                winddr, windsp, signal)

      write(u,*) ' From '
      write(u,510) rye, rmon, rday

      print*, ' from '
      print 510, rye, rmon, rday

510   format (1X, I3, 2X, I2, 2X, I2)

140     rye1=rye
        wye1=wye

        do 210 N=1,8
          tcht(N)=0
          yt(N)=0
210     continue

        do 221 M=1,12
          do 231 N=1,8
            moch(M,N)=0
            momach(M,N)=0
231       continue
221     continue

110   if (rye1.eq.rye.and wye1.eq.wye) then

        rmon1=rmon
        wmon1=wmon
```

```
      do 240 N=1,8
        mch(N)=0
        mcht(N)=0
        mmach(N)=0
        if (ch(N).gt.1) then
          numc(N)=1
        else
          numc(N)=0
        endif
240   continue

70 if (rmon1.eq.rmon.and.wmon1.eq.wmon) then

      do 10 I=1,24
        do 11 N=1,8
          w(N)=0
11        continue

        if (rain(I).gt.0) then
          if (winddr(I).eq.0.or.winddr(I).eq.36) then
            w(1)=1
            w(7)=1
            w(8)=1
            endif
          if (winddr(I).gt.0.and.winddr(I).lt.4.5) then
            w(1)=1
            w(2)=1
            w(7)=1
            w(8)=1
            endif
          if (winddr(I).gt.4.5.and.winddr(I).lt.9) then
            w(1)=1
            w(2)=1
            w(3)=1
            w(8)=1
            endif
          if (winddr(I).eq.9) then
            w(1)=1
            w(2)=1
            w(3)=1
            endif
          if (winddr(I).gt.9.and.winddr(I).lt.13.5) then
            w(1)=1
            w(2)=1
            w(3)=1
            w(4)=1
            endif
          if (winddr(I).gt.13.5.and.winddr(I).lt.18) then
            w(2)=1
            w(3)=1
            w(4)=1
```

```
            w(5)=1
            endif
          if (winddr(I).eq.18) then
            w(3)=1
            w(4)=1
            w(5)=1
            endif
          if (winddr(I).gt.18.and.winddr(I).lt.22.5) then
            w(3)=1
            w(4)=1
            w(5)=1
            w(6)=1
            endif
          if (winddr(I).gt.22.5.and.winddr(I).lt.27) then
            w(4)=1
            w(5)=1
            w(6)=1
            w(7)=1
            endif
          if (winddr(I).eq.27) then
            w(5)=1
            w(6)=1
            w(7)=1
            endif
          if (winddr(I).gt.27.and.winddr(I).lt.31.5) then
            w(5)=1
            w(6)=1
            w(7)=1
            w(8)=1
            endif
          if (winddr(I).gt.31.5.and.winddr(I).lt.36) then
            w(6)=1
            w(7)=1
            w(8)=1
            w(9)=1
            endif
        endif
*
      do 12 N=1,8
       if (w(N).eq.1) then
         uch(N)=0
         ch(N)=ch(N)+1
         if (ch(N).eq.1) then
           numc(N)=numc(N)+1
         endif
       endif

       if (w(N).eq.0) then
         uch(N)=uch(N)+1
         If (uch(N).eq.1) then
           mcht(N)=ch(N)+mcht(N)
```

```
               If (ch(N).gt.mmach(N)) then
                  mmach(N)=ch(N)
               endif
               ch(N)=0
           endif
         endif
12        continue
10        continue

      call readformat (rye, rmon, rday, rain, wye, wmon,
     +                wday, winddr, windsp, signal)

        if (signal.eq.0) then

           do 81 N=1,8
              if (ch(N).gt.0) then
                  numc(N)=numc(N)-1
              endif
81          continue

           do 80 N=1,8
              if (numc(N).gt.0) then
                 mch(N)=mcht(N)/numc(N)
                 mt(N)=mt(N)+1
                 ycht(N)=ycht(N)+mch(N)
             endif
80         continue

          do 90 M=1,12
             if (rmon1.eq.M) then
                do 100 N=1,8
                   if (mch(N).gt.0) then
                      moch(M,N)=mch(N)
                      momach(M,N)=mmach(N)
                      if (momach(M,N).gt.most(M,N)) then
                         most(M,N)=momach(M,N)
                      endif
                   endif
100              continue
             endif
90         continue

          do 111 N=1,8
             if (mt(N).gt.0) then
                ych(N)=ycht(N)/mt(N)
                tcht(N)=tcht(N)+ych(N)
                yt(N)=yt(N)+1
            endif
111        continue

          do 120 M=1,12
```

```
          do 130 N=1,8
            if (moch(M,N).gt.0) then
              tmch(M,N)=moch(M,N)+tmch(M,N)
              tmmach(M,N)=tmmach(M,N)+momach(M,N)
              tmt(M,N)=tmt(M,N)+1
            endif
130         continue
120       continue

        goto  999
      endif

      go to 70

    endif

    print*, rye, rmon

    do 181 N=1,8
      if (ch(n).gt.0) then
        numc(N)=numc(N)-1
      endif
181 continue

    do 180 N=1,8
      if (numc(N).gt.0) then
        mch(N)=mcht(N)/numc(N)
        mt(N)=mt(N)+1
        ycht(N)=ycht(N)+mch(N)
      endif
180 continue

    do 190 M=1,12
      if (rmon1.eq.M) then
        do 200 N=1,8
          if (mch(N).gt.0) then
            moch(M,N)=mch(N)
            momach(M,N)=mmach(N)
            if (momach(M,N).gt.most(M,N)) then
              most(M,N)=momach(M,N)
            endif
          endif
200     continue
      endif
190 continue

    go to 110

    endif

    do 211 N=1,8
```

```
         if (mt(N).gt.0) then
            ych(N)=ycht(N)/mt(N)
            tcht(N)=tcht(N)+ych(N)
            yt(N)=yt(N)+1
         endif
211   continue

      do 220 M=1,12
         do 230 N=1,8
            if (moch(M,N).gt.0) then
               tmch(M,N)=moch(M,N)+tmch(M,N)
               tmmach(M,N)=tmmach(M,N)+momach(M,N)
               tmt(M,N)=tmt(M,N)+1
            endif
230      continue
220   continue

      go to 140

999   do 150 N=1,8
      if (tcht(N).gt.0) then
         gych(N)=tcht(N)/yt(N)
      endif
150   continue

      do 170 M=1,12
         do 160 N=1,8
            if (tmt(M,N).gt.0) then
               gmch(M,N)=tmch(M,N)/tmt(M,N)
               gmmach(M,N)=tmmach(M,N)/tmt(M,N)
            endif
160      continue
170   continue

      do 310 M=1,12
         do 320 N=1,8
            if (gmmach(M,N).gt.mmax(N)) then
                mmax(N)=gmmach(M,N)
            endif
            if (most(M,N).gt.max(N)) then
                max(N)=most(M,N)
            endif
320      continue
310   continue

      print*, ' To '
      print 510, rye, rmon, rday
      print*
```

(the output portion of this program is not listed here)